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Oil Sands and Production Relations

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CONTENTS

ILLUSTRATIONS

INTRODUCTION

PURPOSE OF REPORT

The purpose of this report is to present to the general public and especially to the average oil man engaged in the drilling and production branches of the Petroleum Industry, a brief outline and selected bibliography of the generally accepted opinions of geologists, drillers, petroleum engineers, and production superintendents regarding oil sands and production relations.

The Petroleum Industry, since its beginning in Pennsylvania in 1859 with the completion of the Drake well, probably has had the highest average type of personnel of any of our American industries. For this very reason, during the first fifty years of the life of the Industry, very little need was felt for the keeping of detailed well-records during drilling and during the subsequent production life of the well. Only within the past fifteen years, with the phenomenal growth of the industry, with the greater depth of wells, and with the larger variety of drilling and operating difficulties, has there been a general realization of the need of detailed written records of well completions and production results, in order that those in charge of production, who generally have had nothing to do with the drilling of the well, may have reliable information regarding the condition of each well so that they will not be compelled to work blindly and probably ineffectively.

SCOPE OF REPORT

This report deals with types of oil reservoir rocks or oil sands; structural features favorable for oil and gas accumulation; the physical character of oil sands; subsurface information secured during drilling which will later be of great value to the oil producer; factors which affect oil recovery, depending upon the type of oil sand and the character of the oil produced; methods for oil well rejuvination; effectiveness of oil recovery methods; and the probable trend of future production methods.

This paper does not go into the discussion of different types of equipment used in oil wells, nor does it consider the details of various production methods.

Equipment and methods used in oil wells are discussed in a United States Bureau of Mines bulletin now being prepared by the senior author.

ACKNOWLEDGMENTS

In this report the writers have drawn freely from the following sources of information:

Publications of the United States Bureau of Mines, publications of the United States Geological Survey, bulletins of the American Institute of Mining Engineers, bulletins of the American Association of Petroleum Geologists, bulletins of the various state geological and mining surveys, various text-books dealing with geological and production problems in the Petroleum Industry; data published in the Oil and Gas Journal, the Oil Weekly, the National Petroleum News, the Oil Age, and other trade journals; data secured from operators in the Oil Fields; and data from personal observation in the laboratory and the field.

Acknowledgment for the drawings is due Mrs. Bess Mills-Bullard of the Oklahoma Geological Survey.

Prof. Fred W. Padgett and Dr. V. E. Monnett of the University of Oklahoma faculty have made helpful suggestions.

OIL RESERVIOR ROCKS - OIL SANDS

The term "oil sand" is applied to all types of rocks which serve as natural reservoirs for petroleum. The term originated in Pennsylvania where the oil reservoir rocks in the first wells drilled were sandstones. These sandstones, after being finely pulverized by the drilling operations and when brought to the surface in the bailer, appeared to the driller as sand, hence the name "oil sand."

Sedimentary rocks, or rocks the components of which have been deposited from suspension in water, usually present the best conditions for the accumulation of oil. Common rocks of this type are sandstones, limestones, and shales.

Igneous rocks, or those that have been produced by the cooling of a molten rock mass, because of their usually dense character when in place and unaltered, seldom serve as oil reservoirs. Typical rocks of this class are granites and basalts (trap rocks). However, sands and gravels composed largely of igneous rock material which has been removed from the original igneous rock mass by weathering and erosion sometimes serve as oil reservoir rocks.

SANDSTONES AND CONGLOMERATES

Sands consist of fine, loose fragments of rocks. These fragments or grains are usually less than one-eighth of an inch in diameter, but when larger they are called gravels. These fragments or grains are usually water worn, and generally consist of the harder minerals, of which quartz (SiO_2) is generally the most predominant. When sand is consolidated in nature by being cemented by quartz, lime ($CaCO_3$), iron oxides, or other minerals, then a sandstone is formed. Loose accumulations of water worn pebbles and boulders are called gravels; and in the same manner that sands become sandstones, gravels become conglomerates by consolidation due to mineral cementation.

Sandstones and conglomerates are usually classified as hard. friable, loosely consolidated, etc. These terms generally depend in their use, more upon the kind and amount of cementing material than upon the kind of mineral material of which the sandstones and conglomerates are mostly composed.

Most of the California oil fields produce from loosely cemented sandstones and conglomerates. Most of the Oklahoma oil fields produce from consolidated sandstones, varying from soft and friable to hard and firm. Most Pennsylvania and West Virginia oil fields produce from hard, fine-grained sandstones and hard, compact conglomerates.

Uniformity in size and shape of grains and pebbles, rather than actual size, produces high porosity in sandstones and conglomerates. If all of the grains of sand in a sandstone or all of the pebbles in a conglomerate were true spheres of the same size, it could be demonstrated mathematically that the porosity would be about 26 per cent. However, if the spherical grains or pebbles were of different sizes in the same sandstone or conglomerate, then the porosity would be much less, due to the smaller spheres filling the spaces between the larger.

Sandstones and conglomerates generally are made up of rock fragments of different sizes, so that the porosity generally is less than 26 per cent. Eleven samples of sandstone tested by the United States Geological Survey showed a range of porosity of 10.5 to 19.3 per cent. Only when the sandstone grains are of irregular and angular shape and of a close range in size, can the porosity be greater than 26 per cent.

The porosity of some of the loosely cemented and unconsolidated sands of the California oil fields sometimes has been as high as 35 per cent; and the porosity of some of the hard, dense, fine-grained sandstones of Pennsylvania, sometimes has been as low as .7.5 per cent.

Conglomerates, if not containing much sand and mud, and if not thoroughly cemented, may have porosites as great as sandstones.

LIMESTONES

Limestones are rocks which are composed chiefly or in part of calcium carbonate ($CaCO_3$), commonly known as lime. When a considerable amount of magnesium carbonate ($MgCO_3$) is present, such limestones are known as dolomites or dolomitic limestones. When a considerable amount of clay is present, they are known as argillaceous limestones, and when a considerable amount of sand is present they are known as siliceous limestones. Crystalline limestones are known as marble; and crystalline forms of the mineral calcium carbonate, which is the chief constituent of limestones, is known as calcite.

"Limestone sands" or limestones serving as oil reservoir rocks may be either channeled and fissured, as in the Lima oil field of northwestern Ohio[1], which produces from the Trenton limestone; or porous, granular limestones and chalks; such as are found in northern Louisiana and eastern Texas where the Austin (Annona) chalk is known to contain gas and heavy oil at some places.

The Tampico oil field of Mexico[2] produces most of its oil from limestone.

The important Luling oil field of Texas[3,4] produces its oil from the Edwards limestone.

The larger part of the oil produced in the Texas Panhandle[5] is secured from limestone.

The principal producing horizon of the oil fields of southwestern Ontario, Canada[6] are from Devonian limestone.

The Irvine oil field of eastern Kentucky produces from a Devonian limestone.

The Big Lake oil field[7] of Reagan County, Texas is producing from a dolomitic limestone.

GRANITE WASH AND VOLCANIC TUFF

In the Texas Panhandle oil field, oil is produced from granite wash in that part of the field nearest to the buried granite ridge.

At Sayre, Oklahoma, oil is produced from sands in close proximity to granite wash.

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1. Bownocker, J. A., Petroleum in Ohio and Indiana: Geol. Soc. Amer., Vol. 28, pp. 667-676, 1917.
2. Uren, Lester C., Petroleum production engineering: McGraw-Hill Book Co., 1924.
3. Brucks, Ernest W., The Luling field, Caldwell and Guadalupe counties, Texas: Bull. Amer. Assoc. Pet. Geol., Vol. 9, No. 3, pp. 632-754, 1925.
4. Sellards, E. H., The Luling oil field in Caldwell County, Texas: Bull. Amer. Assoc. Pet. Geol. Vol. 8, No. 6, pp. 775-788.
5. Bauer, C. Max., Oil and gas fields in the Texas Panhandle: Bull. Amer. Assoc. Pet. Geol., Vol. 10, 1926, pp. 733.
6. Williams, M. Y., Oil fields of southern Ontario: Canada Dept. of Mines, Summary Rept. 1926: Part E, pp. 30-42, 1919.
7. Lahee, Frederick H., Production of petroleum in 1924, and operations in Texas outside of the Gulf Coast; Amer. Inst. Mining Eng., p. 136, 1925.

The production of Thrall, Texas[8] comes from a basic igneous tuff or serpentine included in the Taylor marl.

In the Lytton Springs oil field of Texas[9] oil is produced from altered igneous rock or wash from basic igneous rock.

Petroleum frequently is found in commercial quantities in proximity to igneous rocks, as in Mexico; but commercial production has never been known to come from igneous rocks in place, although small amounts have sometimes been found in crevices and openings in granite, basalt, and other igneous rocks.

In the Texas Panhandle (See Fig. 1) much production comes from granite wash, or a conglomerate or breccia composed of granite fragments; and probably at Thrall and Lytton Springs, Texas the porous condition of the basic igneous rocks or serpentine which serves as the "sand" or reservoir rock is due to the fact that it is really a sand composed of volcanic tuff or fragments of decomposed basalt. Surface exposures of similar material in the same general area, at Uvalde, Texas, examined by the senior author, showed in-

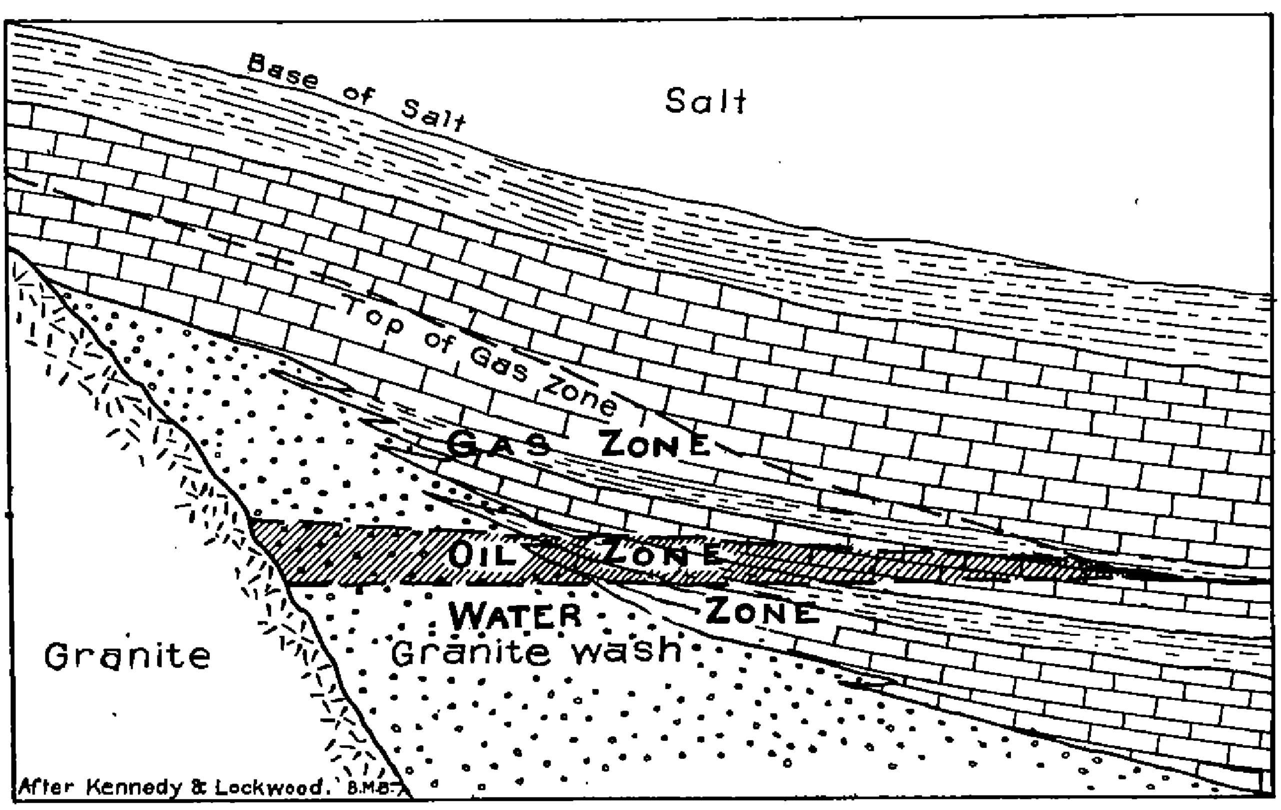

Fig. 1.—Illustration of the occurrence of oil and gas in the Panhandle oil field of Texas. Oil is found in both the granite wash and the overlying limestone.

8. Udden, J. A., and Bybeem H. P., The Thrall oil field: Univ. Texas, Bull. No. 66, p. 39, 1916.
9. Collingwood, D. M., and Rettger, R. E., The Lytton Springs oil field, Caldwell County, Texas: Bull. Amer. Assoc. Pet. Geol. Vol. 10, pp. 935-975, 1926.

cluded fragments of limestone, indicating that the material at the latter place is volcanic tuff which has been water-sorted and cemented to form a porous rock.

SHALES, SANDY SHALES, AND LIME SHALES

Shales are cemented or consolidated muds and clays, which generally are fragile and easily split in the direction of the bedding. Shales which contain considerable sand mixed with the clay are known as sandy shale. Shales which contain considerable calcium carbonate or lime mixed with the clay are known as lime shales or calcareous shales.

Oil is produced in commercial quantities from crevices in shales at Katalla, Alaska[10,11]. (See Fig. 2.)

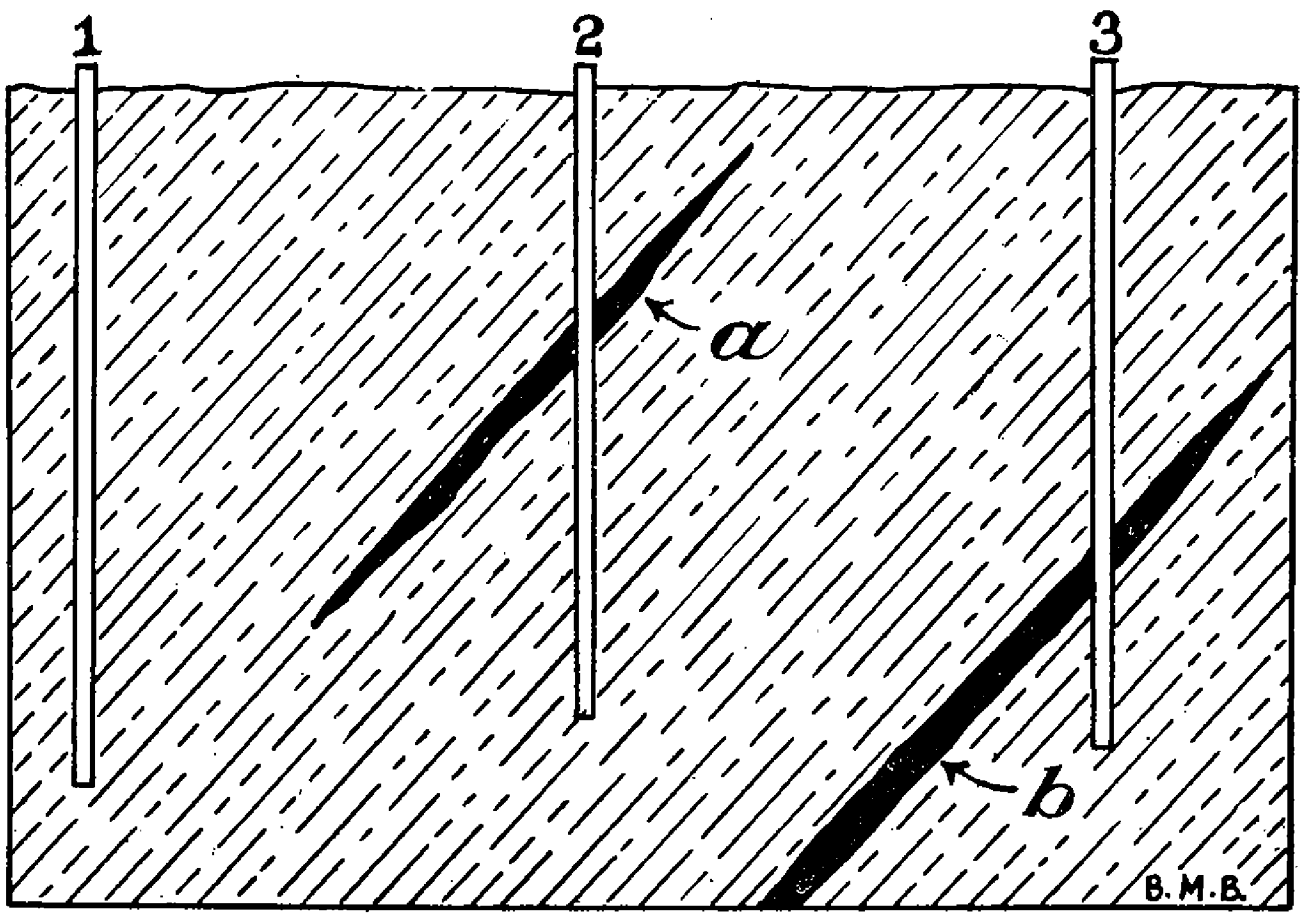

Fig. 2.—Sketch showing oil production from shale at Katalla, Alaska. There seems to be no underground communication between wells. Well No. 1 obtained no production, whereas well No. 2 secured production at three hundred feet, and well No. 3 secured production at 650 feet, without affecting the production of well No. 2, which had been previously drilled.

10. George, H. C., The Alaskan oil fields: Engineering and Mining Journal—Press, Dec., 1922.

11. Martin. George C., Preliminary report on petroleum in Alaska: U. S. Geol. Survey, Bull. 381, p. 719, 1921.

At Florence, Colorado[12] oil is found and produced from fissures in shales.

At Somerset, Texas, oil is produced from the Taylor marl. The wells are small but long-lived.

At Salt Creek, Wyoming[13] oil is produced commercially from crevices in the shale above the First Wall Creek sand. One of these wells producing from shale at Salt Creek, produced 92,000 barrels in 25 months, and another one produced 100,000 barrels in ten years.

SEDIMENTARY ROCK GRADATIONS

Sandstones grade into limestones, and conversely limestones grade into sandstones; and depending upon the relatively larger amount of sand or of lime, they are known as calcarious sandstones in the former case and as sandy limestones in the latter case.

Sandstones also grade into shales, and conversely shales grade into sandstones; and depending upon the relatively larger amount of sand or of clay, they are known as argillaceous sandstones in the former case and as sandy shale in the latter case.

Limestones grade into shales, and conversely shales grade into limestones; and depending upon the relatively larger amount of lime ($CaCO_3$) or of clay (hydrous aluminum silicate), they are known as argillaceous limestones in the former case and as calcareous shales or marls in the latter case.

Sedimentary rocks which in their composition approach the boundary line between sandstones and limestones, between sandstones and shales, or between limestones and shales, generally are much less porous; and hence, much less suited to serve as oil reservoir rocks than are typical sandstones, limestones, or dolomitic limestones.

BROKEN SANDS

Sandstones, limestones, and shales not only grade into each other in composition but also in order of deposition. Sometimes thin strata of sandstone alternate with thin strata of shale, sandy shale, or calcareous shale. These alternate beds of sandstone are known as broken sand, and they are frequently the source of commercial oil production. The sands found in the Graham oil field[14] of Carter

12. Washburne, C. W., The Florence oil field, Colorado: U. S. Geol. Survey, Bull. 381, p. 522, 1910.
13. Jeffery, Walter H., Deep well drilling: Gulf Publishing Co., Houston, Texas, 1925.
14. George, H. C. and Bunn, John R., Petroleum engineering in the Fox and Graham oil and gas fields, Carter County, Oklahoma: Bull. U. S. Bureau of Mines, in co-operation with the Office of Indian Affairs, the State of Oklahoma, and the Chamber of Commerce, Ardmore, Oklahoma.

County, Oklahoma are of this type. The writers know of a well in this field producing from seventeen oil sand horizons by means of a perforated liner.

STRUCTURAL FEATURES FAVORABLE FOR OIL AND GAS ACCUMULATION

ANTICLINES

When in nature intensive lateral compressive force is applied to sedimentary rocks; such as, sandstones, limestones, and shales, buckling or crumpling is produced, resulting in folding of the strata. The crests of the folds are called anticlines, as shown in Fig. 3 at (*a*) and (*b*). The troughs of the folds are called synclines, as shown in Fig. 3 at (*c*).

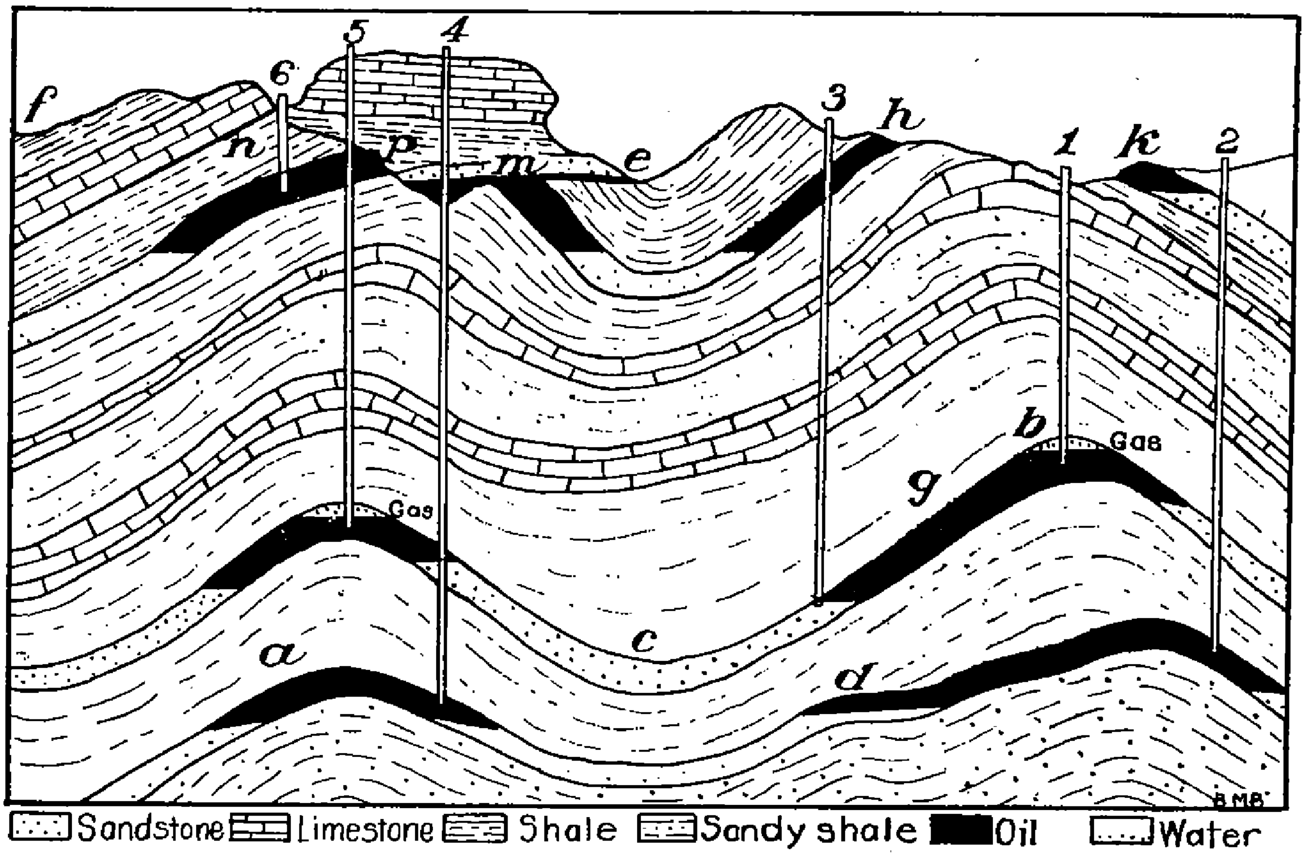

Fig. 3.—Sketch illustrating numerous structural features and showing the position and relation of oil, gas, and water to synclines and anticlines.

In anticlines, the two sides of the fold, which are called the limbs, dip away from the crest-line or axis. Such folds vary from broad and gentle arches, as are found in some of the oil fields of Kansas where the dip is less than 20 to 30 feet per mile, to sharply folded structures which have much steeper dips. The most steeply folded anticline in the Mid-Continent field is the Graham structure in Carter County, Oklahoma. On this anticline the dips range from 2,600 to 3,100 feet per mile.

If both limbs dip at the same angle, the anticline is said to be symmetrical; whereas, if one limb has a steeper dip than the other, the term asymmetrical is applied. However, symmetrical anticlines are rare. Furthermore, the axis is rarely if ever straight, but is usually curved in one or more directions. The crest of an anticline may continue in a nearly horizontal trend for a long distance, but eventually it dips or "pitches" downward, thus causing the fold to flatten out and disappear.

The reader can better understand what has been related above by referring to Fig. 4, which is a stereogram of a plunging anticline. The figure also shows the results secured by the drilling of wells at different parts of the structure. The increased depth required to reach the sand in well No. 3 as compared with well No. 2, and in well No. 4 as compared with well No. 3, is due to the rapid

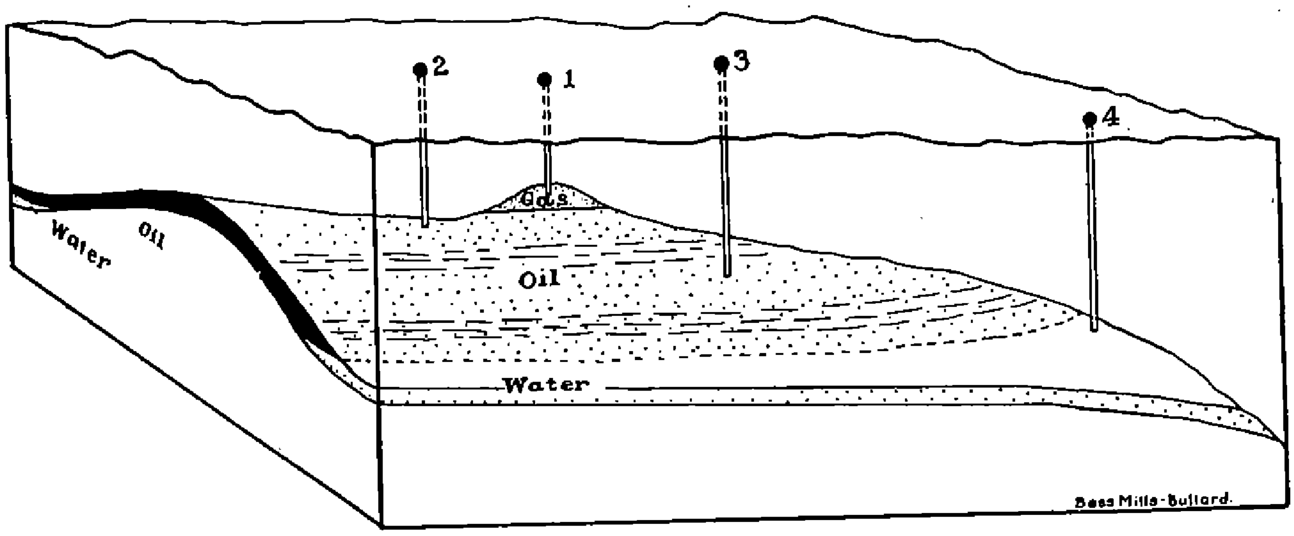

Fig. 4.—Stereogram of a plunging anticline. Note position of oil, gas and edge water within the sand.

plunging of the anticline in the direction of well No. 4. Well No. 1 was drilled on a superinposed dome on the structure and produced only gas. Well No. 2 was drilled high-up on the structure and had good oil production. Well No. 3 was drilled lower down on the structure and had good oil production. Well No. 4 was drilled so far down the structure that it penetrated edge water and produced no oil. As the oil was withdrawn from wells Numbers 2 and 3, the edge water replaced the oil, so that well No. 3 "went to water," then well No. 2 and finally well No. 1. However, if the gas had been withdrawn rapidly from well No. 1, it probably would have been an oil producer before it "went to water."

Anticlinal structure of much economic value is often clearly indicated at the surface. In our own State; for example, the structures at Cushing, Drumright, Davenport, Caddo, and Brock are readily discernible and traceable at the surface. The crest is usually absent, due to the effects of long periods of erosion, but the dip and the strike of the strata are still clearly prominent. This condition of erosion and reversal of dip at the surface is shown in Fig. 3 where wells 1, 2, and 3 are located.

Anticlines are formed by compressional forces which may be operative at various depths in the crust of the earth. This action may be illustrated by placing a sheet of paper on a flat surface; such as, a table. Then if the hands are placed on opposite sides of the sheet, and are slowly pushed toward each other, the paper will be folded upward, quite similar to anticlinal structure. Many anticlines are the result of small folds that have been formed on strata which have been tilted upward by the elevation of large mountainous areas after the sediments or strata have been deposited. If the limbs of the anticlines have been subjected to minor compressional forces, smaller folds may be developed along the sides of the structure. Such minor folds are often called terraces, or anticlinal "noses," (see Fig. 3, at *d*). A study of the subsurface maps of many of the producing anticlines in Oklahoma and elsewhere will portray this condition to the reader.

It has been learned from a study of subsurface conditions encountered in many oil fields that the amplitudes of the folds usually increase with depth, (see Fig. 3). Also, they are known to shift to the right or left as the depth increases. This is the reason why so many wells that have been drilled on the top of the structure as it appeared at the surface failed to produce as well as those drilled farther down on the side of the surface structure. As, for example, in Fig. 3 in the area where wells No. 1, 2, and 3 were drilled, and also on the structure where wells No. 4, 5, and 6 were located, shifting of the folds has been instrumental in the unexpected production results secured. Well No. 2 found water in the first and second sands, and oil in the third. Well No. 1 could have produced from two sands, had it been drilled deeper; whereas, well No. 5 could have produced from three sands. Well No. 3 obtained good production in the first sand, but soon began to produce water in the second sand because the lower part of the sand was saturated with water. Well No. 4 showed a similar condition. Well No. 6 could have obtained good production from three sands if it had been deepened. If wells had been drilled at *e* and *f* they would have encountered water in all three sands, because the structure in both areas is synclinal. As a general rule, the strata along the crest of the anticline are thicker, and the interval between them is usually greater. (See Fig. 3). But especially in unconsolidated or incompetent strata the opposite condition may be found.

Anticlines, to be productive of oil and gas, must have dark colored (usually black, blue, green) shales somewhere associated with the producing sand. These shales serve as the source of the oil. There must also be an impervious stratum of shale or limestone above the "sand." This is called the cap-rock. The fact that it is a non-porous stratum makes upward migration of the oil impossible, and thus aids materially in "trapping" the oil within the structure.

The relative location of the wells drilled on the anticline will have much to do with the nature and kind of production obtained. Wells that are drilled along the crest of the anticline frequently produce mostly gas and little oil; whereas, those drilled farther down on the slope or limbs produce more oil and less gas. However, drilling too far down on the sides of the structure will cause production to be largely salt water, (refer to Fig. 3). This arrangement of gas, oil and water in sequence on anticlines is probably due to the manner in which the differences in their respective densities or specific gravities have caused them to separate from each other. This is probably true especially as far as the separation of the gas and oil is concerned.

The best production is usually found on the basinward side of the structure; that is, the side or limb opposite and farthest away from the major uplift or most intense folding or the mountainward side. On the basinward side of the anticlinal fold the strata are usually dipping at a lower angle. This side or limb has the advantage of a greater area over which the concentration of the oil may be operative. This is illustrated in Fig. 3, at *d* and *g*. Then too, oil will not readily migrate up dips that are very steep.

DOMES

Anticlines with very short axes are called domes. The length of the axis may be two or three times as long as the transverse diameter of the dome, or it may be nearly equal to it; but domes are seldom very circular in basal outline. The strata dip off in all directions from a crestal point, and the oil therefore may be concentrated from all directions over the entire area of the dome toward its summit.

Such structures may be very pronounced, with steeply dipping sides, or they may be so gently dipping that they are scarcely noticeable. Noses and terraces are more commonly associated with dome structure than they are with anticlines. Also, small dome-like structures are often superimposed upon the flanks of large irregular domes.

Many of the most productive oil fields of the world portray dome structure. In nearly all cases the best production of oil and gas is obtained at or near the crest or top of the dome.

The origin of domes is rather difficult to explain satisfactorily. They may be the result of the intersection of two or more anticlines, or they may be due to local variations in dip on the limbs of a very large fold. Sometimes they are formed by pressure from below. This may be due to two principal causes: (1), by the great force often exerted by intrusive igneous rocks, as is well illustrated by the most prolific oil horizons of Mexico; and (2), as a result of pressure developed by intrusions of great plastic cores of salt. The salt dome production of the Gulf Coast fields of Texas and Louisiana is a striking example of the latter.

Since domes are so closely associated with anticlines in form, structure, and character of production, the authors will make no further attempt to discuss them. What has already been written regarding anticlines may be applied to domes in many respects. However, the reader's attention is called to Figs. 5 and 6, which show the general shape, proportions, and variations of typical dome structure.

Fig. 5 shows both a longitudinal and a transverse cross-section of a dome, together with a contour map drawn on the top of the

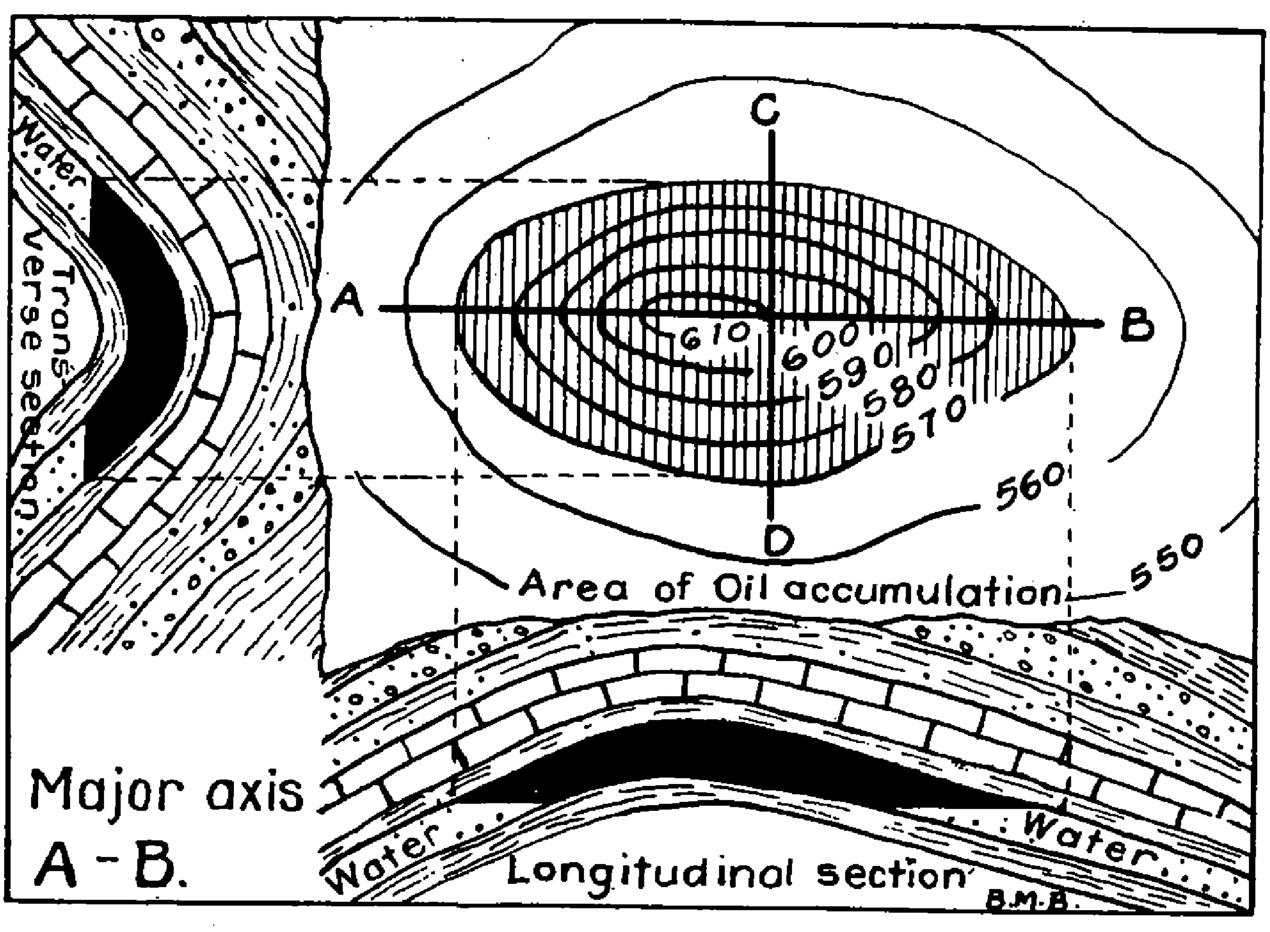

Fig. 5.—Sketch of dome structure, shown by contours drawn on top of the oil sand, and by vertical cross-section through the major and minor axes.

oil sand. *A-B* represents the major axis of the fold, and *C-D* the minor axis. The shaded contours represent the productive area of the structure. The figures on the contour lines represent the height of the top of the sand in feet above the datum plane (sea level). This is the customary method of numbering the contour lines; that is, when the datum plane is below the structure being mapped. However, occasions may arise when it is more convenient to have the datum plane above the structure being mapped, and use "minus elevations," which when applied to Fig. 5 would reverse the numbers; that is, instead of 610 at the top, the reading at the top would be —550, then —560, etc., down to —610, thus indicating the vertical distance from the horizontal datum plane down to the designated intersection point at the top of the sand.

Fig. 6 shows a structure contour map drawn on the top of an oil sand. The major axis of the anticline is in the direction of *A-B*. but it "splits" off at *E* in the direction of *C*, causing an anticlinal "nose". Domes are shown at *D, E,* and *B*, and a synclinal basin at *F*. The domes here are superimposed upon the anticlinal fold.

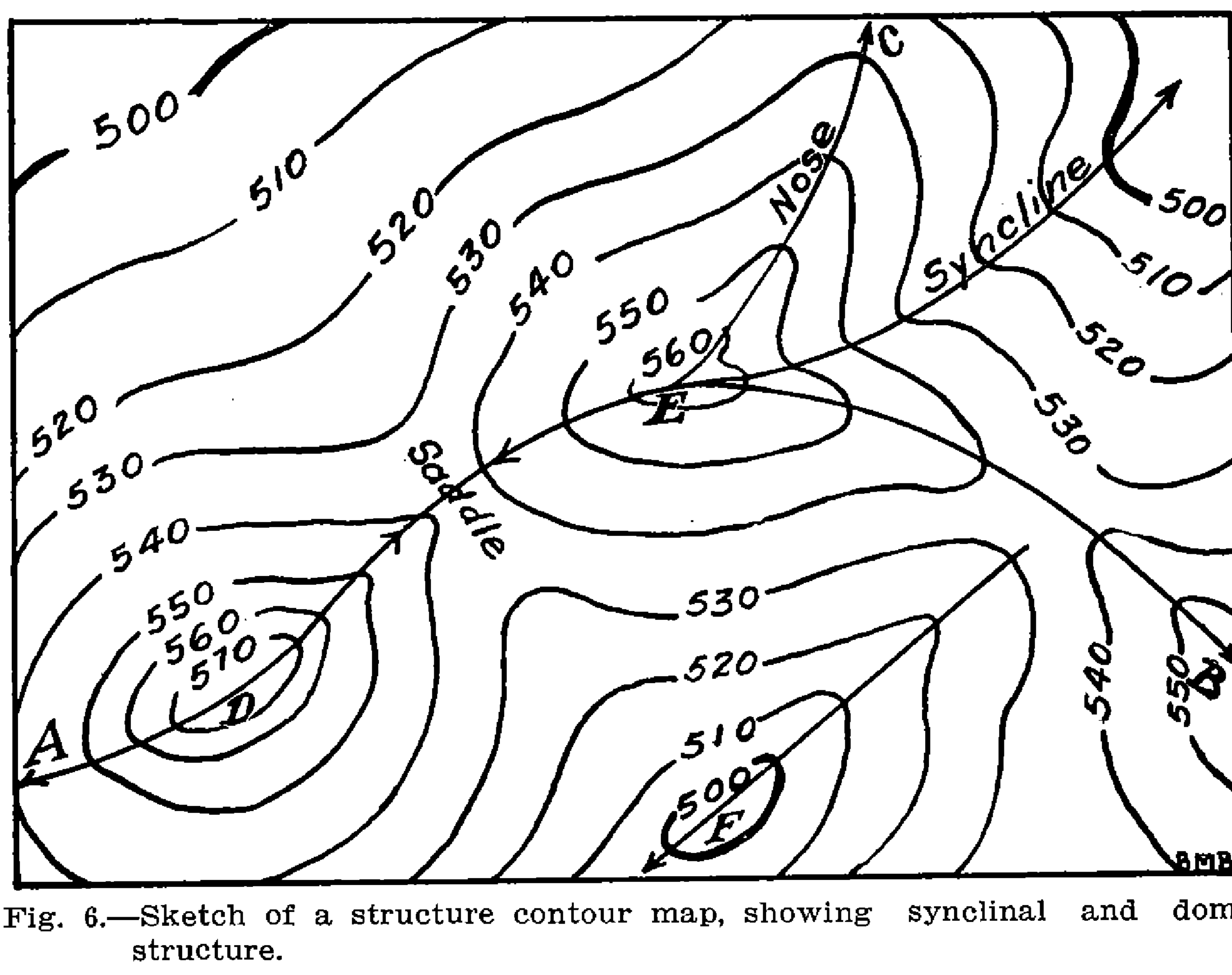

Fig. 6.—Sketch of a structure contour map, showing synclinal and dome structure.

MONOCLINES

Monoclines are structural features wherein the strata dip only in one general direction, as is shown in Fig. 7. There may be certain minor folds and slight reversal of dip at various intervals on a large monocline, but the dominating trend of the strata is in only one direction.

There are two general types of monoclines, classified as to their origin: (1) those that are developed as a result of erosional effects upon the crest of an anticlinal fold, as is shown in Fig. 7; and (2), those that owe their origin to major mountainous uplifts which occur after the deposition of the sediments which compose the strata associated with the monocline. As an example, of the latter, we have in northeastern Oklahoma, several long, westward-dipping monoclines, which were tilted to their present position by the Ozark uplift, thus causing monoclinal structure which dips away from the uplift at an average rate of 20 to 40 feet per mile. These monoclines extend westward and southwestward possibly as far as 150 miles.

When monoclines are formed by the eroding away of the crest of an anticline, a partial cross-section of the strata composing the fold is exposed at the surface. If one or more of the outcropping strata contains oil, its presence may be made evident by accumulations of dark, bituminous materials and asphaltic residues along the outcrop, as is shown in Fig. 7 at *A*. The upward pressure of

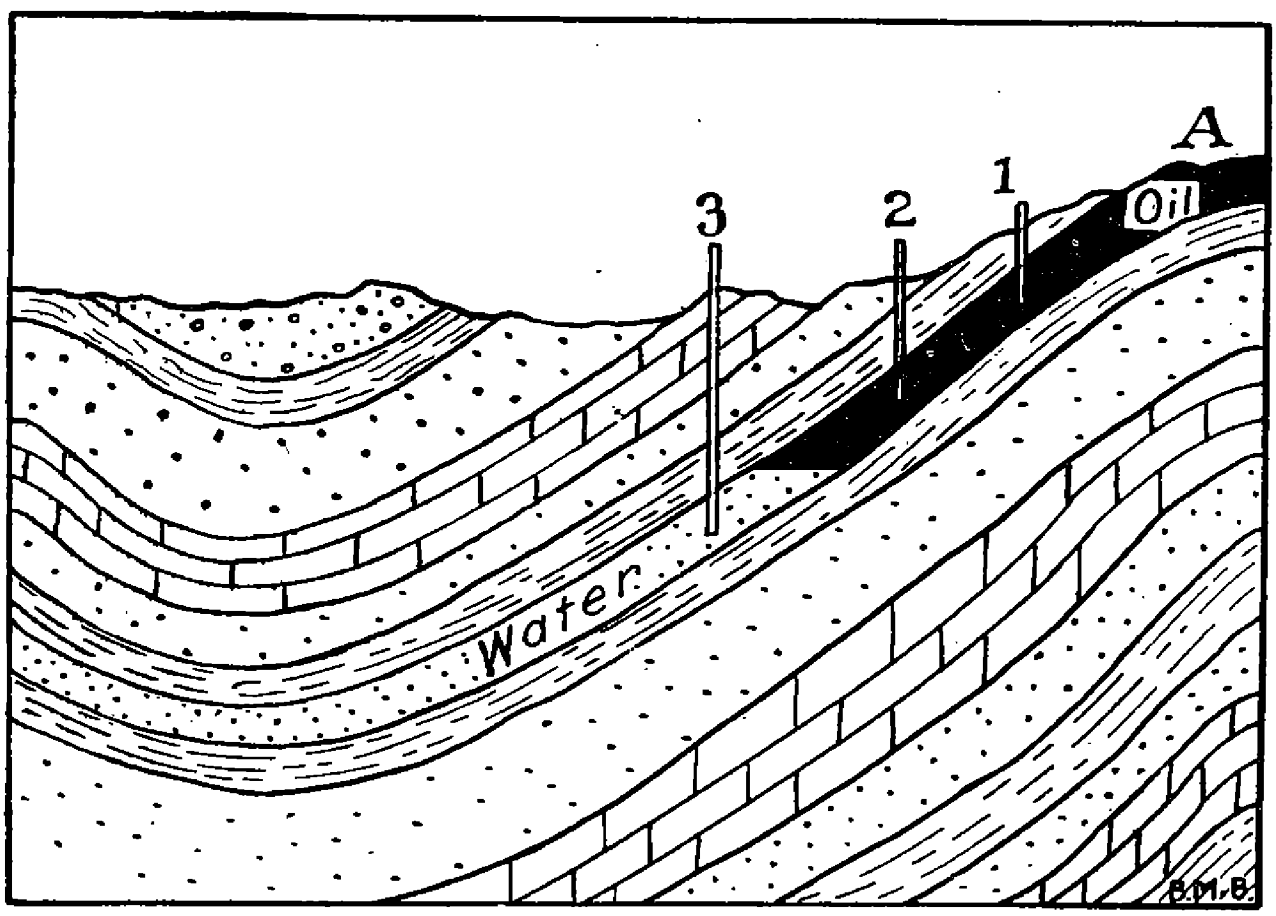

Fig. 7.—Sketch illustrating monoclinal structure. A bituminous outcrop is shown at "A".

gas and the pressure of the water (hydrostatic pressure), both of which may still be operative in the oil-bearing strata, tend to force the oil out of the sand at the surface, where it may accumulate in pools and slowly evaporate. Or, the oil may be carried off down the slope by natural water courses. Such exposures are known as "oil seeps." [See Fig. 3 at *e*].

Waste of oil, as a result of the erosion of anticlinal crests, thus exposing the oil-bearing strata, has likely amounted to excessive quantities during former geologic periods. However, if the oil deposit is a large one, the oil, because of its own physical properties, may seal off the outcrop, leaving a residue of paraffin or asphalt near the surface, and thus prevent further escape of the oil stored in the lower part of the flank of the fold. Fig. 3 portrays this condition at *h* and *k*. This is accomplished by the evaporation of the lighter and more volatile hydrocarbons in the oil, thus leaving a heavier residue in the surface rocks which completely closes the pores between the grains of the reservoir rock.

In locating test wells on such monoclinal structures, the well must be located far enough down the flank to penetrate the oil sand below this bituminous outcrop or "zone of oxidation," as it is often called. This distance may be several hundred feet down the flank below the outcrop. For example, the well No. 2 in Fig. 7 is probably far enough down the flank to secure good production. However, well No. 3 would encounter edge water. Oils produced from the upper portion of the stratum; that is, near the outcrop, are likely to be heavy and viscous, as at *A* and possibly at well No. 1. Furthermore, the wells will be small producers, because of the difficulty of inducing flow from such sands, and because of the absence of gas pressure.

In addition to the monoclinal production discussed above, a considerable number of oil and gas fields of the world lie on monoclines that are sealed in various other ways; such as, by meeting of impervious or non-porous rocks above the reservoir rock; by oil sands becoming impervious as a result of local cementation of their pore spaces, or where the pore spaces are filled with clay particles; by sealing off the oil, due to faulting of the monocline; and by the oil being sealed beneath an overlying unconformable stratum. Only the first two of these types will be discussed under this general topic heading.

Monoclines that are sealed by the "squeezing out" or "thinning out" of the producing sand, and the meeting of impervious rocks above and below the reservoir rock have been found in many places. A typical example is that associated with the Berea sandstone of Ohio. This sand thins out toward the west, thus causing the impervious clays above the sand and the shale below it to meet; which of course, prevents further upward migration of the oil.

Accumulation on a monocline which has been sealed by local cementation or by the deposition of fine material between the grains of the sand, is well illustrated in the famous Glenn pool of Oklahoma. Here the oil migrated up the dip of the reservoir rock until it reached a place where the reservoir rock became impervious. Such oil sands or reservoirs may be made impervious locally by deposits of clay, calcite, iron oxide, or various carbonates in the pore spaces between the sand grains.

Terrace structure is often the cause of relatively small accumulations of oil and gas on monoclinal folds. In this case, a change or reversal of dip on the monocline will form a kind of "trap" where the change of dip occurs, and the oil and gas will accumulate at this place. The extent and amount of this accumulation, of course, will depend upon several factors, the most important of which are; the size of the pore space between the grains, the amount of gas pressure present, the viscosity of the oil, the extent and intensity of the change of dip, and the amount of hydrostatic pressure of the associated salt water farther down the flank of the monocline.

FAULTS

It has been concluded from a detailed study of subsurface conditions as portrayed by well logs, that various phases of faulting associated with monoclinal and anticlinal structure have been responsible for the accumulation of oil and gas in several of the major oil fields of the Mid-Continent area, as well as in other fields of the United States and foreign countries.

A fault is a displacement of the strata of the earth's crust on opposite sides of a fracture plane or surface. The surface along which vertical and horizontal movement of the strata have occured is called the fault plane. (See Fig. 8 at *C*). It is not a perfect plane, except for relatively short distances, but may be curved, warped, or irregularly broken. The fault plane eventually disappears laterally, usually passing into a fold, or it may cease to exist entirely. In areas where faulting has occured, the fault plane usually leaves a topographic irregularity or break on the surface relief. This may have the form and appearance of a cliff of varied height and degree of slope. Such an abrupt change in relief, when due to faulting, is called a fault scarp. It is often the only direct surface evidence that faulting has occurred. In driving from Waco, Texas, southwest through Belton, Georgetown, Austin, San Marcos, New Braunfels, and San Antonio, and thence west through Hondo and Uvalde to Del Rio on to the Rio Grande, a total distance of more than 400 miles, the bluffs to the north and west of the highway are the escarpments of the Balcones fault, which produce one of the chief topographic features of Texas.

Faulting is caused by the same earth forces that produce folding of the strata; that is, compression and tension forces. These forces may affect all kinds of rocks; but as far as faulting is concerned, they are most easily recognized in stratified deposits; namely, sandstone, shale, and limestone.

There are two general kinds of types of faults, the normal fault and the thrust (reverse) fault. Since accumulation of oil and gas is probably more commonly associated with normal faulting of monoclines and anticlines, only this type will be illustrated here. However, most of the oil fields along the Balcones Fault in Texas are associated with reverse faulting. Figs. 8 and 9 show two different phases of normal faulting as affecting the accumulations of oil and gas.

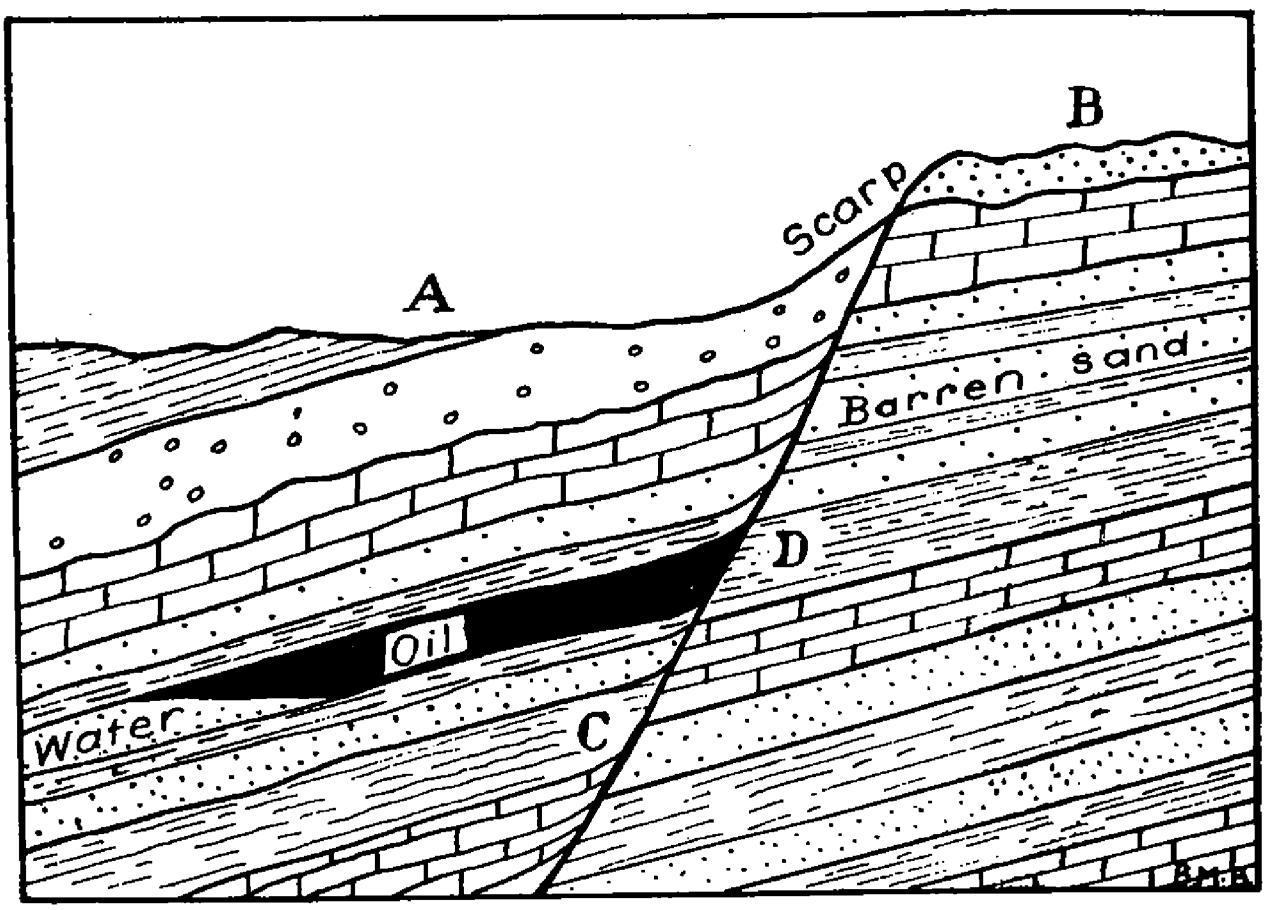

Fig. 8.—Sketch of a faulted monocline. The oil is "trapped" against the impervious shale "D".

Normal faults are usually caused by tensional forces that are operative within competent beds of the earth's crust. In Fig. 8 the side *A*, called the downthrow side, has moved downward with respect to side *B*, along the fault plane *C*. In this case the fault plane has intersected and displaced an oil sand to the extent that further upward migration of the oil in the sand is prevented because the porous stratum containing the oil is resting against an impervious clay or shale at *D* in such a way as to form a structural "trap" in which oil has been concentrated. It must be born in mind, however, that unless the fault plane is well sealed with a finely ground material called "gouge," the oil may migrate along the fault plane itself, thus dissipating the possible accumulations.

By referring to Fig. 8, it can be readily seen that a well drilled on the right side of the fault plane will not produce oil. If faulting causes two different porous strata to be moved to a position where they rest opposite each other on both sides of the fault plane, the sealing action along the fault plane may prove less effective, and thus permit the oil to migrate across the fault plane and probably on up into another porous stratum.

This condition is illustrated in Fig. 9 where sand *a* has been displaced downward until it is opposite sand *b*, thus permitting migration of the oil across the fault plane *N*. Sand *d*, which is saturated with oil at *e*, is barren on the upthrow side *M*. The accumulation

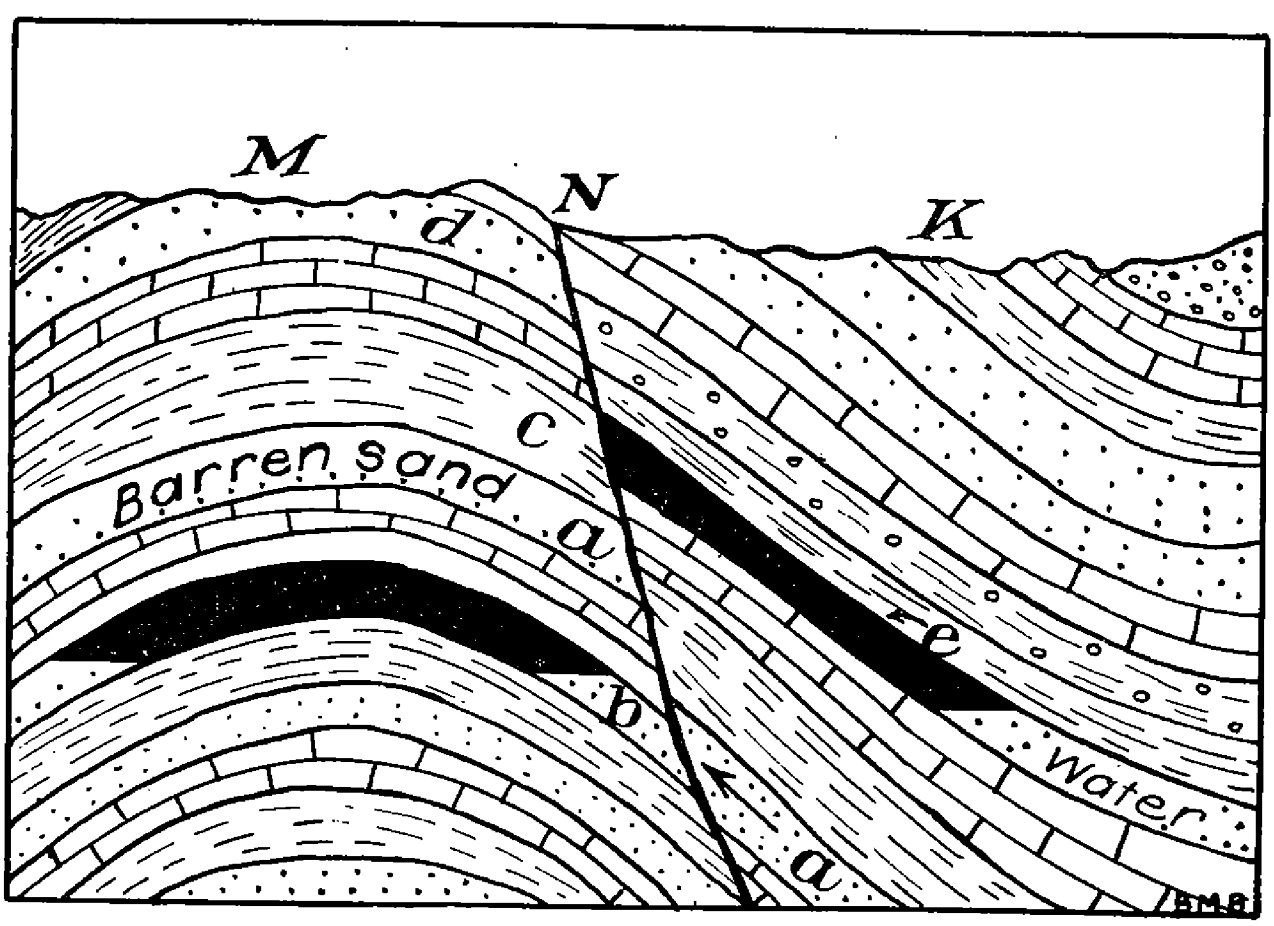

Fig. 9—Sketch of an anticline, which is faulted. Oil has migrated across the fault plane into sand "b".

occured at *e* because farther migration up the dip is prevented by the sealing effect of the clay or shale *c*. The side *K* is the downthrow side in this figure.

The reader can imagine a condition in incompetent beds where the fault plane may depart more from a vertical position than that shown in Fig. 8; that is, it will lie more nearly flat. Such fault planes are usually the result of compressional rather than tensional force, in which case the side *A* would have been moved or pushed upward instead of downward, thus producing what is called a thrust or reverse fault.

Normal faulting has been more or less responsible for the accumulation of the production found in such well known fields as, Eldorado, Arkansas, and Cromwell and Tonkawa, Oklahoma. The three fields in Texas that are closely associated with the Balcones fault; namely, the Luling, the Powell, and the Mexia fields, illustrate both direct and reverse fault conditions. The main Balcones fault is a direct fault, but the secondary faults in the oil fields are reverse faults. While production is not usually so commonly associated with thrust faulting as it is with normal faulting, the field near Baku, Russia and the one at McKittrick, California are known to produce from such structures.

UNCONFORMITIES

It has frequently happened during the various stages of deposition of the sediments of the earth, that after certain sediments were deposited, they were then folded, then subjected to long periods of erosion, after which they were again subjected to deposition upon and above the older folded and eroded strata. Such a condition would result in two separate and distinct series of strata that have a discordant relation to each other, their dips being in different directions and of different degrees, and each series belonging to an entirely different geologic age, the lower series being older. Such a relationship of the earth's strata is known as an unconformity. [See Fig. 3 at *e-n*.]

Unconformities frequently serve as structures favorable for the accumulation of oil and gas. If the underlying, older strata contain sands or other porous rocks, the oil can migrate up the dip of the older porous formations until it reaches the unconformable contact between the older and the younger strata. Here it may be sealed or "trapped" by coming into contact with impervious shales and clays at the base of the upper or younger series, thus providing a favorable condition for accumulation against the unconformity. Such accumulation is shown in Fig. 10 and in Fig. 3 at *p*.

In Fig. 10 the unconformable contact is shown at *a-b.* The oil in sand *c* cannot migrate any farther because of the non-porous bed *d.* It is apparent that the surface outcrops in such an area would be mapped as synclinal, and therefore considered unfavorable for the accumulation of oil.

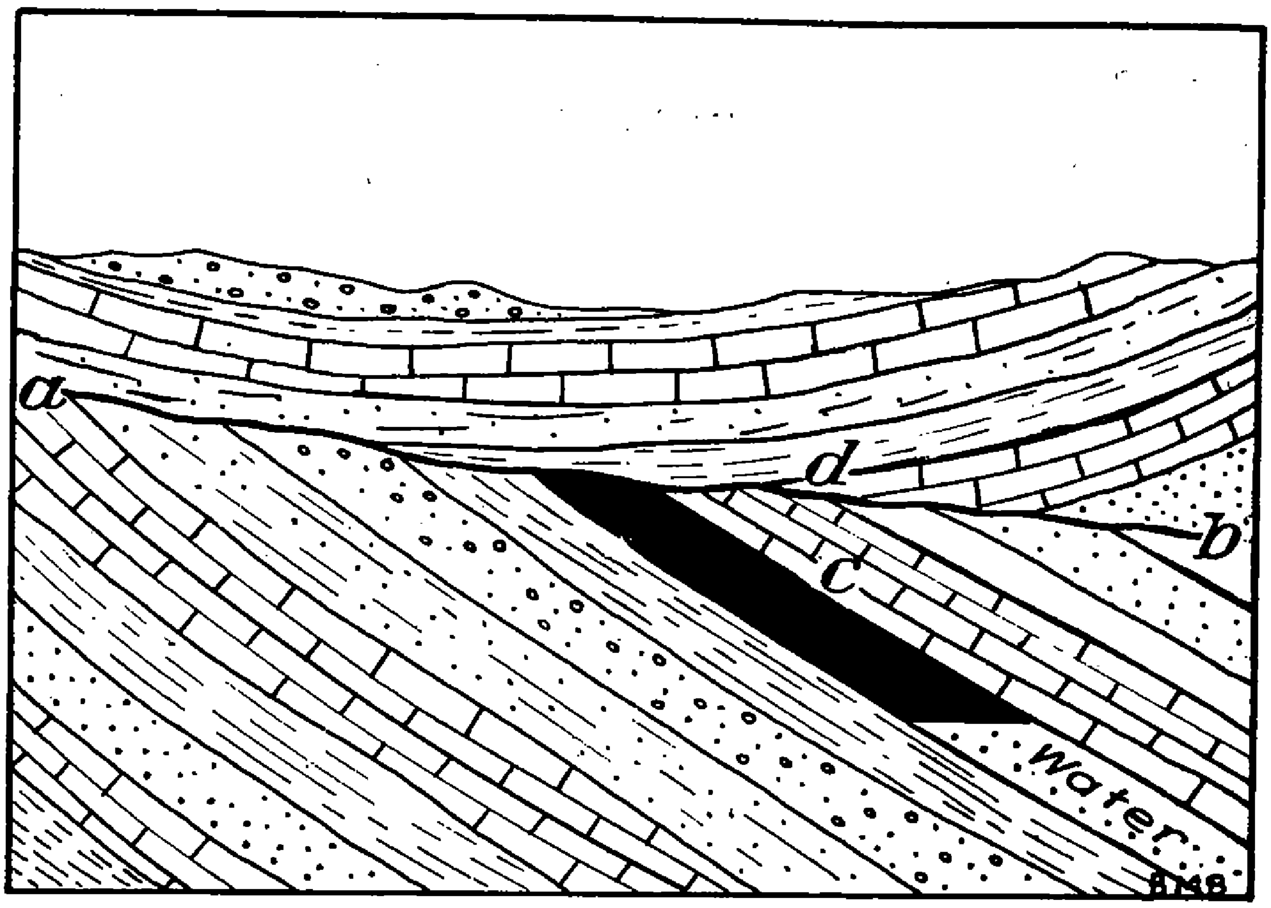

Fig. 10.—Sketch showing accumulation of oil beneath an unconformity.

While such structure as is shown in Fig. 10 is very favorable for accumulation of oil and gas, analyses of subsurface conditions in several oil fields of Oklahoma have shown that such structural relations as are shown in Fig. 11 are more common. The younger or upper deposits at unconformable contacts often have coarse sandstones and gravels near their base. The oil, which originates in the older series below the unconformity, migrates up the dip into the coarse sands and gravels where it has a better chance to accumulate. (See also, Fig. 3 at *m*). Further upward migration is prevented by shales and clays which are usually deposited above the coarse sands and gravels at the base of the younger unconformable series.

In the Madill field in Marshall County, Oklahoma, is a typical example of such structure. Production was obtained in the Trinity sand, which lies unconformable above highly folded sediments that are much older. Some production was obtained also from the sands below the unconformity, proving conditions similar to both Fig. 10 and Fig. 11. This oil in the Trinity sand has migrated upward from the underlying strata, which are known to be petroliferous.

Somewhat similar structural conditions exist in the Healdton field of Carter County, Oklahoma. Also the small production at Gotebo in Kiowa County, Oklahoma, as well as the shallow production at Garber, Oklahoma, is found in coarse sands presumably due to migration from unconformable petroliferous strata below the producing formations, as is shown in Fig. 11.

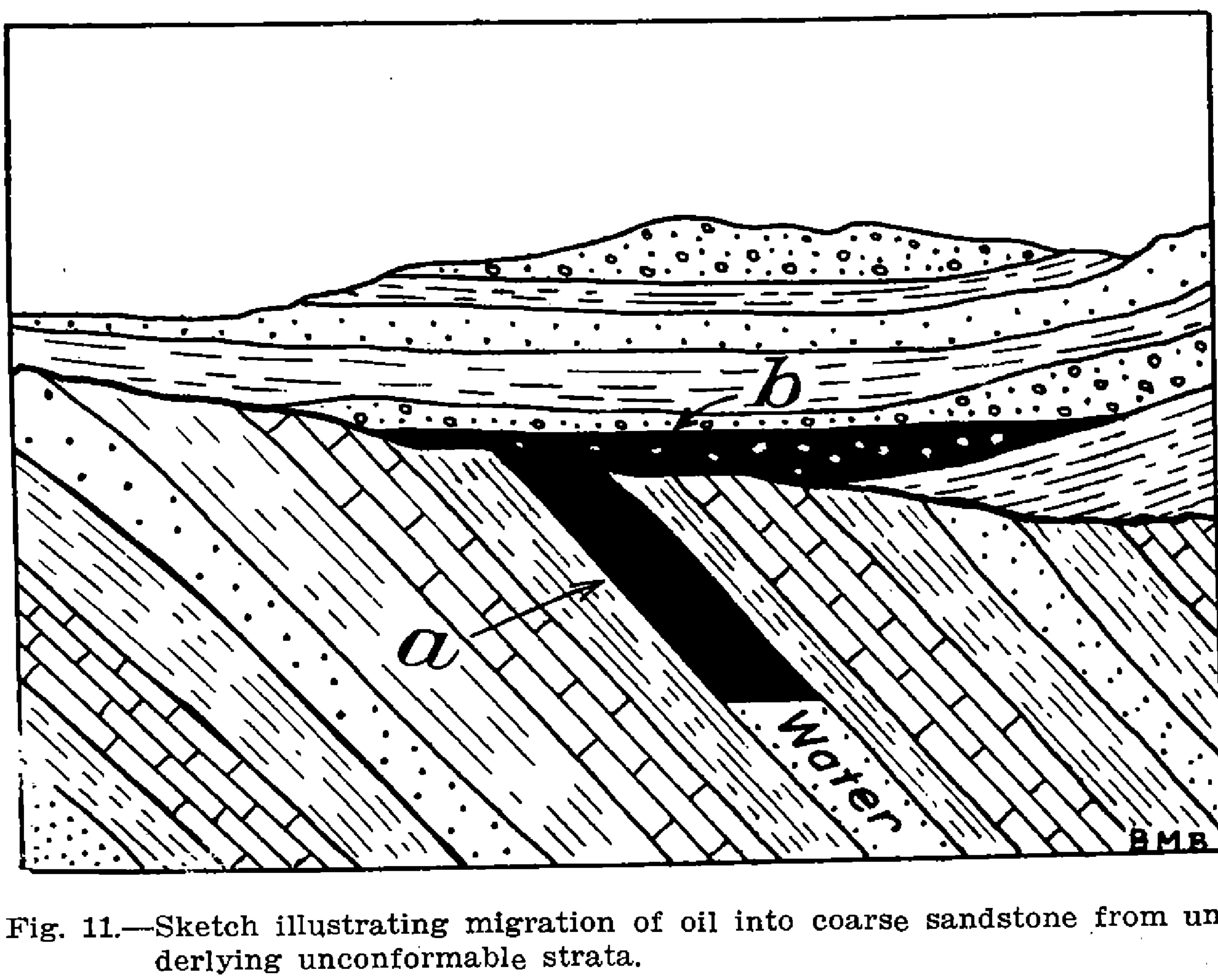

Fig. 11.—Sketch illustrating migration of oil into coarse sandstone from underlying unconformable strata.

Generally speaking, unconformities are not discernible at the surface. As for example, in the Madill field mentioned above, the surface rocks are much younger than those beneath the unconformity, and lie nearly flat, thus portraying no surface evidence of favorable structure for the accumulation of oil and gas. Therefore, since unconformities are exceedingly difficult or quite impossible to decipher at the surface, it is always best to have the subsurface conditions of an area checked by a reputable geologist before drilling for oil. From his knowledge of the age, trend, thickness, character, and stratigraphic conditions present during the periods of deposition in certain areas, as compared to those of neighboring producing areas, he can usually foretell the probability of the existence of unconformities, and advise one as to the possibility of finding production.

LENTICULAR AND IRREGULAR SAND CONDITIONS

Where there is a lateral variation in the thickness, character, and extent of the oil bearing strata, then the producing sand is spoken of as being lenticular.

Lateral gradation from coarse-grained, porous sandstones into sandy shales or sandy limes, conditions which do not alter the extent or thickness, but do greatly decrease the porosity, produces one type of lenticular sands.

Extensive uniformity in porosity and character of material, but marked changes in thickness from place to place or gradual thinning out laterally, produces another type of lenticular sands.

Lenticular sand conditions may be caused by changes in the amount of deposition, change in the rate of deposition, and change in the type of material presented for deposition from place to place in the same series of sediments.

Fig. 12 shows how oil may accumulate in sandstone lenses. It shows also how erratic the production may be in such structure. Thus, well No. 1 may produce from two different sands; whereas, well No. 2 may miss the "sand" entirely. On the other hand, well No. 3 may be a good producer. Therefore, in such deposits we might find good production on either side of a dry hole.

Sand deposits usually are formed and are seen to occur in comparatively shallow water; that is, along the shores of bays and lagoons, where the grains are subjected to much shifting and cross-bedding before they become permanently lodged off-shore. In the course of this shifting, bars, and lenses are formed which are roughly parallel to the shore line against which they have lodged. Further deposition of relatively fine-grained material; such as, clays and silts containing organic matter, may leave the bars and lenses embedded in what is apparently one continuous, fairly well-defined stratum. This condition is shown at *D* in Fig. 12. The oil, which is formed later, naturally migrates to the more porous strata; that is, to the sand lenses, leaving less porous clays and silts above, below, and on the sides comparatively barren.

As a usual consequence the major concentration even in sandstone lenses is influenced by anticlinal structure, but the per cent of saturation of the lenses at various places on the structure will be variable. That is, a well drilled on the crest of the structure, which should naturally be the best place for accumulation, might find the lens dry or entirely absent. While a well drilled at a much less favorable position, with respect to structural evidence, might be highly productive.

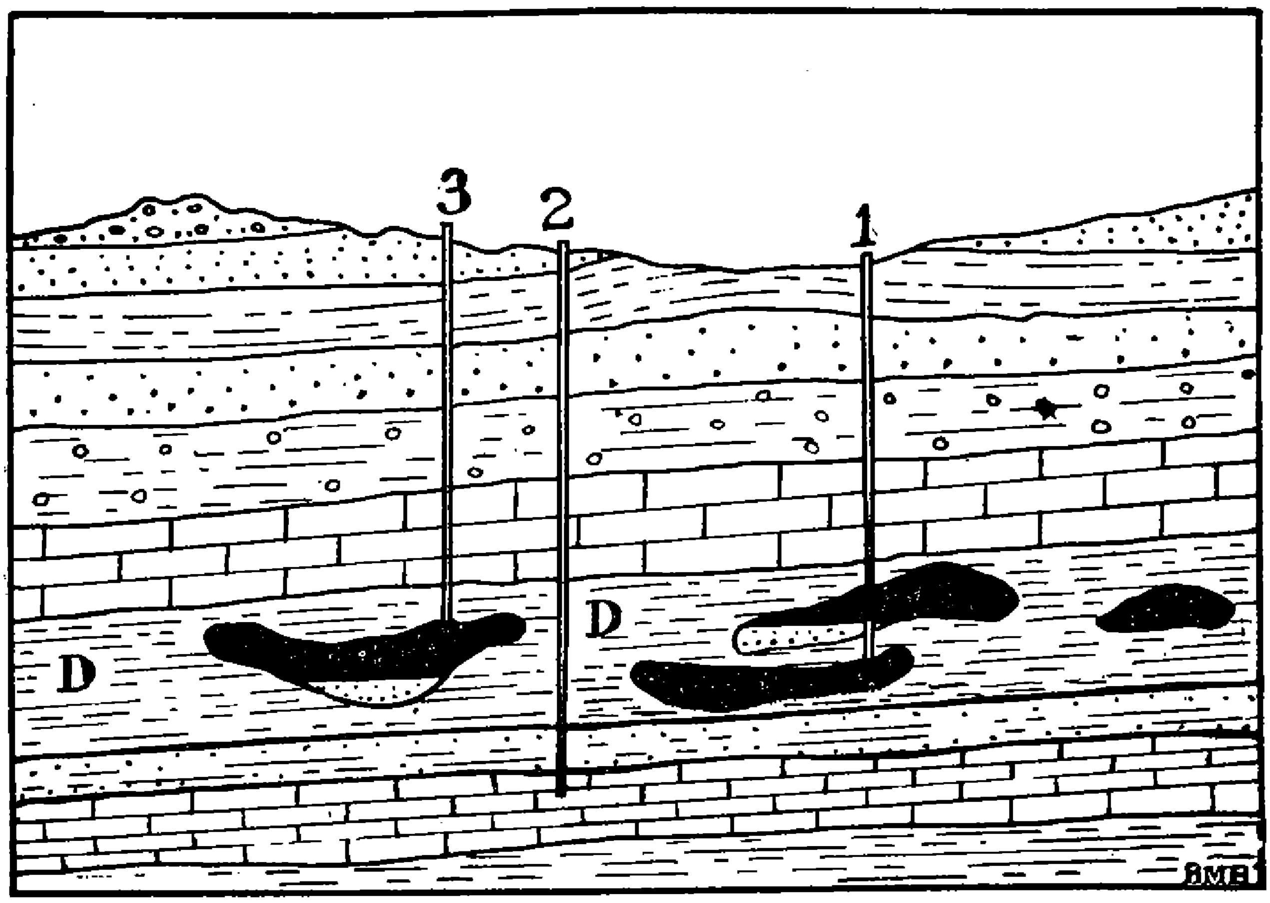

Fig. 12.—Sketch showing accumulat.on of oil in lenticular sandstone deposits.

As the reader can readily see, such variable subsurface conditions cannot be recognized in the usual process of surface surveys for the proper location of test wells. They constitute another one of the geologic uncertainties with which the average field operator has to deal in his quest for oil. However, it is a well known fact that lenses usually occur approximately parallel to the old shore lines from which the sands composing the lenses were derived. It follows that such accumulation of petroleum that may form later should be found parallel to the shore lines that existed during the geologic period in which the producing sediments were deposited. Subsurface studies of well logs have established this truth in many instances. This is another case where it would be best to have a reliable geologist help the prospector predict the possible trend of the lenses that are responsible for the unequal distribution of the oil in such areas. No doubt, many fields have been abandoned too soon because of the lack of such subsurface knowledge.

As an example of fields that have produced from lenticular structure, the reader is cited to the Graham oil field of Carter County, Oklahoma, which is discussed in a U. S. Bureau of Mines Bulletin.[14]

SHOE STRING SANDS

Shoe string sands, such as the long, narrow, lens-like sands of eastern Kansas, have usually been classified as lenticular sands, but as shown by John L. Rich, they differ in many respects from the ordinary type of lenticular sands.

Rich[15] says, "In thinking of various ways in which sand bodies like the Kansas shoe strings may have been formed, the following have come to mind: (1) shore beaches and bars, (2) off-shore sand bars, (3) ordinary river channels, (4) delta distributory channels, (5) tidal channels."

Rich[16] further says, "Recent developments in the "Shoestring" sand territory of Anderson and Linn counties, Kansas, by opening new pools and extending others, have thrown new light on the origin of these interesting sand bodies and on the accumulation of oil in them. The "shoe string" sands herein described lie at or close below the top of the Cherokee shale. They occupy gently winding channels cut sharply to a depth of about 50 feet into that shale. The available evidence leads to the belief that the channels were cut by streams during a slight uplift of the Cherokee sea bottom, and were later silted up."

JOINT PLANE SEALS

Joint planes in sandstones sometimes serve as seals to oil and water migration when the joint planes have previously served as channels for the deposition of secondary quartz or other minerals. In Fig. 13 suppose for instance that the two series of joint planes *a* and *b* serve as seals, and oil migrates into that part of the sand lying between *a* and *b*. Then, of the three wells penetrating the sand, No. 1 would show no oil, No. 2 would secure production, and No. 3 would show no oil. However, if No. 1 had been drilled deeper into the sand it would have cut the joint plane seal and been productive.

Cores from some of the wells of the Graham oil field, Oklahoma show this condition existing. Outcrops of sandstone and conglomerates in Warren County, Pennsylvania show conditions of sealing

15. Rich, John L., Shoe string sands of eastern Kansas: Bull: Amer. Assoc. Petr. Geol. Vol. 7, pp. 103-113, 1923:
16. Rich, John L., Further observations of shoe string oil pools of eastern Kansas: Bull. Amer. Assoc. Petr. Geol., Vol. 10, pp. 568-580, 1926.

along the joint planes which would produce conditions similar to those shown in Fig. 13. Conditions of this sort would similate lenticular sands in the irregularity of oil productivity.

SALT DOME DEPOSITS

Salt domes have been responsible for the accumulation of crude oil in the Gulf Coast fields of southern Louisiana and eastern Texas, as well as in the Baicoi oil field of Roumania.

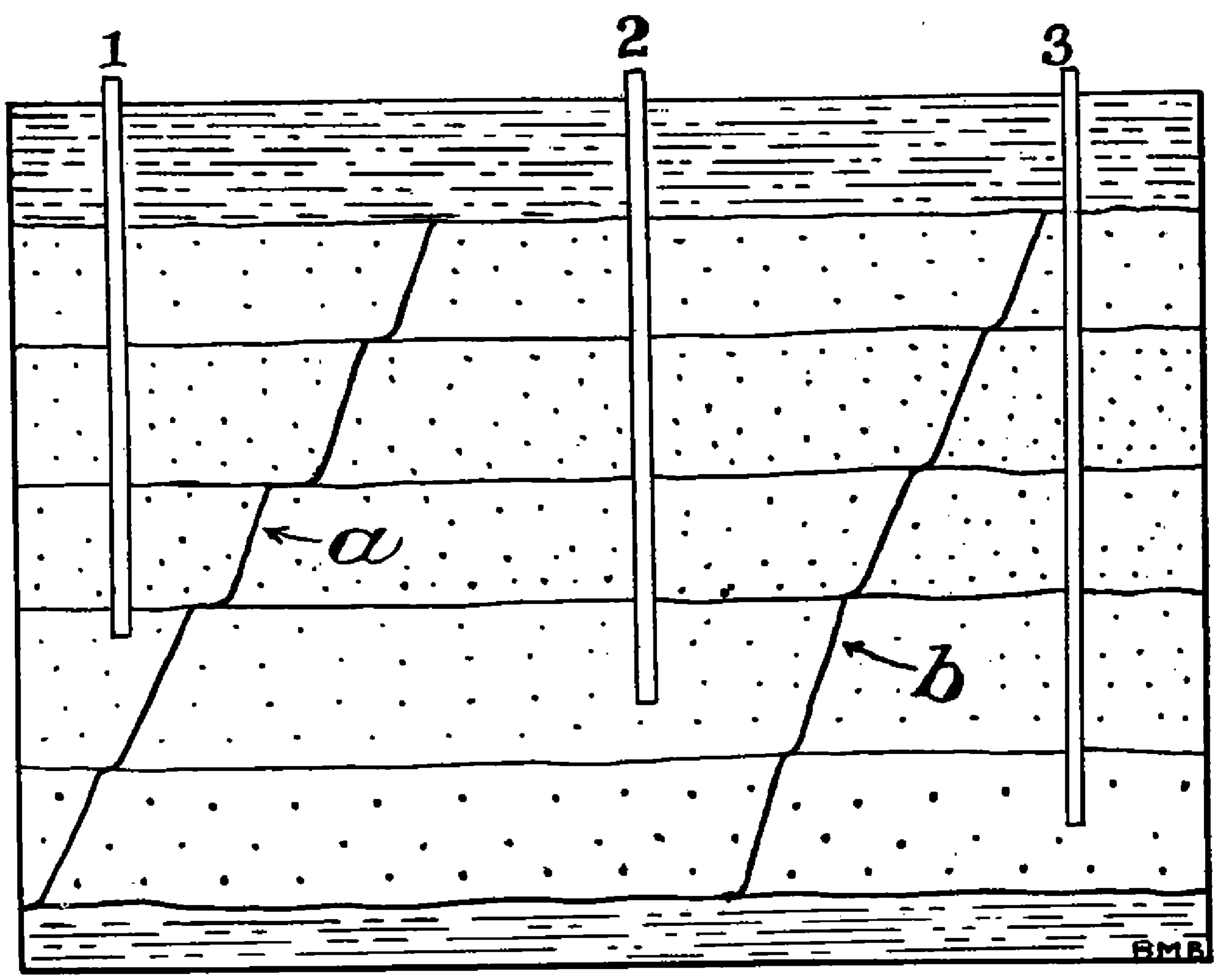

Fig. 13.—Sketch illustrating how the accumulation of oil may be limited by sealing along joints or fracture planes within a sandstone. Well No. 2 was productive, whereas No. 1 and No. 3 were dry holes.

In the Gulf Coast area some fifty or sixty salt domes have been located. Most of them have served as a trap for the concentration of oil and gas in more or less prolific quantities. The discovery well drilled at Spindletop, near Beaumont, Texas, produced 75,000 barrels a day during the first few days of its existence. Many other wells had initial production as large as 30,000 to 40,000 barrels daily, together with as much as 10,000,000 to 15,000,000 cubic feet of gas. However, most of the wells showed a very rapid decline.

The salt deposits, whether they were caused by the upward migration of plastic salt along fractures in the rocks or by the expansive force of growing crystals of salt upon solidifying, have been responsible during their intrusion or accumulation for considerable upward pressure. This has resulted in the doming of the overlying sedimentary rocks, as well as in folding the rocks upward adjacent to the salt. It is believed that some of the strata adjacent to the edges of the salt have been folded upward as much as 200 feet within a depth of 4,000 feet. Possibly faulting is responsible for some of this apparent folding. At any rate, this folding, doming, or faulting of the associated sedimentary rocks paved the way for the concentration of petroleum in the strata thus affected.

The salt does not extend to the surface, but is encountered at depths ranging from 600 to 1,600 feet below the surface. This condition, together with the customary associated oil deposits is shown in the cross-section, Fig. 14.

In the Gulf Coast area the adjoining country is approximately flat. As a result, the details of structure are best derived from a study of logs of drill holes. At many places low, smooth mounds or hills rise slightly above the generally level plain. On some of the low hills there were some shallow lakes from which gas bubbles once escaped. This constituted about the only direct surface evidence of the existence of petroleum.

The oil is not found in the dome-shaped salt cores, but is found in the gypsum and dolomitic limestone beds often found above them, and especially in the sedimentary rocks which surround the salt cores on all sides, as is shown in Fig. 14. Good production has been obtained as deep as 5,200 feet in wells drilled near the edges of the crystallized salt in the Spindletop area.

In Roumania, plugs of salt have been literally thrust through clays and sandstones, the oil sands being sealed off above by the central salt mass itself. Such intrusions have left the sedimentary clays and sands dipping away from the central mass in all directions at high angles. As might be expected, local faulting has occured adjacent to such salt dome structures, and the entire area has been intensely folded.

According to Emmons[17] structure of this sort is probably developed where rigid rocks alternating with unconsolidated weak rocks are deformed and pushed upward by great pressure. In this particular case the crystalline salt was much more rigid and heavier than the clays and sandstones.

17. Emmons, William H., Geology of petroleum: McGraw-Hill Book Co., 1921.

Powers[18], Deussen[19], Barton[20], Kelley[21], Kennedy[22], De Golyer[23], and others have discussed salt domes and oil production relations.

PETROLEUM DEPOSITS ASSOCIATED WITH VOLCANIC INTRUSIONS

A large amount of the volcanic activity which occurs within the earth never extends up to the surface to cause volcanic eruptions. Instead, the lavas as they ascend intrude themselves into the overlying sediments, and then solidify underground (intrusions). Occasionally such igneous deposits may reach the surface before they solidify. Such masses of solidified lavas are called volcanic or igneous extrusions.

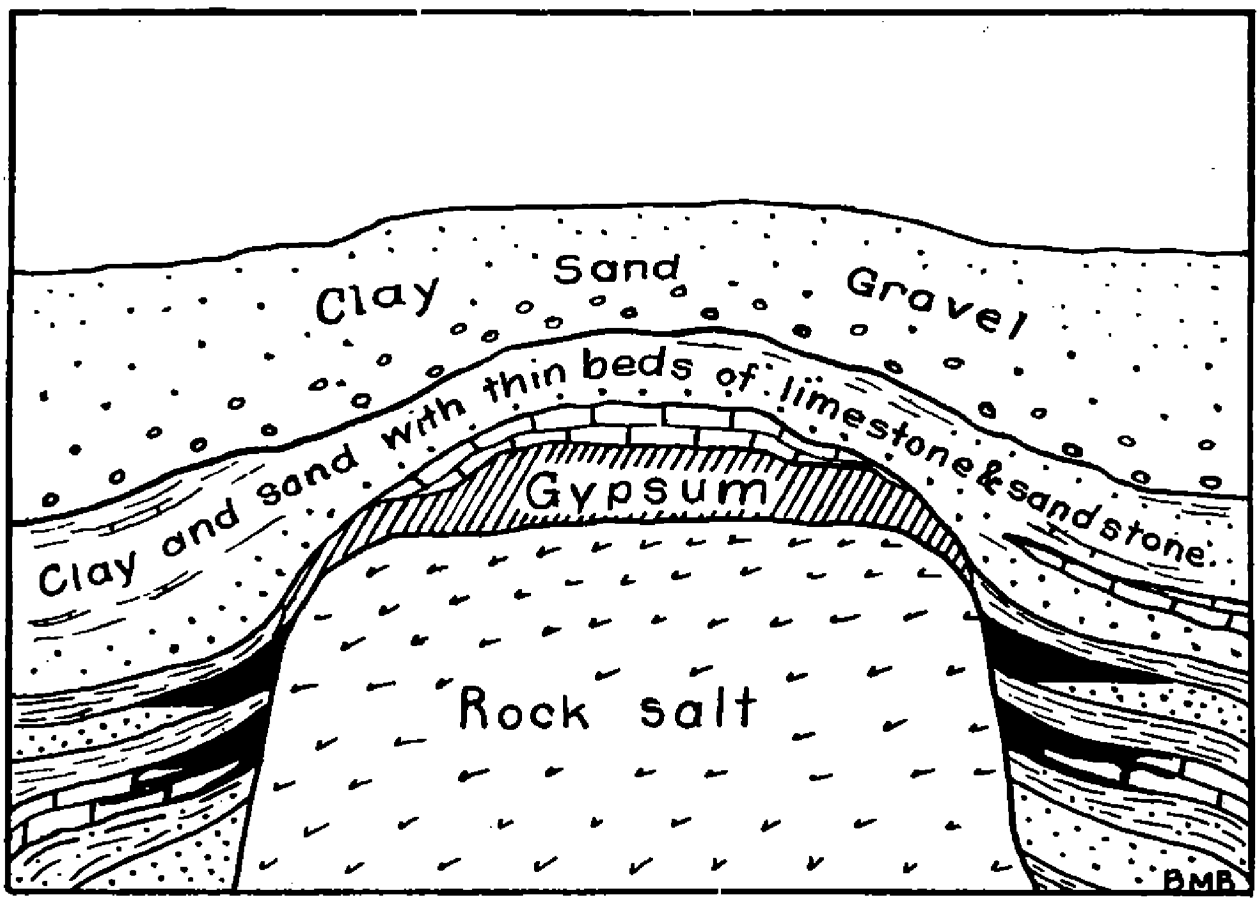

Fig. 14.—Sketch showing accumulation of oil against a core of salt, typical of the salt domes of the Gulf Coast area of Louisiana and Texas.

18. Powers, Sidney, Interior salt domes of Texas: Bull. Amer. Assoc. Petr. Geol., Vol. 10, No. 1, pp. 1-60, 1926.

19. Duessen, Alexander and Lanes, Laura Lee, Hockley salt domes, Harris County, Texas: Bull. Amer. Assoc. Petr. Geol., Vol. 9, No. 7, pp. 1031-1060, 1925.

20. Barton, Donald C., The salt domes of south Texas: Bull. Amer. Assoc. Petr. Geol., Vol. 9, No. 3, pp. 536-589, 1925.

21. Kelley, P. K., The sulfur salt dome, Louisana: Bull. Amer. Assoc. Petr. Geol., Vol. 9, No. 3, pp. 479-496, 1925.

22. Kennedy, William, The Bryan Heights salt dome, Brazoria County, Texas: Bull. Amer. Assoc. Pet. Geol., Vol. 9, No. 3, pp. 613-625.

23. DeGolyer, E., Origin of North American salt domes: Bull. Amer. Assoc. Pet. Geol., pp. 831-874, 1925.

Intrusions may have varied shapes and sizes, depending upon the amount of molten rock, the amount of heat present, the expulsive force of the lava, the weight and the thickness of the overlying sediments or strata, and the number of cleavage and fracture planes along which the lava may migrate with least resistance. If the liquid rock is forced into fissures and fracture planes and then solidifies there, dikes are formed. And if the lava solidifies in chimney-like passages, pipes or plugs result. While there are various other forms of volcanic intrusions, it is with these two types that petroleum is most commonly associated.

Petroleum deposits associated with volcanic intrusions are rare. However, much of the production of Mexico is associated with such structure. In the Tampico-Tuxpam oil field of Mexico, oil accumulations are found in areas where plugs or other igneous bodies cut across the petroliferous beds. The edges of these beds seem to have been folded upward along the flanks of these intrusions, thus forming anticlinal or domical structure into which the oil has migrated until it was trapped against the igneous mass. This type of structure and associated concentrations of oil is shown in Fig. 15. The igneous rock core is shown at *a*, with its top extending up through the

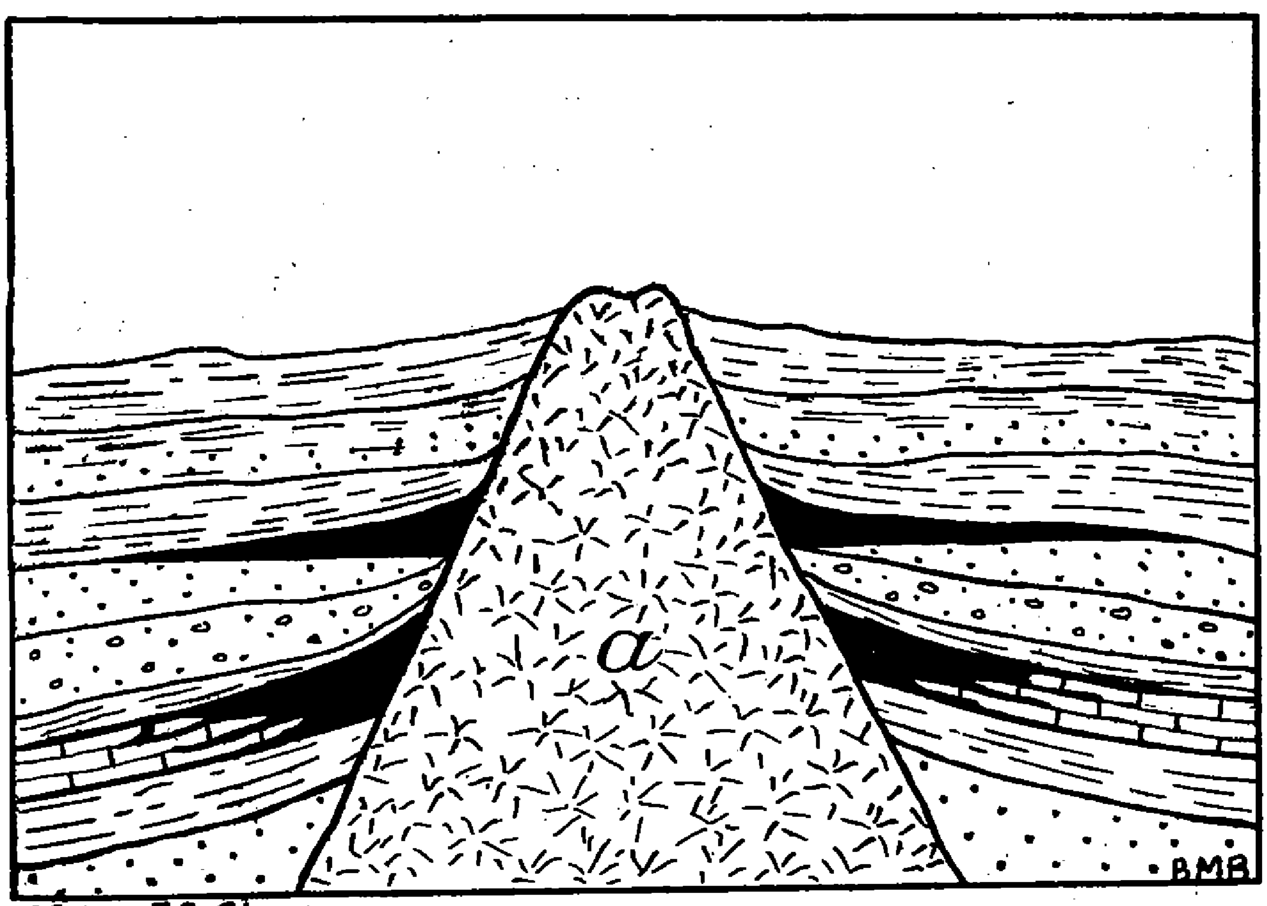

Fig. 15.—Sketch showing oil accumulation against rocks of igneous or volcanic intrusion, typical of parts of Mexico.

surrounding sedimentary rocks. The heavy black shaded areas meeting the sides of the igneous rock core represent accumulation of economic deposits of petroleum in the sedimentary rocks, which are usually channeled limestones. Petroleum accumulations of this type in Mexico are described by Clapp[83] and by Garfias and Hawley[84].

THE CHARACTER OF OIL SANDS - RESERVOIR ROCKS

PHYSICAL PROPERTIES

Porosity

Emmons[17] discusses rock openings with respect to both size and origin. Openings in rocks are classified as supercapillary, capillary, and subcapillary, depending upon their size[24].

Capillary openings are tubes less than two one-hundredths (0.02) of an inch in diameter, and greater than eight millionths (0.000008) of an inch in diameter, or sheet openings less than one tenth (0.01) of an inch wide, and greater than four millionths (0.000004) of an inch wide. Openings greater than capillary openings are known as supercapillary openings, and openings smaller than capillary openings are known as subcapillary openings.

Supercapillary openings are those in which water and oil obey the ordinary laws of hydrostatics, as when flowing through pipes. In capillary openings water and oil do not obey the ordinary laws of hydrostatics, but are affected by capillary action.

Water may enter subcapillary openings, but it tends to remain as if fixed to the walls; and since water has about three times the surface tension of oil, it tends to remain in the subcapillary openings to the exclusion of oil, one reason for oil occurring in the larger openings, as advanced by Washburne[25]. As a result, subcapillary openings are not considered a source of commercial oil production.

When we speak of the porosity of an oil sand we ordinarily mean the effective porosity, hence we do not take into consideration subcapillary openings or unconnected openings.

Experimental work with sands has been conducted in the laboratory of the U. S. Geological Survey[26,27] and by the U. S. Bureau

83. Clapp, F. G., Occurence of oil and gas deposits associated with quaquaversal structure: Econ. Geology, Vol. 7, No. 4, pp. 364-381, 1912.
84. Garfias, V. R., and Hawley, H. J., Funnel and anticlinal ring structure associated with igneous intrusions in the Mexican oil fields: Amer. Inst. of Mining Engineers, Bull. 128. pp. 1147-1159, 1917.
24. Daniel, Alfred, A Text book of the principles of physics: p. 316, 1895.
25. Washburne, C. W., The capillary concentration of gas and oil: Trans. Amer. Inst. of Min. Eng., Vol. 50, pp. 829-842, 1914.
26. Melcher, A. F., Determination of pore space in oil and gas sands: Trans. of Amer. Inst. of Min. Eng., Vol. 65, pp. 469-497, 1921.
27. Melcher, A. F., Apparatus for determining the absorption and the permeability of oil and gas sands for certain liquids and gasses under pressure: Amer. Assoc. Pet. Geol. Bull., Vol. 9, No. 3, pp. 442-450, 1925.

of Mines[28,29]. These experiments cover porosity, absorption, and permeability, texture and bedding relation, and subsurface relations of oil and gas sands.

For the purpose of this report we shall consider that the porosity of an oil sand is the ratio of the volume of effective pore space to the volume of the sand. Hence, a porosity of ten per cent means that for every hundred cubic feet of sand, there are ten cubic feet of voids which respond to the laws of capillarity or supercapillarity.

Whether or not the oil and water within an oil sand respond to the laws of capillarity or of supercapillarity (hydrostatics) largely determines the rate of decline of oil production and the percentage of recovery of the oil existing in the sand during the economic life of the well.

Melcher[26] has discussed "Results Obtained from Pore Space Determinations," and the "Relation of Pore Space to Productivity of Pool" which are quoted in full as follows:

Results Obtained from Pore Space Determinations

Pore space determinations have been made from 107 chunk samples of oil and gas sands, cap-rocks, and shales collected from Pennsylvania. West Virginia, New York, Ohio, Kentucky, Oklahoma, Texas, Louisiana, Wyoming, and Montana. The distribution of diameter of grains of 36 of these samples have been determined. The pore space with density and distribution of diameters of grains of oil-and gas bearing sands and associated rocks are given in the accompanying tables. None of the pay sands in which oil was found that had a porosity less than 10.1 per cent, were producing sands. The most probable explanation for this fact is that there are sufficient fine grains, including cementing materials, between the larger grains in these samples to reduce the interstitial openings to a size sufficiently close to the subcapillary size so that the oil, on account of the resistance it meets under existing pressure and temperature, will not move rapidly enough to produce in commercial quantities. A pore in an ideal sand, in which the grains are uniform spheres, does not have a constant diameter thoughout its length, but varies in diameter and cross-section, passing continuously from a minimum to a maximum cross-section.

Professor Slichter[30] has shown that the flow of water through a sand may be reckoned as passing through an ideal sand, the pores of which are continuous tubes of the minimum size. This reduction of the cross-section of the pore to the minimum for the flow of the oil would make the size of the pore approach much closer to the subcapillary than at first it would ap-

28. Mills, R. Van A., Experimental studies of subsurface relationships in oil and gas fields: Econ. Geol. Vol. 15, No. 5, pp. 398-421, 1920.
29. Mills, R. Van A., Relations of texture and bedding to the movement of oil and water through sands: Econ. Geol. Vol. 16, No. 2, pp. 124-141, 1921.
30. Slichter, C. S., Theoretical investigation of the motion of ground water: U. S. Geological Survey, 19th Annual Report, Part. 2, pp. 305-325, 1899.

per from the diameter of the grains. On the other hand, the grains of sand can be of such a shape and laid down in such a way that the width, or diameter of the pores at places is sufficiently close to the subcapillary to interfere materially with production. The production in such a case might not be suff.cient for commercial quantities, even when the well is repeatedly shot.

In Ohio, there are four wells of which production or non-production are given. The depths of the sands from which samples 5, 7, and 10 were obtained are about the same; but depth of the sand from which samples 16 was procured is not given, but is probably about the same as the others. Sample 10 has a pore space of 16.9 per cent., the grains of its maximum column are larger in diameter than the grains of the maximum column of samples 7 and 16, and are about the same diameter as the grains of the maximum column of sample 5. The well from which sample 10 was collected had an initial product.on of 440 barrels. Sample 5 had a pore space of 13.1 per cent, and the well from which this sample was obtained had an initial production of 80 barrels.

Sample 16 had a pore space of 16.8 per cent, and had its maximum column at a much smaller diameter of grain than samples 5 and 10; and the well from which this sample was collected had an initial production of 100 barrels. Sample 7 had a pore space of 4.7 per cent, and its maximum column had a small diameter of grain; the well from which this sample was taken was non-productive.

Relation of Pore Space to Productivity of Pool

Pore space is undoubtedly one of the several factors that control production from an oil or gas pool. Professor Sclichter has also shown that if two samples of the same sand are packed, one sample so that its porosity is 26 per cent, and the other sample so that its poros ty is 47 per cent, the flow through the latter will be more than seven times the flow through the former. If the two samples of the sand had been packed so that their porosities had been 30 per cent, and 40 per cent respectively, the flow through the latter would have been about 2.6 times the flow through the former. He states that, "These facts should make clear the enormous influence of porosity on flow, and the inadequacy of a formula of flow that does not take it into account."

Melcher[26] has shown that the effective porosity of a sandstone depends also upon the pressure applied to the contained liquid. For instance, one sandstone absorbed 12.9 per cent of water by volume at atmospheric pressure, 14 0 per cent at 250 pounds pressure, and 17.9 per cent at 1,000 pounds pressure.

Texture and Bedding

In an article entitled "Relations of Texture and Bedding to the Movements of Oil and Water Through Sands," Mills[29] summarizes conclusions drawn from the result of his experiments, as follows:

Through these experimental studies which supplement extensive field investigations, the fact is made clear that conditions of texture and bedding have an important influence upon both the natural and induced movements of oil and water through sands. Oil accumulations, as well as recovery depends directly upon deep-seated movements of the fluids, and is consequently governed largely by conditions of texture and bedding. Studies of these conditions and their relations to fluid movements are of economic, as well as scientific value. By demonstrating the fact that there are enormous underground losses of oil through retention in sands, and by establishing the causes for these losses, a logical step is made toward the more intelligent development and application of improved methods of recovery. With a view to contributing toward this important work. the writer outlines the following principles and relationships that have been indicated by the investigations therein described:

1. Variations in the textures and bedding of oil and water bearing sands cause corresponding variations in the movements of the fluids through the sands.

2. Movements of oil and water through sands tend to follow the paths of least resistance, generally through the relatively coarse, open-textured parts of the beds, the directions of movement tending to parallel rather than to cross bedding planes.

3. Frictional and capillary resistances to the movements of oil and water through saturated sands increase as the s zes of the interstices decrease. It is recognized, however, that under favorable conditions "gravitational" and hydraulic migration of oil of low viscosity occur in uncemented sands composed of grains ranging in diameter from 0.417 millimeters to less than 0.074 millimeters.

4. When a water-saturated sand of irregular texture is invaded by oil. and conversely, when an oil-saturated sand of irregular texture is invaded by water, the fluid originally contained is retained most persistently in those parts of the bed that are of relatively fine, close texture.

5. A water-saturated sand of fine texture is more permeable to water than to oil, and conversely, an oil-saturated sand of fine texture, is more permeable to oil than to water.

6. The selective permeability of sands with respect to oil and water is one of the factors determining the paths of least resistance to the movements of these fluids.

7. Selective permeability with respect to oil and water is most pronounced in sands of relatively fine texture.

8. As an oil-saturated sand of fine texture becomes wet or saturated with water, it becomes increasingly permeable to water and decreasingly permeable to oil. Conversely, as a water-saturated sand of fine texture becomes wet or saturated with oil, it becomes increasingly permeable to oil and decreasingly permeable to water.

9. Under conditions of rapid flow through sands of uniform texture, the differential movements of oil and water, whereby water tends to advance ahead of oil, are more pronounced in sands of relatively fine, close texture than in those of relatively coarse, open texture. This relationship varies according to the rate of flow, and may not hold where the rate of flow is extremely slow.

10. Under conditions of rapid recovery, water cones are more readily formed, and are more detrimental to the recovery of oil in sands of relatively fine, close texture than in sands of relatively coarse, open texture.

11. Under favorable conditions, the occurrence of bedding planes together with breaks or partings parallel to the dip of a sand may retard or prevent the formation of water cones; whereas, other conditions of bedding, especially where there is cross-bedding, such irregularities of texture and bedding may facilitate the formation of water cones.

12. Part of the oil retained in sands incident to flooding by water may or may not be profitably recovered. This depends, among other things, upon the time required for the retained oil to segregate and reaccumulate above the water, the readiness with which the oil then moves to the wells, and the amount of water to be pumped to the surface prior or during the recovery of oil. Oils of "low viscosity" can be much more readily recovered under these conditions than can oil of high viscosity. Sands of uniform texture, as well as those of relatively coarse open texture, are most favorable for the reaccumulation and recovery of oil subsequent to flooding.

13. In sands of uniform texture (as in the Bradford sand of northern Pennsylvania and western New York), or in sands where the upper parts of the pays are of relatively coarse, even texture (as in the Keener sand of southeastern Ohio), especially if the gas pressures have been depleted, edge water advancing under hydrostatic pressure in flat lying beds may assist in the recovery of oils of low viscosity. The water may benefit favorably situated wells; that is, wells tapping the relatively high parts of the sands or parts of the sands that are favored by conditions of texture and bedding, by facilitating induced segregation by maintaining fluid levels in the sands, thus regarding the by-passing of gas, by exerting propulsive force, and by flushing oil toward the wells. These relationships do not hold for oils of high viscosity.

14. Where the upper parts of the pays are of relatively fine texture, especially, where the gas pressures have been depleted, edge water advancing under hydrostatic pressure may cause the loss of much oil through entrapment and retention in those parts of the sands that are of relatively fine texture. This is especially true where the oil in the fine or tight sand is left behind by water advancing more rapidly through those parts of the sands that are of relatively coarse, open texture. Under such conditions, oils of high viscosity are subject to greater loss through retention than oils of low viscosity.

In an article entitled "Texture of Oil Sands with Relation to the Productivity of Oil," Melcher[31] gives a bibliography of work previously done in this field of research, and discusses reservoir rocks for oil, factors influencing size of openings and percentage of pore space in rocks, field examination and collection of samples of oil and gas sands, methods of the determination of pore space, fields visited, oil sands from Pennsylvania, oil and gas sands of Wyoming, oil sands of Oklahoma, chemical analysis of Burbank, Oklahoma sands, and a table giving percentage of total pore space; specific gravity of grains, and field information on wells; such as, data on production, shooting, and thickness of sands for 148 wells in Pennsylvania, Ohio, Illinois, Wyoming, Kentucky, Oklahoma, Kansas, New Mexico, Texas, Louisiana, and California.

Any one contemplating the study of oil sands should first read this paper, the introductory paragraphy of which is quoted, as follows:

> In an investigation of oil and gas production a study of the physical properties of sands that serve as reservoirs, as well as the physical properties of oil and gas, is very important. Physical factors of oil sand that should be studied are, pore space; size and shape of grains; size and shape of pores of the sand; permeability or rate of flow of oil through the sand under definite drops in pressure between the entrance face and exit face of the sample; absorption, or the quantity of oil which a unit volume of the sand will absorb under physical conditions similar to those that exist in nature; the degree of saturation of oil sands with oil; retentivity, or the capacity of an oil sand to retain its oil under given conditions; and the relation between thickness and extent of the producing part of the sand and the oil content and yield. Temperature, specific gravity, and viscosity of the oil are important; and relations of oil, gas and water, and influence of capillarity should be considered. To study effectively relations of oil, gas and water, and influence of capillarity, some pool should be selected; and changes in the relative positions of the oil, gas, and, water should be observed from the beginning of development until the pool is abandoned, in order to ascertain the relative progress of water encroachment in various textures of sands, and the influence of structural conditions. Not only is it important to study these natural factors in the production of oil and gas, but it is also important to take into consideration the artificial factors especially methods of management of wells after they are drilled-in. Such artificial factors which should be considered are: Diameter of hole through pay sand; influence of offset wells and offset leases; spacing of wells for most efficient recovery; dates of completion of wells, which would influence the production of the well or tract considered; casing troubles; size and position of casing at time of shot; number of times well is shot; size of shots; depth to top and bottom of shot; dates of shots; production of wells before

31. Melcher, A. F., Texture of oil sands with relation to the production of oil: Bull. Amer. Assoc. Pet. Geol., Vol. 8, pp. 716-774, 1924.

and after shots; and influence of shots on offset wells, as well as on the wells shot. In such an investigation, the observer should study field conditions collect field data, combine laboratory and field work, develop methods and make careful quantitative measurements upon as many of these physical properties as possible; and ascertain the relations existing directly or indirectly between these physical factors and the normal and ultimate yield of oil.

Consolidated and Unconsolidated Sands

In a series of laboratory experiments conducted by the senior author[32], oil was pumped into packed but unconsolidated sand, as well as into sandstones of different porosities. It was noted that the oil entered the packed but unconsolidated sand without any registration of pressure on the pressure gage attached to the pump; whereas, pressures ranging from 500 to 1,500 pounds per square inch were shown in pumping the same oil at the same rate into sandstones ranging in effective porosity from 12 to 22 per cent.

From these data and from observations in the field, the authors are inclined to believe that capillary resistance frequently is replaced by supercapillary (hydraulic) resistance in unconsolidated sands, even when the size of the openings between the grains would indicate a condition, of capillarity instead of supercapillarity. This condition, if so, may be produced by the movement and spreading of the sand grains when flow is induced within the sand by changes in fluid pressure in different parts of the sand, as when rotary mud sometimes flows from wells being drilled by the rotary method through unconsolidated sands to producing wells, because of the pressure of the hydrostatic head of the column of mud fluid within the drilling well being greater than the fluid pressure within the sand; and when oil flows into a completed well carrying with it large amounts of sand, as often happens in some of the oil fields of California and the Gulf Coast.

Suman[33], in discussing the function of screen casing in oil wells in the unconsolidated sands of the Gulf Coast fields says,

> Screen casing of proper mesh serves its best usefulness in permitting the regulated entry of the maximum amount of sand and oil while excluding gravel and small stones which would sand up the pump by sticking the valves or otherwise preventing its proper action. It probably serves another use in that it results in a more even distribution of the oil and sand channels radiating from the well than is the case with ordinary perforations. This even drainage of sand and oil equalizes the pressure in all directions around the casing; whereas, the use of a per-

32. George, H. C., Experiments and recovery of oil from Petroleum sands: Rept. to Director of U. S. Bureau Mines, Apr. 1923.
33. Suman, John R., Petroleum Production Methods: Gulf Publishing Co., Houston, Texas, 1923.

forating machine may result in the sand being drained from one side more than the other, thus creating a pressure against the casing. This unequal drainage due to faulty perforation is an argument for the use of screen pipe, and a possible explanation of deflection and damage to oil strings.

The senior writer has observed in the drilling of some water wells by the cable tool method in the glacial drift areas of Wisconsin, that it frequently takes several weeks to drill from one hundred to two hundred feet through unconsolidated glacial sand, even when casing is driven as drilling progresses; whereas, it may take only several days to sink to the same depth by closing the bottom of the casing with a plug of green wood when driving the casing, thus forcing the sand ahead and to the side. In the same way it is conceivable that oil or water under greater pressure may force its way and channel a course in unconsolidated sands, and flow under the laws of supercapillarity instead of capillarity.

As an illustration of unusual results produced at wells drilled through unconsolidated sands and shales in areas of faulting and minor earth movements, the wells completed four or five years ago in the Ventura oil field of California furnished some interesting examples.

Frequently in drilling these wells the movement of the sand and shales while drilling was progressing, resulted in the loss of part of the hole. Completed wells were often ruined by the collapse and bending of the tubing and casing. Some casing and tubing pulled from the wells was so "cork-screwed" that it looked as if it had been "dropped." In other cases both tubing and casing were sheared at points other than at the collars.

CHEMICAL PROPERTIES

Regarding the mineral and chemical composition of reservoir rocks Emmons[17] says, as follows:

> Few data are available regarding the mineral character of sands as shown by microscopic study. Most petroliferous sands consist mainly of quartz, but in some, feldspar, mica, and chlorite are present. Pyrite is often abundant. Some oil sands contain fragments of heavy residual minerals; such as, garnet, magnetite, ilmenite amphibole, and monozite. Recently the method of identifying sands by microscopic study of the minerals present has been used by various operating companies. Such study is expected to aid much in the correlation of sands.
>
> Many minerals, on altering, yield clay. The fine particles of clay and the colloidal matter that is present in many clays tend to seal openings between the original mineral particles. Many of the ferromagnesian minerals form clay on weathering. These are more abundant in general, in basic rocks than in acidic rocks like the granites. Sands derived from basic rocks are generally less

porous than sands derived from acidic rocks. Woodruff states that certain sands of Cuba are deprived largely from gabbro fragments, and that they have altered partly to clay, which fills the pores and limits their capacity. It is noteworthy, however, that fragments of limburgite, a rather basic rock, are found in the Thrall field of Texas, and that basic igneous rocks, in part tuffs and volcanic sands, constitute part of the reservoir at Furbero, Mexico.

The porous limestones that form reservoirs include dolomites and also limestones that are not high in magnesium. The Trenton limestone of the Lima-Ind:ana oil field is in the main a dolomite (CaMgCO). and Orton maintained that its porosity and ability to hold oil are due to dolomitization. He showed by analysis that the dolomitized part of the formation is productive, and that where it is barren it is low in magnesia.

Variation in Chemical Content

The chemical composition of oil sands—and probably all reservoir rocks in general—varies laterally, as from one well to another, as well as vertically.

The lateral variation in chemical content is due to lensing conditions; that is, the grading-out (due to the difference in the weight and chemical content of the sediments carried) into a shaly sand or a limy sand as conditions during the process of sedimentation changed; or when sand grains are deposited in sea water as compared to deposition in fresh water.

Core samples taken at regular intervals while drilling through a sand may vary in chemical content from top to bottom. This vertical variation may be due to several causes.

During the depositional process there may have been a period of time when certain small, shell-covered sea animals died, leaving their shells (largely $CaCO_3$) embedded in the sand. Also, there may have been a deeper submergence for a time, causing shale and clay (largely hydrated aluminum silicates) streaks or breaks within the sand stratum. This condition might result from an abrupt change in the type of sediments carried, but it is a well-known fact that the coarse sands and gravels are deposited first because they are the heavier. The finer sand grains, muds, silts, etc., remain in suspension longer; and therefore, would be deposited later or farther out from the shore line in deeper water.

Gravity alone then may be responsible for the vertical variation in the chemical composition of an oil sand, as it is manifest that many sand strata contain largely quartz (SiO_2) near the bottom; whereas, the middle and upper parts may have a variety of chemicals present depending, of course, upon the nature and content of the sediments carried and the physical conditions under which they were deposited.

The amount and character of the chemicals present in an oil sand will affect its porosity. Ordinarily an oil sand is composed of quartz grains cemented together by such chemicals as the oxides or iron, the common salts of calcium and magnesium, as well as by the silicates of aluminum: If the percentage of these chemicals (cementing materials) is high, the effective porosity of the sand will be reduced because of the spaces between the sand grains being filled with them. Whether the sand is light-colored, red, brown, or dark depends upon the relative amounts of the various chemicals present between the sand grains, as well as the color of the grains themselves.

Effect of Chemical Content Upon Recovery

The amount and kinds of chemicals present within an oil sand should be considered before applying any of the recent methods of more complete recovery; such as, the compressed air drive or the flooding process. For example, the oxygen in the air that is introduced into the wells by the compressed air process may combine with the iron, calcium or aluminum between the sand grains, and thus form a larger amount of the oxides of these elements which would materially reduce the pore space. Or, if the sodium carbonate method of flooding is used to drive the oil out of a sand, the pore space may be clogged by the precipitation of calcium carbonate ($CaCO_3$) or magnesium carbonate ($MgCO_3$), as a result of the mixing of the sodium solution with the chlorides of calcium or magnesium present within the oil sand.

Effects of Chemical Content Upon the Crude Oil

The chemicals present in an oil sand and the associated shales and clays evidently have a marked influence upon the chemical constitution and physical characteristics of crude oil. Underground filtration through certain types of clays and earths, especially fuller's earth, partly decolorize and fractionate the oil into light-colored, nearly transparent oils of lower viscosity and specific gravity.

The junior writer has noticed while experimenting with percentages of crude oil retained in loosely packed sands of different mesh as a result of capillarity and adhesion, that the crude which had percolated through the finer sands had the lighter color. In one particular instance, where a dark green oil of 42° A. P. I. gravity was percolated through a red shaly sand which had passed through a 100 mesh sieve, the oil recovered had a light orange or amber color, and the A. P. I. gravity was reduced approximately 1.5°. This reduction in gravity was evidently due to the reaction of the chemicals in the crude with the iron salts present in the sand. However, this reduction in gravity is exceptionally rather than generally true, because filtration of crude oil through light-colored clays and shales that are high in aluminum content usually slightly increases the A. P. I. gravity, lowers the viscosity, and extracts part of the color.

While underground filtration and migration of crude oil may have much to do with its ultimate color, the writers are inclined to believe that the character and nature of the organic matter from which the oil was derived, as well as the temperature at which natural distillation occurred are largely responsible for its wide range of color. However, the distance that crude oil may have migrated would materially affect the amount of chemical impurities (sulphur, nitrogen, oxygen) present, since the farther it migrates the more likely it is to absorb them.

Some Effects of Sealing Along Bedding Planes Within the Sand

In a latter section of this bulletin, the effects of sealing along bedding planes within the sand, in its relation to oil and gas pressure is discussed in a quotation from Millikan[49].

The sealing along bedding planes within the oil sand may cause different hydrostatic pressure in each stratum or part of the sand sealed. This is caused by edge water. Al Peake at the 1927 meeting of the American Institute of Mining Engineers, stated that this is the condition existing at the Salt Creek Field, Wyoming. The senior author noted in several water wells drilled into the St. Peter sandstone at New Diggings, Wisconsin, as many as five different hydrostatic heads in the same water well secured at different depths in the sand in drilling a total thickness of eighty feet of sand.

Conditions of this sort existing in an oil sand may greatly affect the amount and quality of oil secured from a well, depending upon the depth that it is drilled into the sand. It may also cause much loss and trapping of oil when the migration of edge water is more rapid along one stratum than along others. For instance, Figure 16 shows three wells, Numbers 1, 2 and 3 drilled to different depths in a sand of this character. This sand contains three productive strata, *a*, *c* and *e* and two non-productive strata, *b* and *d*. Well No. 1 is producing from stratum *a*, well No. 2 is producing from strata *a* and *c*, and well No. 3 is producing from strata *a*, *c* and *e*. Variations in the character of sand, character of oil and hydrostatic pressure in the three strata, *a*, *c* and *e* will give the reader some idea of the possible variations in the life history of the three wells 1, 2 and 3.

VALUABLE SURFACE AND SUBSURFACE INFORMATION

The existence of petroleum over a considerable area in the United States was a fact known to the white settlers at an early date. The oil springs of western New York, western Pennsylvania, and West Virginia, the bituminous outcrops and seeps of southern Oklahoma and Texas, of Brea, Brea Canyon, and Ojai, California were observed and described by early explorers. The oil seeps of Salt Creek, Wyoming were described by Captain Bonneville in his travels in the early thirties of the last century. He mentioned that

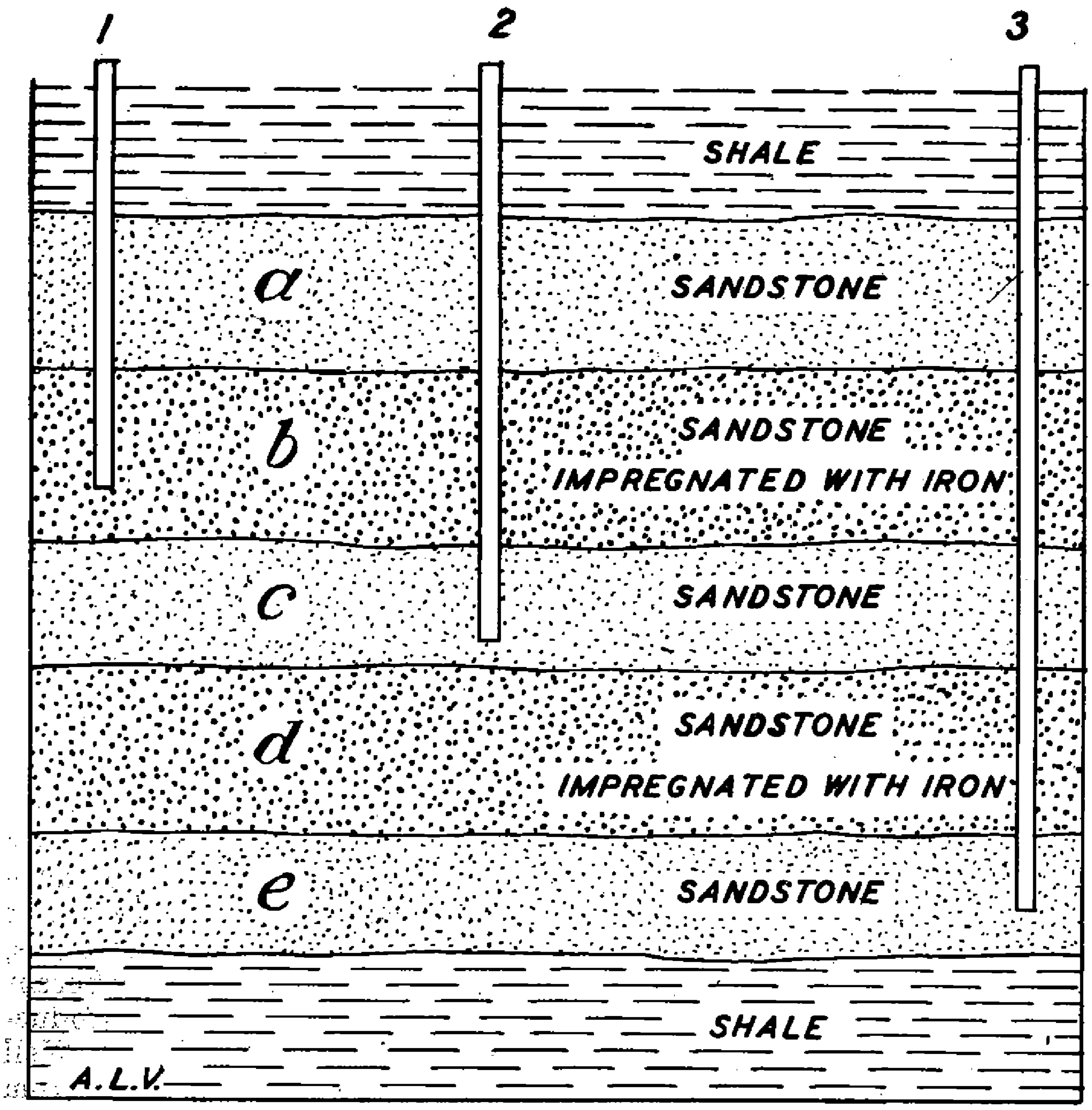

Fig. 16—Sketch illustrating the effect of sealing along the bedding planes within an oil-producing sandstone. Beds "b" and "d" are impervious, and act as seals, separating the fluid contents of beds "a," "c", and "e," thus producing three distinct oil horizons within the same "sand."

he used the oil to grease his wagons. About the same time, wells drilled for the recovery of salt brine in western Pennsylvania and West Virginia frequently encountered petroleum with the brine, necessitating in many cases the abandoning of the wells.

The oil spring on Oil Creek, near Titusville, Pennsylvania, in 1859 lead to the drilling of the first well in search for oil. Success secured in this well stimulated the search for petroleum near oil springs, bituminous outcrops, hydrocarbon gas seeps, and saline springs in other parts of the country. In many cases these wells discovered oil in commercial quantities, and some of the many wells drilled later in search of water or oil, where there was no surface indication of its presence, discovered oil. After about thirty years of the use of methods of this type in the search of petroleum, there came a general recognition by men in the industry, of the geologic structural features occurring in areas of oil production; so that during the past fifteen or twenty years, geological information has occupied a larger and larger place in the determination of favorable location for the drilling of "wild-cat" wells in search for new oil fields, and in the more efficient development of the fields already discovered.

INFORMATION SECURED FROM SURFACE STRUCTURE

In areas where the rocks outcrop at the surface, a careful survey of the surface structure may serve as a guide to the subsurface structure, and thus aid in predicting the most favorable site for the location of the test well.

This surface survey should be directed by a competent geologist, who may know in advance whether or not the petroliferous strata lie beneath the area in question. Then the problem resolves itself largely into the locating and mapping of suitable structure where-in to drill. The possible thickening and thinning of formations and the probability of overlapping and unconformities must be taken into account, as the presence or absence of such will determine whether or not the surface beds and the underground strata are approximately parallel.

Even though the surface outcrops are favorable, and it is known that petroliferous strata underlie the area, no concentrations of oil in commercial quantities will exist unless the subsurface structure is favorable. This, of course, can be determined accurately only by the drill. But with a clear knowledge of the nature and importance of structure, the careful geologist will devote much time and effort toward making the proper deductions as to the existence of a favorable source long before drilling is commenced. All possible pertinent data that will aid in deciphering the structural relations between surface and subsurface strata should be secured and correlated before any conclusions are drawn. In this case, good judgment and practical experience in field methods and operations are a valuable asset.

Before an area can be recommended or condemned for drilling purposes, other details of surface conditions in addition to those mentioned above must be worked out and checked. The presence or absence of bituminous outcrops, gas emanations, and oil seeps must be checked. The dip and strike of the outcrops must be carefully measured, and a contour map of the area should be made. An areal map will also assist, as it will indicate the position of the contacts of the different surface strata, show the location of the outcrops, and point out the relative position of any faults that are in evidence at the surface. In addition to this, a detailed study of the fossil remains in the rocks should be made if the relative geologic age of the strata is unknown. Also, surface outcrops several miles distant may furnish an appreciable amount of direct evidence as the subsurface conditions of the sediments beneath the area under observation.

INFORMATION SECURED BY PRELIMINARY DIAMOND DRILLING

In prospective areas where the surface outcrops are ill-defined or absent entirely, the geologist is practically helpless, so far as mapping structure is concerned. To locate and correctly map structures in such areas would be comparatively easy if all the surface terrain, vegetation, loose and displaced rock, sand, and gravel were scraped off. As it is in many parts of north and west Texas and in practically all of the west half of Oklahoma and Kansas the geologist gets only an occasional view of the strata, visible enough to be mapped. In many parts of these red bed areas mentioned above, there are no exposed strata for miles; at least, none that might be called dependable.

Again, the geologist may find exposed strata in these areas that, by their dips and strikes indicate the existence of an anticline; but so few outcrops of the strata can be found that no knowledge of the size of the structure can be obtained with much accuracy. Such conditions have resulted in many cases in the drilling of expensive test wells that were "off structure."

The diamond core drill, now used in many parts of Texas, Oklahoma and Kansas, eliminates these handicaps. At any desired depth it will cut a continuous core of the formation or strata. When a stratum is reached that is easily distinguished from the others, it is usually selected as a "key bed," and its depth, together with the elevation of the location, is recorded. The drill is then moved about a mile away, usually to another corner of the same section of land, where the "key bed" is sought again. The position and depth at this location is recorded, and the "key bed" is checked to ascertain whether it is running higher or lower than it was found at previous locations. In this way the folding of the earth's strata is readily detected, and may be accurately mapped, since the character, thickness, dip and strike of the strata have been definitely established. Frequently three or four such holes are enough to locate a subsurface structure, and ten or twelve are sufficient to define the limits of a dome.

The diamond drill is not a new invention, as mining engineers and mining geologists have used it in prospecting for mineral deposits and ore bodies for many years. However, its use in locating structures favorable for the accumulation of oil and gas has been a comparatively recent development in the oil industry.

Most of the diamond drills used in the Mid-Continent area are manufactured by the Longyear or Sullivan Companies, and are constructed for drilling to depths of 900 to 1,000 feet. However, most of the work that has been done to date rarely if ever has exceeded a depth of 600 feet before a suitable "key bed" has been located. In the Thomas, the Hubbard, the South Braman, and the Tonkawa pools, all of which were discovered as a result of core drilling, the depths ranged from approximately 300 to 500 feet.

The diamond drills mentioned above were equipped with the two-inch core barrel fittings, and 500 to 600 feet of small drill stem or rods, which are cut and threaded in 10-foot lengths. Small "fishtail" bits are used while drilling in soft formations, but circular steel bits set with black diamond cutters are used in hard strata. A double-action duplex pressure pump is used to circulate water down the inside of the drill pipe and up on the outside, thus keeping the bit cool, flushing out the "cuttings," and preventing the walls of the hole from caving.

The diamond drill is described by Uren[2], Jeffery[13], and Edson[34]. Core drilling for structure has recently been discussed by, Officer, Clark, and Aurin[35].

WELL RECORDS

Accurate well records form the basis for successful future operation of any oil field property. The cost of compiling various forms of well records is very little when compared to their inestimable value when future troubles arise and accurate data of drilling and methods of completion are needed. The records needed vary with each field, and a set that will best meet the needs of each property should be adopted by each company operating in the particular field.

34. Edson, Frank A., Diamond Drilling: U. S. Bureau Mines, Bull. No. 243, 1926.
35. Officer, H. C., Clark, Glen C., and Aurin, F. L., Core Drilling for Structure in the north Mid-Continent area: Bull. Amer. Assoc. Pet. Geol., Vol. 10. No. 5, pp. 513-530.

Most operators, especially the most successful ones, realize that accurate well records are necessary. Every operator realizes the value of records of the sales of oil, and should place equal value on records of well logs, drilling procedure, what the wells have done, are doing, and what they may be expected to do.

The records should be kept on suitable forms, so that all information will be readily accessible. Files can be made, using letter-size sheets for all office reference; and field notes can be compiled in pocket-size note books which are durable and well bound. With such a system the petroleum engineer and his associates can readily find such data as the superintendent or executives may desire. Complete records of each well should be kept from the time the location and surface elevation are known until the well is abandoned. The engineer should review these records from time to time if necessary, in order to keep familiar with the drilling history and past performances of each well.

After the information has been gathered and filed as compact records, it should be worked up into graphic forms; such as, cross-sections, subsurface contour maps, and graphic well logs. By this procedure the operators have a "picture" of casing depths, well depths, the location of various oil and gas sands, as well as the places at which water troubles may occur.

Before cross-sections and graphic logs can be prepared, it is necessary that the exact location and elevation of each well be known. These are then recorded on a field map that is drawn to some conventional scale. Elevations should show the height of the derrick floor above sea level, and should be accurate to within one or two feet. They can be "run" accurately with a transit or plane table and stadia rods, or by using a wye-level. Well elevations sometimes have been taken by using an aneroid barometer and hand level or a Brunton compass; but such work is often inaccurate, and therefore cannot be recommended.

Field maps and property maps are very essential records used while operating oil field properties. The former is most convenient when drawn on a scale of 1,000 or 2,000 feet to the inch, and should show only the property lines, railroads, names of the landowners, and the locations and numbers of the wells. Various symbols should be used to designate whether the well is drilling, producing, is a dry hole, or abandoned, etc. The property map should be drawn on a larger scale, often 200 to 300 feet to the inch is used. This scale affords opportunity for indicating everything on the property; such as derricks, producing wells, buildings, tanks and reservoirs, roads, pipe lines, telephone lines, fences, stream lines, "jack plants," or "powers," etc.

A wall map furnishes ready and complete information as to the present condition of the wells. It can be pasted to a soft piece of beaver board that has been tacked to the wall in the field office. Sharp pins that have round glass heads of various colors can be pushed into the map at various locations to portray the status of each well. For example, a yellow pin may mean that the well is drilling; a black one, that it is abandoned; whereas, a red pin may mean that the well is producing a certain amount of water with the oil.

Before any constructive or repair work on an underground problem can be undertaken with any degree of accuracy, the old records and well logs should be reviewed carefully. This may mean the collection of all books, records, and other data giving information regarding the wells in question. Such data naturally includes log books, office drilling records, drillers' tour reports, drillers' notebooks, re-drilling books, production reports, tubing and casing records; in fact, all information that deals with the problem in hand. Old records are awkward and confusing to use unless they have been compiled in convenient and accessible form. Where the records are not clear the foreman and drillers should be consulted if possible.

The well log itself has developed as a matter of convenience because it brings the data together in a brief, concise form, so that whenever a well is discussed its complete history is available. The most important features should be emphasized on the log. This should be done in such a way that they will be easily discernible. Ink of different colors, printing, and italicized letters are quite helpful in this respect. Color and hardness, as well as a brief description of each formation should be noted. The occurence of pyrite, sea shells, "sulphur smell," "cavey sand," and "showings" of oil and gas should be recorded opposite the figures showing their respective depths at which they are encountered. Any casing, drilling tools, lugs, or bailers side-tracked in the hole may cause future trouble, and it is well to include their depths in the log. Other important items that should be included in an ideal log are: the different sizes. weights, and depths of the various types of casing used; the thickness, nature, and depths of strata drilled through; the depth and characteristics of water sands; how the casing was landed, and if it was cemented, including the amount of cement used; how and where water shut-off tests were made; the descriptive location of the well, its elevation and ownership; repair work and redrilling jobs; names of the drillers, tool dressers, and others employed at the well; and the dates of starting and completion of drilling, together with the initial production.

Many states are too lax in their requirements for the proper compilation of well log data. California is quite ideal in this respect, however. The various oil companies operating there are required to compile their logs on durable well-log forms, the size of which is 8½ by 21½ inches. Both sides of the form are used. The front side is reserved for the name of the company, the name of the field, the descriptive location of the property, the elevation of the well, and the formations penetrated, together with their depth, thickness, and a brief description. On the back or reverse side is included the complete drilling history of the well.

Well records have been discussed in detail by Ambrose[36] and by Swigart and Schwartzenbek[37].

SAMPLING AND CORING

Collecting and Filing

In drilling wildcat wells, in particular, it is very important that the well be drilled in such a manner as to furnish definite information as to the possibilities of the area. While such wells are drilled primarily to obtain production, any methods and devices that can be used to make the subsurface information more exact and complete should not be cast aside or neglected because of the necessary increase in the total cost of the well. It is poor economy to try to save a little money by not testing every likely oil-bearing formation.

The petroleum engineer or geologist in charge should collect samples of any oil and water, as well as samples of all strata penetrated. This should be done especially in wild-cat areas where there are no good horizon markers to indicate the stratigraphic depth, in places where the dip of the beds is unknown, and where for other reasons the correlation is doubtful. Where correlation of strata is uncertain, formation samples should be collected every five feet. Many instances can be cited where productive oil and gas horizons have been overlooked, because of either improper testing or too much haste in drilling.

In areas where correlation of sands is doubtful, all samples should be carefully marked, and then saved for future reference. The cost of collecting them is very small in comparison to their possible future value. A convenient container is a short, wide-mouthed, four-ounce bottle having a tin screw top. Tobacco cans are satisfactory for temporary use, but if the samples are kept in

36. Ambrose, A. W., Underground conditions in oil fields: U. S. Bureau Mines, Bull. No. 195, pp. 201-229, 1921.

37. Swigart, T. E. and Schwartzenbek, F. X., Petroleum engineering in the Hewitt field, Oklahoma: Report to the U. S. Bureau of Mines, in cooperation with the State of Oklahoma, and the Chamber of Commerce, Ardmore, Oklahoma, 1921.

them very long they will become discolored by rust. For filing samples a large cabinet having long, narrow, but shallow drawers may be used. On the face of each drawer a label may be pasted which shows the well number and the depths between which the first and the last samples were taken. Within the drawer the sample bottles should be arranged in rows according to depths. Each bottle should be labeled to show the well number, depth, name of the formation, if known, date collected, and whether it was taken from a rotary or a cable-tool well.

METHODS AND DEVICES

When the wells are drilled by a drilling contractor, the company should provide for the collection of samples. Contractors are interested primarily in "making hole," and may naturally be inclined to do so at the expense of knowing and recording the formations drilled. On contract wells "sample grabbers" or "formation men" are often employed to work under the supervision of the geologist or petroleum engineer. The presence of such men on the derrick floor often displeases some drillers, so it is a good idea for the company supervisor or engineer in charge of drilling to try to establish friendly relations with the drillers. Drilling is an art within itself; and if the engineer and the driller realize that each is a specialist working for the same purpose, a marked degree of friendly understanding and co-operation can be created which will greatly aid in proper sampling. If the geologist or engineer talks to the driller about the various samples, how the formations drill, the evidence of oil, gas or water, and washes the samples at the well, the average driller will eventually collect the samples in the manner desired. In order to obtain these results the engineer or geologist must possess a pleasing personality, and should have his headquarters on the lease, so as to be in close touch with the drillers and the well.

In this same connection the necessity of uniform names of identical strata might be mentioned. It is frequently the case that the same formations are known by different names in different parts of the same field. In a new field, as soon as a few wells have been drilled, a conference of neighboring superintendents, drillers, and engineers should be held to discuss, among other problems, the subject of formations penetrated in drilling. The driller can relate how the different formations respond to the drill, and how the cuttings appear, and the engineers can make suggestions as to the proper names that should be applied to them. In this way a uniformity of names can be established for the entire field.

Collecting Samples from a Cable-Tool Well

More satisfactory samples of formations can be obtained from wells drilled with cable tools than with rotary tools, because there is usually less open hole which precludes cavings, the tools are pulled out more often, and the cuttings cannot be scattered and contaminated by the circulating system as is the case in rotary drilling.

Samples can be secured in two ways: samples that have been pulverized by the bit can be brought up from the bottom of the hole in the bailer; and, if the formation is sticky, fragments will be found on the bit when it is pulled out. The contents of the bailer are mostly mud. When the bailer is dumped, a bucket full of the contents can be caught for a sample.

Samples of sand and other coarse material can be best obtained from the bailer after the upper part of the sludge in the hole, which may contain cavings, has been bailed out so as to permit the bailer to be run to the bottom. After the sample of sand has been collected from the bailer, the sand should be placed in a bucket, the nozzle of the derrick hose placed on the bottom of the bucket, and a slow stream of water turned on to float out the mud. Hot water will cause the oil color to show up better than cold water. The shale or clay samples that are brought up on the corners of the bit should be examined.

Cable-tool samples may also be secured by use of various core barrels or "biscuit cutters" that are on the market. Some of them can be successfully used in any reasonably soft formations; such as, coal, clay, shale, and sand. These tools should take a more representative core out of loose, sandy formations than a rotary core barrel, and they can be used much more quickly. They are especially adaptable to prospecting with portable rigs, but may be used on any cable tool rig where it is necessary to secure a large sample that is not finely broken up by the drill. Collom[38] describes one type as follows:

> The core drill, which is about 14 feet long, is screwed to the jars; the tool string consisting of the rope sockets, jars, and core drill. The lower end of the top piece of the drill is threaded externally to receive the hollow drill stem, a wrought-steel tube about 10 feet long which telescopes over it. The joint at the top must be set up as firmly as a drill bit. Before the tool is swung into the derrick the core barrel head with its swiveled weight is inserted into the hollow drill stem.
>
> Before taking a core, the hole should be bailed or flushed clean of cuttings, and an exact measurement taken. The tools are then spudded in the usual manner, using about an 18-inch stroke. Since the barrel projects about four feet, it will not be lifted off bottom by the motion of the drill. After about twenty or thirty inches have been drilled, the tools are withdrawn and

38. Collom, R. E., Prospecting and testing for oil and gas: U. S. Bureau of Mines, Bull. No. 201, 1922.

the core extracted. It is frequently the case that the core will be broken into "biscuits" of a few inches in length due to the intermittent "jar" of the drilling tools.

Competent drillers can keep an approximate log by carefully noting the mechanical reactions of the drilling tools while drilling in the various kinds of rock, and by noting the nature of the mechanical wear or abrasion on the bit. When drilling in shales the tools run smoothly, and drilling is easy in a dry hole; the bit is not cut or worn. In gumbo or sticky shale, the tools jerk, and the beam will not drop quickly; the bit is not worn. Soft sand drills fast and easily with a "loose" line, and the tools often plunge; the bit is cut a little vertically. Sandstone drills smoothly with some "kick back"; it wears the bit badly out of gauge. In limestone the drilling is slow and difficult, and the tools respond with much "kick back"; the bit is usually cut and worn, and the face is often battered, but is not worn out of guage as badly as when drilling in sandstone. Gypsum drills smoothly and more easily than limestone, and the bit is not worn much.

Careful collecting and preserving of formation samples should be accompanied by careful measurements of the depths from which they were taken. However, the careful driller will know the depth of the hole at all times. In case the exact depth at which a different stratum is encountered is not known, the hole should be measured soon after the stratum is "tapped." There are two ways to do this. A steel measuring line on a reel may be clamped to the fly wheel of the engine, thus using the power of the engine to raise and lower the line. A weight must be attached to the end of the line. After enough line has been reeled out to reach nearly to the bottom of the hole, the line should be carefully let out a few inches at a time, a man holding the line to keep it centered in the hole as nearly as possible. By keeping the line taut, and by feeling for the impact of the weight on the bottom, the true depth can usually be quickly determined. Difficulty is sometimes encountered in measuring deep holes by this method; especially if there is a long string of casing in the hole, as the casing may cause a metallic lag of the line, or cause it to become magnetized. This can be partly eliminated by using a heavier weight on the line and by coating the line with a heavy grease.

The other method of measuring, the one which is more often used, especially in deep holes, is that method whereby the sand line or drilling line is used instead of a steel measuring line. By knowing the exact distance from the derrick floor directly upward over the crown pulley and down to a point near the bull wheel shaft that is determined by standing the driller's five foot stick on the floor in an upright position, the drilling line is measured as the tools are pulled out of the hole. This is done by placing a piece of hemp around the drilling line at a point level with the top of the hole when the tools are resting on the bottom. When this marker or "flag" reaches the point near the bull wheel shaft that is five feet above the floor, it should be removed and another tied at the top of the hole. By this method, assisted in finishing the process by using the drillers measuring stick, a fairly accurate measurement can be made.

If the sand line is used, the distance from the top of the floor or hole up over the sand line pulley and thence down to the top of the sand reel flanges must be accurately measured. Then with the bailer resting on the bottom of the hole, the measuring is done in a manner quite similar to that related above.

Collecting Samples from a Rotary-Tool Well

It is more difficult to secure accurate logs of wells drilled by the rotary method than with cable tools. However, it is quite possible to obtain accurate logs while using rotary equipment. Rotary tools are used mostly in proven territory, where off-setting is vigorous, the main purpose being to drill down to the oil sand as soon as possible. Therefore, the drillers naturally tend to devote less attention to the proper compiling of logs.

In cable tool drilling it is a simple operation to stop drilling at any depth, and then run the bailer to secure samples of the formation in which the bit is cutting. But with the rotary, however, the bit is usually many feet below the top of the formation before the cuttings begin to appear in the slush trench.

Drillers usually know when the formation changes by the mechanical reactions of the pumps, the rotary table, and the drill stem or "tools." Thus, they are able to judge with a fair degree of accuracy the character of the formations in which they are drilling. For example, when drilling shale the rotary table and chain usually run smoothly, the pumps require a medium head of steam, the bit is cut or worn a little, and drilling is rather fast. When the drill stem is "crowded" the pumps labor a little, but the cuttings will not ball up badly on the bit. However, hard shale or slate drills like hard sand, and is often mistaken for it. It may, however, slow the pumps when the bit is crowded, and have a slight pick-up when spudded, in which case it is usually correctly identified. The bit is badly cut. Clay drills easily but slowly, with but slight wear on the bit. The pumps require high steam pressure to prevent stalling, and the mud fluid should be thinned out. The rotary runs smoothly but under great tension, and the drill stem must be picked up frequently to prevent stalling of the pumps. When drilling in gumbo or sticky shale it is necessary to run the pumps with a full head of steam. The tools and table jump and jerk, and it is frequently necessary to reverse the engine and spud the tools to clean the bit of the balled-up cuttings. When this is done the pumps have a large pick-up. Shaly limestone cuts the bit a little. The pumps do not labor, but the bit balls-up when crowded. The tools jump occasionally, and the pumps have some pick-up when the tools are spudded. Sandy shale, usually drills rapidly, and cuts the bit considerably. The pumps do not labor, even when the bit is crowded, and they run with rather low steam pressure. Usually the cuttings do not ball-up. This depends upon the amount of shale present, however. Hard sand cuts the bit badly. The pumps run with low pressure, and do not pick-up when the tools are raised off bottom. The rotary and tools often jump. The fluid level in the slush pit may be appreciably lowered, as the sand often absorbs water. The tools may plunge when drilling in loose sand. Limestone drills hard and slowly, and smooths the bit and knocks it out of guage. The tools jump and jerk, but the pumps run easily with low steam pressure. Shell drills like sand. Rock salt drills like soft sand, but the mud is whitened, leaving a salty crust on the slush trench. Gypsum does not require much steam pressure, and the pumps can be run slowly. The cuttings ball-up, and cause the rotary to jump a little, but has no effect upon the pumps. The bit is not worn very much.

The various mechanical reactions mentioned above apply especially when fish-tail bits are used. Recently most drillers are showing much favor to the general use of such "rock" bits as the Hughes rock bit, the Hughes self-cleansing bit, the Reed roller bit, and the "K-P" bit. While the mechanical reactions produced when using these bits are somewhat similar to those produced when fish-tail bits are used, they are less reliable; so that it is now necessary to rely more upon the "timing" of returns that are carried into the slush trench, in order to draw definite conclusions as to the nature of the formations being drilled.

Rotary samples may be obtained by three methods:[13] (1) Bit samples may be secured by shutting down the pumps, then drilling a few feet; after which the drill stem is withdrawn, and any material clinging to the bit can be removed for a sample: (2) flow samples may be secured from the mud fluid as it emerges from the hole into the slush trench; and, (3) by the use of various types of core barrels. The principal objection to these methods is the length of the time required in each case.

Most rotary samples are obtained by collecting the cuttings as they appear in the ditch or trench. If the mud is thin, the coarser particles will settle out in the trench. Sand will remain in suspension long after the mud has passed on through the trench. Some drillers throw a large thread protector into the head of the trench and catch samples in it. Any sort of baffle in the trench will hasten the dropping of cuttings from the mud.

An accurate sample can be obtained by throwing the rotary table out of gear, then circulating all cuttings out of the hole while the bit is resting on the bottom. When mud fluid free from cuttings appears in the ditch, clean out the ditch and baffles and resume drilling. The first cuttings that appear at the surface will be from the depth at which drilling was resumed. This method will require two to four hours if the hole is about 3,000 feet deep.

The greatest need in taking rotary samples is some definite means of knowing the exact depths from which the sample came without having to stop drilling and flush out the hole. Certain tests, such as introducing paint or dye into the mud stream to indicate the time required to travel down the stem and back to the ditch, have been tried; but the results are not very accurate. Introducing shelled corn under the foot valve of the pump has given more accurate results.

In using this method, the exact depth of the hole is noted, and marked on the grief stem or "kelly" joint. Note the number of strokes the pump is making per minute, as well as the length of the stroke, and then estimate the efficiency of the pump delivery. Then, after computing the comparative volumes of the drill stem and the hole, the time required for the corn to reach the bit can be calculated. A permanent pump displacement table, figured out and posted in the rig, will make such calculations easy. When the time required for the corn to reach the bit has expired, the depth drilled within this interval should be noted. At the bottom of the hole the corn is mixing with the cuttings, and the depth from which they are starting to rise in the mud stream is known. When the corn appears in the ditch, a sample of the cuttings associated with it will be from the depth already noted.

The total time required to make the round trip in any depth of hole can be computed for the total diameter of the hole. No allowance is made for the displacement of the solid material of the drill stem in the hole, as this is undoubtedly offset by the irregular variations in the diameter of the hole, owing to the caves and irregularities of hardness of various strata. The most important factors to know are the length of time it takes for the corn to reach the bit, and the depth of hole drilled within that time. The corn and cuttings may take more time to travel from the bit to the surface than was calculated. This, however, will vary with the efficiency, speed, and length of stroke of the pumps, and with the size of the bit and drill stem used.

Accuracy in taking measurements at rotary wells is just as important as when cable tools are used; that is, if the keeping of accurate logs is necessary. The depth at which different formations are encountered can be kept correctly to within two or three feet if ordinary care is used. The method used is to keep a record of the drill stem in this manner: The Kelley joint, which is usually about 30 feet long, is first drilled completely down. Then as each joint of drill stem is added, it is accurately measured with a steel tape line; and as each "fourble" (about 85 feet long) is added, it is measured also. In this way the depth of the hole is accurately known when each joint is "down." It is a good practice to mark the Kelley with a cold chisel every foot of its length, beginning at the bottom as "one" and increasing the numbers in order to the top. The driller can then keep accurate account of the depth of the change in the formations by noting the mark on the Kelly joint, at the time he enters the new formation. This gives an accurate measurement to the top of the new formation, if he has a correct total of the amount of drill stem in the hole at all times. By making a similar notation when the drill passes through the new formation, the driller knows the thickness of the formation, as well as its depth.

Steel line measurements should be taken in addition to this method at important places; such as, "key beds" or horizon markers, possible casing seats, and above the point which an oil sand is expected. This is desirable because in measuring pipe in the hole no account is taken of the stretch due to its own weight. The same steel line should be used each time a measurement is taken at the same well, and it should be discarded when it has become stretched.

During recent years it has become a common practice in rotary drilling to take cores of the formations penetrated. Intelligent methods of coring eliminates the uncertainties of drilling through strata that might be oil-bearing, and in disclosing the presence of intermediate or bottom water.

Coring originated in the diamond core drilling method used in mining. Its first application to oil well drilling was probably in the Gulf Coast fields. There the first coring device was simply a piece of drill pipe having a few teeth cut in the bottom, similar to a Baker casing shoe. This type of core barrel, called the "basket core barrel," is used often in the Mid-Continent fields at the present time. It is easily made, and is simple to operate; but is objectional because the frictional heat developed often burns out all traces of oil, and the fresh water in the associated mud fluid may neutralize any salt water present in the core taken.

Uren[2] and Jeffery[13] describe various other types of core barrels used to best advantage in rotary drilling.

After cores have been taken it is then necessary that they be examined by geologists or others who are competent to determine their value as accurate samples of the formations, and to ascertain whether they contain oil or water. A perfect core would be an unbroken sample, the diameter of which is large enough to show the true lithologic character, texture, and dip of the fromation penetrated, and whose characteristics were unaltered in any manner while securing the sample. From such a core it is quite possible to ascertain the characteristics and economic importance of the formation.

If it were mechanically possible to take such cores with any degree of consistency, correct interpretation of subsurface conditions would be easy. Until the various types of core barrels now used are perfected mechanically, many cores will continue to misrepresent the formation from which they are taken. This is because they are often altered by the heat of coring or contaminated by foreign material from rotary mud so as to become misleading, and thus convey false conclusions as to the nature and character of the formations under observation.

The Halliburton sand tester[39], a device for testing the fluid contents of the sand penetrated, has been perfected during the past year. The tester consists of a tapered packer, below which is a perforated pipe extending into the "rat-hole" drilled into the sand. There is a steel stop-cork enclosed in a case above the packer. By giving the drill pipe a quarter turn the stop cock is opened, after the packer is properly sealed above the sand. The fluid in the sand enters the perforated pipe and flows up through it into the drill pipe. Samples of water or oil in the sand are thus secured, and gas if present will readily fill the drill pipe. After the sample is taken the valve is closed and the drill pipe with attached tester and sample is removed from the well.

EXAMINATION OF CUTTINGS AND CORES

Physical Examination

The principal physical characteristic of a rock will usually suggest the name used in classifying it. Shale, clay, mud, slate, and limestone are usually denoted by color or hardness; and sand, sandstone, and gravel, and other porous material by their texture and hardness. The name that is given to any rock by the driller depends upon the way it responds to the drill, how it affects the drill bit, how the cuttings appear at the surface while wet and also after they have been dried out, and the probable amount of fluid the sample contains.

39. Halliburton, Erle P., The Halliburton sand tester for drilling wells: The Halliburton Oil Well Cementing Co., Duncan, Oklahoma.

Log terms used by various drillers are often confusing and misleading. For instance, sandstone is frequently logged as sand, sandrock, rock and sand, sand shell, and sand boulders. Shales or argillaceous beds are often recorded as shale, mud, gumbo, slate, clay, mud and boulders, cavey sand, shale and mud, talc, soapstone, shale and clay, slate rock, quicksand, and various indefinite terms. Due to the fact that only a small per cent of rocks penetrated are limestones, for them a smaller variety of terms have been devised. Such names as lime, lime shell, and lime rock are alternately used.

Such a variety of terms is very confusing, and makes correlation exceedingly difficult. This situation can be materially remedied by a closer association and cooperation of drillers, geologists, and engineers.

All samples should be examined carefully for small fossils, impressions of leaves, plant remains, salt, pyrite, mica, gypsum, sulfur water, abnormal temperature, etc. The driller or engineer should note whether a sand is fine-, medium-, or coarse-grained, its color, whether the grains are angular or round, and whether it is largely quartzose or not before it is logged. It will materially assist the geologist or engineer when examining the samples if he can ascertain if the formation drilled is sticky, cavey or tough.

Care must always be exercised when examining the contents of the bailer. These contents are predominately mud, and must be washed and stirred carefully until the coarser parts of the sample settle out. If no coarse and heavy ingredients are present, the examination may be difficult and misleading. A sandy shale is liable to have its shale content converted into mud, and the bucket sample after washing may seem to be fine sand. Thus, the formation may be logged as sand instead of sandy shale. Cuttings of flinty shale, chert, hard limestone, in fact any brittle rock that can be broken by the bit into fairly uniform small grains will resemble sand when dumped into a bucket; but if they are examined under a microscope or even a good hand lens they will be observed as being quite angular and sharp-edged. In this connection then, microscopic slides may be made by grinding down the larger fragments from the bailer until they are thin enough to transmit light. This will permit an examination of the relation of texture to pore space, and will afford a better opportunity to find small fossils and traces of petroleum.

Many color designations are of no value or significance. On the other hand, color is often the principal feature whereby a horizon marker is identified. The color of wet samples may differ from that of dry samples. For example, shales that are logged while wet as brown or blue, are usually pale red or gray when dry. Since it is easier to wet a dry sample than to dry out a wet one, it is possibly best to log all samples as they would appear when wet. Then if it becomes necessary to examine them again after they have been filed for some time, and therefore have been dried, they should again be wet before any decision as to color is made.

Samples from wells drilled with rotary tools are very difficult to collect and examine because they are contaminated by the rotary mud, and are often promiscuously diffused through it. For this reason, the rotary driller does not often resort to physical examination of cuttings unless cores are taken. He compiles his log largely from the mechanical reactions of the pumps and drilling equipment.

Physical examination of cores by use of the various types of rotary core barrels are often misleading. Rubel[40] has summarized the principal difficulties encountered in examining rotary core barrel samples, as follows:

> In the first place it is seldom that the length of core represents more than 75 per cent of the formation cut. Out of 186 runs with a standard make core barrel operated by erperienced core drillers, in a district which may be said to fairly represent the formations of all parts of the Los Angeles Basin, 181 cores were recovered. The average distance drilled by the barrel was 55.2 inches, and the average length of the core recovered was 41.8 inches, or 76 per cent of the hole made.
>
> The condition of the core barrel and the way in which drilling progressed gave the best clue to the location of any given sample in the interval from which the core was taken. It has been the observation of the writer, confirmed by the opinion of core drillers and those who are in a position to watch such operations, that if a very hard shell or a hard sand is encountered at any point in the core, so that the cutters are ground down, usually little is to be gained by attempting to recover more core. If, for example, a 10-foot run is made, and the first 2-ft. show shale with a hard shell on bottom and the rest is missing. it is likely that the remainder of the interval was a soft shale or sand which could not exert enough pressure on the shell to force it into the barrel and was consequently washed away and lost.
>
> A core of fair length may often be recovered in such a condition, due to the generation of heat either by rotation at the shoe or within the inner barrel, so os to completely change its appearance and character. By this means a loosely consolidated sand may be "burned" to a quartzite, a sandy shale may be changed to a hard crystalline mass resembling igneous material, a rich oil sand may be burned to a black carbon-like substance. and a bituminous shale may be burned to a coke. Usually such conditions are so exaggerated as to be readily recognidable; but there are times, particularly in regions where igneous material is known to be present, when the operator may be greatly puzzeled.

40. Rubel, Albert C., Determining core barrel samples: Oil and Gas Jour. Sept. 18, 1924.

In coring, as in drilling, there is always a certain amount of whipping or pumping of the drill pipe, particularly with pipe smaller than 4 inch, which results in breaking up the core in the inner barrel and churning it around until at times little is left of its original form or texture. A typical example was encountered recently in a well where the formation was alternate streaks of oil sand and brown shale, the sands becoming leaner and thinner with depth. It was desired to determine the vertical limits of production. Three successive cores of an average length of eight feet were taken, showing in each case a very soft, sticky, brown shale resembling well-mixed clay, with a few fragments of oil sand and harder shale disseminated throughout the mass. These cores were logged as sticky shale. A careful examinattion of the cores showed a few small 'biscuits' of hard brown shale not greater than one inch in diameter imbedded in a matrix of ground-up shale, drilling mud, soft rope, and other foreign matter, together with a few fragments of oil sand. Nothing could be ascertained of the relative amounts of the sand and shale; and the cores, for the purpose for which were taken, were worthless.

Drilling mud will also be built up in this matter and, under the pressure which exists in the inner barrel, will become so consolidated as to resemble formation and be logged as 'sticky' shale, 'brown' shale, or 'gumbo.'

A very serious difficulty, and one which cannot be entirely eliminated from core drilling, is the danger of contamination of a barren sand by oil and saturated mud. In a hole where oil saturated mud is being circulated, or where oil has been circulated previous to coring, the sample will always be more or less contaminated, and one can never be entirely positive as to the source of a 'show' in a relatively lean sand. A barren sand or water sand will absorb sufficient oil in a very short time to give it the appearance of a fairly rich oil sand, and in some cases it is almost impossible to determine the source of the oil. If an ordinary core of two or three inches in diameter, taken with oil saturated mud in the hole, be examined immediately after pulling out, a stain of oil can usually be seen around the contact between the drilling mud and the core, which works concentrically toward the center of the core, the central portion being barren. In a short time, however, the oil will work throughout the entire core and the sand will show a uniform oil content.

This impregnation of a water or dry sand with oil from oily mud has been too little recognized by operators, and has resulted in useless setting of numerous strings of casings above what was thought to be oil sand. Such contamination can be usually detected by examining the core immediately after it is removed from the barrel; and with the larger diameter cores now in general use, the difficulty is reduced to a minimum.

The reverse of this condition may occur in a sand which is comparatively rich in oil. If the sand be burned sufficiently to drive off the oil, but not enough to fuse the sand, the result will be a gray, barren or almost barren sand which may be easily mistaken for a water sand, and which may cause the operator to believe that he has passed the productive horizons or has not drilled enough for a shut-off.

The common practice in examining a core after it has been taken from the barrel is to remove the outside coating of mud, shave off perhaps a quarter to a half inch of formation for a test, and classify the core from what appears of the sample thus exposed. This procedure is not sufficient to bring out the more serious alterations and contaminations outlined in the foregoing, and sooner or later will lead to costly and unnecessary mistakes. By this means, for instance, a good cut will be shown by a sand which may be entirely barren at the center of the core a sticky shale may be logged where the formation is entirely oil sand, or, in other words, the operator will not get the true nature of the formations from which the core was taken. The mere breaking up of a core and examining its ends is also misleading, as a core will usually break along sand partings; and in this manner a section a foot long may be logged as a sand, whereas in reality it is shale with sand partings along which the core most easily broke. The sand partings may be but a fraction of an inch in thickness yet the section of core thus broken will show at each end, and will be called solid sand.

The only way in which a core may be made to yield the maximum amount of information is to split it down the center, so that a complete transverse section is exposed; and then dig into it until it is determined as far as possible just what real information is represented, and how much alteration and contamination have taken place.

There is a tendency among certain operators to regard a core more as a thing of beauty than a possible source of valuable information, and there are cases where no one is allowed to mar the appearance of the sample. Such a procedure will result in a minimum amount of information. After a core has been thoroughly examined by a careful observer, it retains little of its original form.

Fettke[41] has written an interesting paper on, "Core Studies of the Second Sand of the Venango Group from Oil City, Pennsylvania," which emphasizes the local variations of texture and chemical content of oil sands as portrayed by core samples.

Microscopic Examination

Within the last few years the microscopic study of well cuttings has proved to be valuable in identifying and correlating different subsurface horizons that have proved to be of much economic value. As a result, many geologists and oil operators are showing considerable interest in the subject.

If the ordinary method of examining well samples does not convey sufficient information as to correctly identify the formation be-

41. Fettke, Charles R., Core studies of the second sand of the Venango Group from Oil City: Pennsylvania Pet. Devel. and Tech., Amer. Inst. of Mining Engineers, 1926.

ing drilled, the microscope may be brought into use. This method affords a means of correlating strata by comparing the amount and similarity of tiny fossils and crystallized minerals that are present. A shale may contain a particular type of Diatom, Foraminifera, or some other microscopic fossil which may be used as "horizon markers." Whereas, a certain sand may contain an unusual amount of some distinctively colored or crystallized mineral; such as, hornblende, biotite, olivine, feldspar, pyrite; or it may contain grains that are unusually coarse or fine, angular, or wéll-rounded—all of which are readily rceognized by one familiar with microscopic analysis.

Until recently, most of the microscopic study of well cuttings was centered upon a study of only the minute fossils, especially the Foraminifera. While the correlative value of microscopic fossils is known to be of no small consequence, the minerals composing the sediments often produce good evidence where the fossils are absent. Therefore, a microscopic study of the so-called "heavy minerals" constitutes a valuable aid in the correlation of oil-field formations, supplementing and verifying the evidence of the tiny fossils, or filling the gap where fossils are not found.

Micro-Paleontology

This term may be briefly defined as a study of minute fossils by the use of the microscope. So far as the oil industry is concerned, most of this work to date has been applied to Diatoms and Foraminifera.

The Foraminifera, which are so abundant in the seas today, were equally prolific during many divisions of geologic time, especially in Tertiary and Cretaceous strata, and are ideally constructed for good preservation as fossils and for use in stragraphic geology. Until recent years their study has been largely a matter of pure science, but at present they are regarded as having important future possibilities in connection with the Petroleum Industry.

In the drilling of wells, most fossils are so broken up that they become unrecognizable in the samples. The Foraminifera are usually so small and are so numerous that enough of them escape the destructive force of drilling, so as to form a recognizable part of the well samples themselves. And by careful microscopic study of the section through which a well is drilled, it becames possible to recognize various zones which may be again found in adjacent wells. As a result of such study, a subsurface map may be made, which will show the geologic features of the underground structure. By this means it is quite possible to designate the best locations for additional wells in a field with greater or less certainty of increase in production.

Where the age of the strata is not definitely known, a drilling well may be abandoned before it actually reaches a producing horizon; or the drill may pass through such a horizon for a considerable distance with out being recognized. In either case a large economic loss results, as well as a loss of the identity of the formations penetrated.

It is through the knowledge of the distribution of the various species and genera in various geologic formations that the great economic use of the Foraminifera lies. When geologic type sections of certain areas are known in detail, it becomes possible by the study of well cuttings to determine subsurface structure within the area. As a result, much is being done in the way of the refinement of the study of small fossil forms, as well as in the establishment of the limits of the vertical and horizontal ranges of such species within the various geologic age limits where they are known to exist.

Examination of the Heavy Minerals

Certain minerals are present in nearly all sedimentary rocks, and the relative proportion of these common minerals may have very little correlative significance. For example, quartz and feldspar compose about 95 per cent of most sandstone. Therefore; the ratio of one to the other is usually immaterial and not worthy of calculation.

There is another group of minerals, the representatives of which are seldom perceivable in a sediment, being quite rare in most cases; but they contribute very much toward the proper identity of certain sedimentary rocks. They are the so-called "heavy minerals," minerals of high specific gravity, with which property is usually combined great resistance to abrasion and to chemical action. The durability of these minerals insures their preservation under most conditions of sedimentation; and they are found, therefore, in all sediments, whether fine- or coarse-textured. The mineral grains are hard enough to escape being crushed by the drill, and their high specific gravity permits an easy separation from the principal mass of the rock.

The heavy minerals most commonly found in oil field sediments are: hornblende, pyrite, augite, the micas, zircon, tourmaline, apatite, topaz, corundum, staurolite, the garnets, and a few others.

To prepare[42] the well cuttings for microscopic study, a representative sample of about 300 grams is heated for several hours in 50 percent hydrochloric acid or until all the limy material and iron oxides are dissolved. The acid does not affect the heavy minerals

42. Tickell, F. G., Correlative value of the heavy minerals: Bull. Amer. Assoc. Pet. Geol. Vol. 8, No. 2, p. 158, 1924.

present. After pouring off the acid, the sample is "panned" in order to float off the light minerals, some of which may be mounted for microscopic study. The residue is dried, and then placed in a large evaporating dish with enough bromoform to float off the quartz, feldspar, and other relatively light minerals. After several such washings, only the heavy minerals remain. This residue is washed with benzol, then dried. The magnetite, ilmenite, chromite, and other similar minerals are removed with a bar magnet. The heavy remains may then be mounted on glass slides, by use of Canada Balsam.

The specimens are then ready for an expert petrographer, who is familiar with the various characteristics of the heavy minerals, and can recognize them almost on sight by placing them under a polarizing microscope. This is done by noting the color, cleavage, relief, fracture, position and length of axes, and crystal shape.[43]

Chemical Testing

Even when uncontaminated samples are obtained, they are often so finely ground by the bit or otherwise altered so as to make them confusing unless certain chemical tests are applied to them. For example, a calcareous sandstone may resemble a limestone, diatomaceous shale may be mistaken for chalk, and oolitic limestone often resembles sand grains.

Dilute hydrochloric acid, strength about 20 per cent, will cause all carbonates to bubble or effervesce. A few drops may be let fall upon a small amount of the questionable sample, which has been previously placed upon a clean porcelain surface. By this method chalk, limestone, and calcareous sandstone will effervesce rapidly; whereas, dolomite, calcareous clay, and marl will react slowly. If sandstone that is coated with calcareous material is used in this test, effervescing will continue until the carbonate is dissolved, leaving the quartz grains unaffected. Such materials as sandstone, quartzite, chert, flint, gypsum, clay, shale, and igneous rocks do not react to this test.

Well cuttings are also identified by heating them almost to redness and then noting the odor of the fumes given off. This can be done best by placing the dry sample in a test tube, and then holding the tube over a flame until the contents are heated almost to redness. The presence of oil or asphalt can be determined by the "oily" odor. Practically all minerals that contain sulfur; such as, pyrite, barite, and gypsum, can be detected by the "rotten egg" odor of hydrogen sulfide or the odor of sulfur dioxide in the fumes. Most

43. Reed, R. D., and Bailey, J. P., Subsurface correlation by means of heavy minerals: Bull. Amer. Assoc. Pet. Geol., Vol. 11, No. 4, p. 359, 1927.

bituminous shales and clays, as well as some limestones contain small amounts of ammonia. If the sample used is heated almost to redness, the presence of ammonia may be detected by the characteristic pungent odor in the last fumes driven off.

Similar practical tests of well cuttings may be made by using the blow pipe and Bunsen burner; or if the testing must be done in the field, one may place a small amount of the sample on a shovel or piece of sheet metal, then heat it at the derrick forge. The sample should be washed well before heating, and all pieces of iron, steel or rusty scale must be picked out. If coal, asphalt, or oil is present the sample will fume and then flame. Such minerals as shale, sandstone, or chert will not be affected by heating to redness if they are withdrawn from the fire before they begin to fuse. Samples that are largely limestone or dolomite will be slaked if placed in a small amount of water after having been heated to redness. Gypsum will change to a lighter color, but will not slake in water.

When it is necessary to carefully test a porous formation for the presence of oil, the chloroform or carbon tetrachloride test will give satisfactory results. To apply this test, the unwashed samples are pulverized, placed in a glass bottle, and covered with one of these liquids. The bottle is then corked, and the contents shaken at intervals during a period of fifteen or twenty minutes. After this the contents are filtered into a white dish or saucer. If oil is present, a dark ring will be left on the filter paper. If any liquid residue remains in the dish after the chloroform or tetrachloride has evaporated, it is the oil that was in the sample.

Within the last few years there has been a growing tendency among some petroleum engineers to have analyses made of all water encountered at various depths during the drilling process. While this is done primarily to ascertain the possible source of the water in the event that future water troubles may develop, it is now generally believed that in some oil fields there is a definite relation of mineral content in oil field waters to the producing horizons. For instance, in the Coalinga field of California various chemical analyses established the fact that the relative amounts of sulfates decreased and the sulfides and carbonates increased as the oil sand was approached. Edge water and bottom water contain mostly chlorides of calcium, magnesium, and especially sodium.

Whether analyses of oil field water can be generalized so as to usually indicate the proximity of the oil-bearing sands still remains to be proven, but their value in determining the source of future water troubles has been quite satisfactorily established.

AUXILIARY AIDS

Graphic Logs

A large amount of important subsurface data may be indicated on a graphic log. Very frequently such graphic representations, where a set of conventional symbols is used, are more desirable and accessible for certain purposes than written well records. A graphic record, plotted to vertical scale, is especially valuable in that it conveys quite readily by pictorial means, facts that are very difficult to convey in the ordinary form of written record. Such logs show a true condition of relative depths, thickness of strata, and indicate clearly the manner in which the well was cased or plugged.

A set of symbols to be used in connection with graphic logs should be selected in such a way as to be simple and yet be easily and readily applied. Such predominating strata as clays and shales may be left blank. In some cases it is advisable to differentiate the strata by using various colors; as, limestone may be blue, sand shown as red, and oil sands shown in black. Water and gas may be conveniently indicated at the side of the graphic log by using only the initial letter of each word. Small figures placed at the side of the formation record will indicate the depths to the top and bottom of the various formations.

The casing record should form an important part of the graphic log. This is usually shown by drawing a series of vertical lines about 1/16 of an inch apart along the left side of the graphic column, one line being drawn to represent each string of casing placed in the well. Then conventional "markings" may be used to indicate casing landed, casing cemented, casing side-tracked, perforated casing, together with the different sizes and landing depths printed in small figures near the lower end of each vertical line or "string."

Uren[2] and Ambrose[36] give a more detailed description of how to devise and construct graphic well logs.

Graphic Charts

The oil industry affords an excellent opportunity for the application of graphic charts. Within the last few years they have been used with much success in conveying a clear idea of the existing conditions as found on an oil field property. In studying any perplexing problem that is replete with a large amount of tabulated figures, the average person finds it difficult to retain the various relative values of the different factors involved during the investigation. If the same data are presented in graphic form, it becomes an easy matter to draw correct conclusions, as the facts are forcefully impressed upon the mind, and the mental picture is more vivid.

Ambrose[36] in his resume of underground conditions in oil fields, gives a practical and complete description of how to construct various types of graphic charts used to "picture" daily well production of oil and water, average daily production of oil and water, daily trouble chart for producing wells, drilling wells progress and casing depths, time-depth reference chart for comparison of drilling wells, and daily receipts and deliveries of crude oil.

Peg Models

The most satisfactory method of conveying to the average person the structural conditions disclosed by a series of well logs is by constructing what is called a "peg model." Contour maps and cross-sections are likely to be confusing to the average layman, but peg models have the advantage of presenting the subsurface structural conditions directly in three dimensions instead of in two, as is the case when referring to contour maps, for instance.

Peg models are of special benefit to the operator in making correlations of strata between wells; and are especially valuable in determining the proper points at which to land or cement casing to exclude water, in predicting the possible depth at which the oil, gas, and water sands will be encountered, and in showing where marked irregularities in the various sands have occured.

The U. S. Bureau of Mines uses the following method in constructing peg models: square pin base boards about 1½ inches thick are cut to a horizontal scale of 200 feet to the inch. This results in a baseboard that is 26.4 inches square, and it corresponds to a section of land. The well locations and property lines, names of the property owners and lessees are then carefully printed on the respective leases, thus producing a rough map of the area that is represented. At each well location a half-inch hole is drilled to a depth of about one inch. Care must be used in drilling these holes; for if they are not vertical, the pegs will not stand vertically after being inserted in the holes. The base boards are then covered with two coats of varnish. The dowel pegs used should be made from seasoned pine, and should have a uniform diameter of one half inch.

Then a graphic log of each well is made, using a vertical scale of 100 feet to the inch. The logs are then blue printed, and cut just wide enough to wrap around a peg. The blue prints are then "spotted" to the datum plane of the peg which is usually sea level, and then glued to the peg. The pegs should be long enough to show all formations penetrated in each well.

The pegs are then pushed into their respective holes in the baseboard, and sharp pointed push pins having colored glass heads are placed at the top of each formation that is to be correlated. The principal oil or water sands are then correlated by running bright colored twine strings to the various push pins that have the corresponding color of the string.

Correlation is usually first made on blue print sections of the well logs, taken not only across the oil structure but also along the strike of the structure. Many difficult correlations have been made in this way, when it would have been practically impossible to correlate formations from the well logs after they had been assembled and pasted on the respective dowel pins on the peg model.

FACTORS AFFECTING OIL RECOVERY

CONTROL OF OIL IN SANDS

Herold[44] has discussed in a series of articles which were published in the fall of 1924, some of the laws of physics and mathematics which are demonstrated by the production of oil from wells. He says, "The several classes of reservoirs which are of interest in determining the laws of delivery from oil and gas wells, and likewise, these oil and gas reservoirs themselves, are separated into three groups according to the 'control'. The groups are designated thus:

(a) Hydraulic Control.
(b) Volumetric Control.
(c) Capillary Control.

The classification is based solely upon mathematical relations which are prescribed by the laws of physics.

In his concluding remarks regarding his investigations regarding the different types of "control" in oil reservoirs, Mr. Herold says:

> Why do oil and gas flow from the well? What is the source of energy which is extended in performing the work of expelling the fluids?
>
> We shall state briefly the findings of this investigation.
>
> #### Hydraulic Control Wells
>
> The porous formation of this class of wells either outcrop or is in communication with a porous one which does so.
>
> Pressure is exerted by the weight of the column of liquid in the formation. Such liquid may be either oil or water. Rain water maintains the height of the fluid column. If oil is present in the reservoir, it is certainly being gradually replaced by water as production proceeds.
>
> Gas, if present, may act temporarily and only in the capacity of "agent" for the liquid. The pressure which gas possesses here is by virtue of the weight of fluid compressing it.

44. Herold, Stanley C., Functions pertaining to fluid delivery: Oil and Gas Journal, Nov. 13, 1924; Oil and Gas well is in a sense an Orifice: Oil and Gas Journal, Dec. 4, 1924.

Volumetric Control Wells

Perhaps universally the same as in the preceeding case except that the supply of rain water is insufficient to maintain the head. The function of gas is the same.

These reservoirs are of the 'open type', in that they are open to the atmosphere at their outcrop. We cannot exclude the possibility that some well reservoirs of this control are of the 'closed type' corresponding to the Rigid Tank. In case these ex st gas alone is the source of energy.

Capillary Control Wells

These wells are all of closed type reservoirs. The formation many outcrop or it may not. If it does so there is no rain water entering the formation to create a pressure head. Gas alone is the source of energy. The liquid present may be either water or oil. Both act in the same manner mathematically and mechanically. with slight differences physically. This control is not confined to the oil and gas fields. Water wells with hydrogen sulph de gas are also known to belong to this class frequently.

It cannot be said that we are unfamiliar with reservoirs of this control because it is probable that fully 75 per cent of the oil and gas wells in the Un.ted States, east of the Rocky Mountains, belong to this class. We shall say, rather, that we have overlooked the fact that, below critical pressures which may differ widely as between one resrveoir and another, depending upon the physical state of the reservoir inter or, the action of capillarity completely control the laws of fluid delivery. We have made our calculations upon wells, and because their results were subsequently not borne out by the well's performance, we have ascribed the discrepancies to many causes, such as the imperfection of the gases. the curatic nature of handl ng a thing so crude as a well, the difficulty of obtaining reliable data, etc.

Mr. Herold's series of articles on the "Mathematics of fluid Production from Oil and Gas Wells"[44] are worthy of considerable study, especially by Petroleum Engineers, who are familiar with higher mathematics, physics, and hydraulics.

CHARACTER OF OIL PRODUCED

The nature and character of the crude oil in a reservoir rock determine to a great extent the total amount that can be ultimately recovered. Such physical properties as gravity, viscosity, temperature, surface tension, together with variable amounts of paraffin and asphaltic residues present, all affect the amount and rate of flow underground, as well as the amount that will be retained in the "sand."

Asphalt, Paraffin, and Mixed Base Oils

These three designations constitute the popular classification of petroleum oils. Asphalt base oil is sometimes termed naphthene base.

Paraffin base oil is practically free from asphaltic matter, and contains hydrocarbons of the paraffin series (paraffin wax) in the lubricating distillates. Asphalt base oils contain asphaltic matter, but the lubricating distillates are essentially free from paraffin wax. Generally speaking, it may be said that the viscosity of crude oil increases from the paraffin base to the mixed base to the asphaltic base oils. Also, on an average, the percentage of sulphur, oxygen, and nitrogen in the crude increases in the same order.

Viscosity, Gravity, Temperature, and Surface Tension

Therefore, since viscosity is an important factor in the movement of oil through the reservoir rock to the drill hole and even afterwards, it is readily seen that the type of oil is an important factor to be considered in recovering the maximum amount of crude from the sand.

The viscosity of crude oil is extremely important in relation to the recovery from the producing formation. Not only does the viscosity of oil vary between extremely wide limits, but is also influenced by temperature, as well. Increase in temperature reduces the viscosity, but the lighter oils decrease less for a given temperature increase than do the more viscous or asphaltic base oils. So, the result is that, while the viscosities of two oils may be greatly different at ordinary temperatures, the difference at higher temperatures (200° F. or above) may be only slight. The paraffin and mixed base oils do not show as great a change in viscosity upon application of heat as do asphalt base oils. Therefore, the type of crude oil in the oil sand will cause the movement and percentage of recovery to vary in proportion to the temperature.

Oil in producing formations is often associated with large volumes of natural gas under pressure. This results in a very complicated set of conditions when the formation is penetrated by the drill and the pressure released. Due to the presence of gas under pressure, some of it is in actual solution in the oil. This reduces the viscosity of the oil, and will permit it to flow more readily through the pores of the sand to the drill hole where the pressure has been released. When the pressure is released, the gas comes out of the solution in the oil, appearing in the form of small bubbles moving in the direction of reduction of pressure, thus pushing and carrying the oil as it moves.

On the other hand, the removal of gas from the crude oil solution tends to increase the viscosity in two ways: (1) by the simple fact that it is removed from solution, and (2) because of the cooling effect produced. It is definitely known that in some cases the cooling effect is sufficient to cause separation of the so-called amorphous wax at the sand face and in the casing or tubing, causing a rapid decrease in production within a comparatively short time. As an example of this, the granite wash production of flowing wells in the Panhandle field of Texas is often reduced to practically nothing within three or four days. The crude oil in that area, however, has an abnormally low temperature (85°-90°F.) while still in the bottom of the well.

The viscosity of crude oils also has an influence in connection with the formation of emulsions. Oils that are highly viscous are more susceptible to the entraining of water, and will retard the settling out of the water.

Gravity, probably has some effect upon the entrainment of water in oil. In the original accumulation of oil in the reservoir rock, the difference in gravity may influence the stratification of oil and water. In the recovery of oil, the greater the difference in gravity between the oil and water, the greater the tendency to separate from each other. Also oils of lower specific gravity are generally lower in viscosity, which also aids the separation of oil and water, and assists the water in moving the oil.

Generally it can be said that petroleum oils of higher specific gravities have higher viscosities; although two crude oils from different areas having the same specific gravity, may differ considerably in viscosity, due to the difference in the chemical nature of the substances composing the two types of crude oil.

The variation of the surface tension of different types of crude oil is another factor that influences the amount of oil that can be recovered.

Surface tension may be defined as that tendency of a liquid to act as an elastic membrane, the surface of which always tends to contract to the minimum area. It is a characteristic property of all liquids, but varies in different liquids, and in the same liquids at different temperatures and pressures. Thus, gas dissolved in crude oil under pressure, and increasing the temperature of crude oil both reduce the surface tension of it. This being the case, it is quite plausible that oil sands of highest temperatures and which contain the most gas in solution under pressure, will ultimately produce the greatest amount of oil.

The force of capillarity will be greatest in reservoir rocks that contain oils of high surface tension. Therefore, in sands where migration of oil depends upon capillarity, the movement will be proportional to the surface tension of the oil. Also, since water has about three times as much force of surface tension as crude oil, in pore spaces of capillary size, the water associated with the oil may drive the oil ahead of it, thus affording one of the propulsive forces which materially aid in the drainage of oil from a sand.

In concluding, it may be said that while the various effects of natural gas upon recovery of oil are generally known, the positive effects of such other factors as viscosity and surface tensions, and effects of gravity and chemical content upon viscosity and surface tension are only theoretically true, and have not been generally proven.

THE WELLS AND THEIR RELATION TO THE FIELD

Relation of Oil and Gas Pressure to Recovery

As has been previously stated in this bulletin, the amount of natural gas associated with the oil depends upon the location and position of the wells upon the structure; that is, wells located upon the crest of the structure usually have higher initial volumes of free gas. The relative amount of this gas generally is found to be less in wells that are drilled on either side of the crest of the anticline or dome.

Crude oil is capable of dissolving and absorbing large quantities of natural gas. The amount that can be absorbed and carried in solution with the oil depends primarily upon the intensity of the pressure exerted upon the oil; but the viscosity, density, and temperature of the oil affect this amount, also. For example, the absorptive capacity of the oil is directly proportional to the pressure, while it varies inversely as the temperature.

The gas carried in solution with the oil greatly increases its expulsive force. As soon as this pressure is reduced, the gas begins to assume the vapor phase, and thus comes out of the oil solution. This action is comparable to the effervescing produced by quickly pulling the cap off a bottle of soda water. Similarly, when the cap rock above the oil is punctured by the drill, the gas begins to come out of solution, and carries the oil with it—thus the well "flows."

It is generally agreed that in most instances this gas pressure is chiefly responsible for the high initial or "flush" production. This is evidently true, because a decline in gas pressure is closely followed by decreased production of oil; and when the gas is exhausted, flow usually ceases, although there may be much oil left in the sand. Therefore, since the production of oil is largely dependent upon the amount of gas and its associated pressure, the producers should do all in their power to prevent its waste, and use production methods that will save the gas pressure. This will result in a prolonged life of the wells, and materially reduce future lifting costs.

The rate at which gas pressure declines is important in determining the relative amounts of oil to be obtained between different periods during the flowing life of the well. The maximum rate of production is usually reached within less than two or three weeks from the date of "drilling-in" the well. The initial rate during the first few days or a week may be erratic or irregular, due to the manner in which the well cleans itself, and to the gradual establishment of drainage channels leading to it. Some wells may require several months before they reach their maximum productivity, but such wells have usually been improperly completed.

The maximum flow or "production peak" is generally followed by a period of rapid decline, the rate of decline gradually diminishing as time passes. This is due to the rapid escape of the gas, thereby reducing its volume and pressure, and dissipating the expulsive force. Then, it is natural to expect that after a field has reached such a stage of development that its boundaries have been fairly well determined and the productive possibilities of different areas within it are understood, the peak of initial production will have been reached, and therefore production will rapidly decline.

Depth and Drainage of Sands

The economic life of a group of oil wells will depend upon the extent to which the sand may be drained. Drainage is influenced by the porosity of the reservoir rock, the size, shape, and continuity of the rock pores, and the density and viscosity of the oil. The presence of water in association with the oil also has an important influence upon the completeness of drainage; but the most important propelling forces are due to the pressure exerted upon the stored-up oil by natural gas, hydrostatic head, and the weight of the superimposed rock masses which is called "rock pressure." These forces tend to drive the oil out of the sand or reservoir rock; but the viscosity of the oil assisted by friction, adhesion and capillarity, resist such movement. The relative amount of oil retained in the oil sand adjacent to a well after it has reached economic exhaustion, under our usual methods of production is probably inversely proportional to the size of the pores, for it is within the smaller pores that adhesion and capillarity exert their greatest force.

Pumping Life

After a well ceases to flow, the usual procedure has been to install pumping equipment. Tubing, sucker rods, and a working barrel of sizes most suitable to the possible pumping capacity of the well are lowered into it to a depth best suited to the most efficient operation. This depth will vary with the height at which the oil stands in the well, the amount of sand or sediment present, and the proximity and pressure of edge or bottom water. Shallow wells of moderate depth may be pumped by installing any of the various types of jack pumps on the market, but deep wells are pumped most satisfactorily, individually "on the beam."

The efficiency of the pumping equipment[45] is important, not only from the standpoint of using the least possible power, but also to insure the removal of the full production of the well, as well as to prolong its pumping life. The speed and length of the stroke of the pump are adjusted to keep pace with the inflow of the oil, keep the fluid level fairly constant, and maintain a steady drainage through the sand without having to stop the pump occasionally to permit the well to fill up again. Wells should never be pumped dry. Neither should the fluid level be permitted to rise abnormally, as this retards the flow of the oil from the sand.

Pumping wells should be cleaned out at regular intervals. This keeps the liner free from accumulated sand and affords better drainage into the well. This may be done by using the bailer after the rods and tubing have been pulled. If the oil contains any paraffin, a small (5 to 20 quart) shot of nitro-glycerin might be used before the hole is bailed out. Cleaning out will be needed less frequently if the well is drilled through the sand 15 or 20 feet into the underlying formation. This will afford a pocket or sump into which the sediment may accumulate. This cannot be done, however, if the lower part of the oil sand or underlying formations carry water.

When the well ceases to produce a profitable amount of oil by pumping, and there is no plausible means of rejuvinating it or of obtaining deeper production, it should be abandoned. This involves withdrawing as much of the casing and liner as can be pulled out or cut, and the proper plugging of the hole so as to prevent migration of gas, oil, and water from other wells into it. After pulling as much of the casing as possible, the hole should be filled with cement to the top of the oil sand, then the remainder of it filled with thick mud fluid. This mud fluid will confine any gas and water in their respective sands, and will therefore lessen the possibility of the abandoned wells affecting adjoining wells with migrating waters.

Spacing and Arrangement of Wells

There are many factors, in addition to those mentioned above, that may affect the total production or ultimate recovery of a field. Some of them are: The intensity of the angle of dip of the structure, the manner of spacing and arranging wells, the rate and order of drilling, the depth and thickness of the sand, and the density, temperature, and viscosity of the oil.

45. Uren, Lester C., Problems of Pumping deep wells: Amer. Inst. of Min. Engineers, Pet. Devel. and Tech., 1925.

A steeply dipping dome or anticline indicates a narrow producing area, which is likely to be a long, narrow strip of drilling area along the crest of the structure. And the plunging end of this axis or crest will mark the end of production along that position, (see Fig. 4). This explains why fields are larger and wider where the strata dip at rather low angles.

Ultimate recovery is influenced by the spacing of wells. If the sand is close-grained, and the oil is heavy and viscous, the wells should be spaced nearer together, possibly as near as 100 feet in shallow fields. Whereas, if the sand is porous, the oil light in gravity, and there is plenty of gas pressure, the wells are usually placed 660 feet apart, resulting in one well on each 10 acres. However, a thick oil sand will support a larger economic number of wells than a thin sand. Drilling more than the economic number of wells will not produce much more oil in the long run; and while the oil may be extracted in a shorter time, the increase in the amount of money invested, due to the shorter period of getting returns on the investment, would not compensate the increased development costs incurred in drilling the additional wells.

While most operators arrange the wells in parallel rows across the property, a triangular or "staggered" arrangement will sometimes promote more complete recovery. The wells should be placed closer together along the strike of the strata than in the direction of the dip. This is especially true where the oil is gradually pushed up the dip by hydrostatic pressure. But where gas pressure is the dominant expulsive force, this will not make so much difference.

Rate and Order of Drilling

The rate and order of drilling the wells has a marked affect upon the total amount of oil that can be obtained from a sand. Drilling all the wells at once will result in a larger ultimate recovery, but such a plan of development over-taxes the construction program, storage and transportation facilities during the early part of the drilling campaign, and results in equipment far in excess of the needs during the declining years of the property. Also, over-production usually causes a reduction in the price of the oil. It is probably best to drill only enough wells in the beginning in order to bring a reasonable return on the money invested; provided, of course, that enough offset wells have been drilled to prevent drainage of the reservoir rock by adjoining leases, then drill future wells only as they are needed in order to keep the production at the desired peak.

As has been intimated in the preceding paragraphs, the activity shown by the neigboring lessees will affect the rate and order of drilling; and therefore it will affect ultimate recovery, also. The outside or edge locations should be drilled first, so as to prevent drainage across the property lines. Just where this early drilling should be concentrated will depend upon where the adjoining lessees are most active, and the position of the property upon the structure. The operator who first brings his property to full development will secure more of his neighbor's oil than they will of his, because closely-spaced wells in an area yet undeveloped will usually drain the oil sand much more rapidly because of the smaller area from which each well will secure its production. This may result in the closely drilled property securing the greatest ultimate production.

Other conditions being the same, the well that is completed first, will have the greatest "flush production," because of the higher pressures existing at the time and oil sand is first developed. The first well drilled, probably will have the largest settled production, also, because of the early establishment of drainage channels. For example in Figure 17, Well No. 1 was drilled before any of the surrounding or offset wells were drilled; and presumably began to produce under high gas pressure, which would tend to establish drainage channels through the most porous and open parts of the sand. These drainage channels are established in part by the high pressure of the gas and oil literally blowing the silt and very fine sand into the well.

By the time that wells 2, 3, 4, and 5 are drilled the pressure may have been so much decreased by the production from Well No. 1, that there will be insufficient force to remove the silt and fine sand, necessary to establish drainage channels towards the later drilled wells, resulting in the condition of a greater daily settled production from Well No. 1, than from any of the offset wells subsequently drilled.

In the repressuring of oil sands by the introduction of air through a centrally located well to force oil with the compressed air to other wells, wells of the type of Well No. 1, best serve as the air wells because of the ease of introducing and distributing the air in the sand because of existing drainage channels.

Effect of Thickness of Sand

While the depth and thickness of a sand will have much to do with the ultimate recovery of an oil field property, it does not necessarily follow that the thickest sand will produce the most oil. A study should be made of the relationship between the thickness of the sand and the ultimate production per acre. In studying the productivity of a sand of varying thickness, account must be taken of the fact that different parts of the same sand may have varying factors of productivity, due principally to changes in the effective porosity and sand texture.

With a high gas pressure an enormous amount of oil may be obtained from a few feet of sand. Some wells have made several thousand barrels of oil a day while being drilled only two or three feet into the sand. In some fields where there is supposed to be a very thick sand, very likely only a small part of this sand furnishes the oil obtained. The producing parts of a thick sand are probably

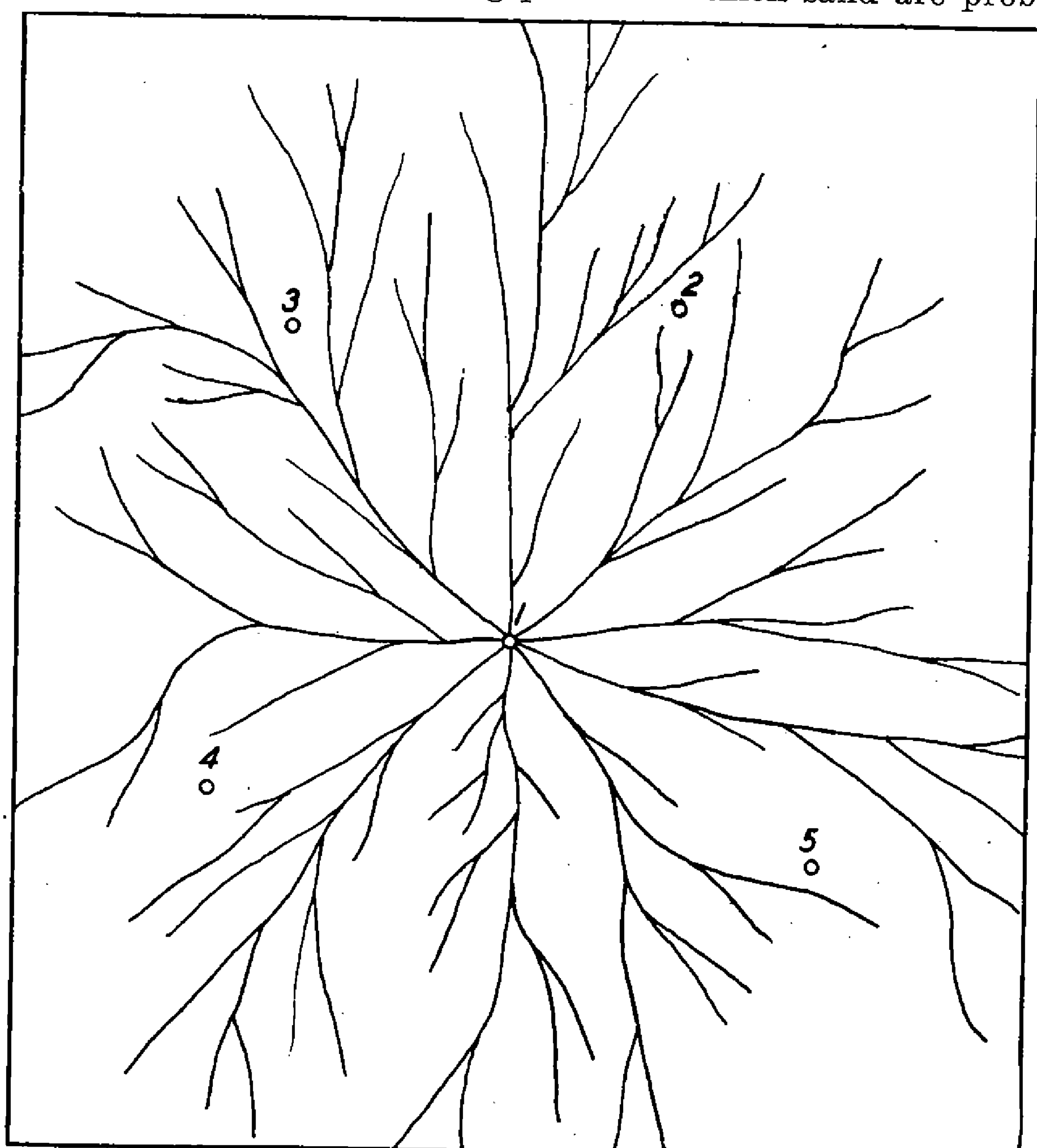

Fig. 17.—Sketch illustrating drainage channels produced at the well drilled first in the field. These channels have drained oil from the vicinity of the offset wells.

separated by fine-grained, tight streaks or layers firmly cemented with iron oxide or limy streaks, or even by thin streaks of shale that were not detected by the drill. Also, the lower part of a thick sand that may be assumed to contain oil, may be saturated with salt water. All of these factors will greatly reduce the actual oil content of the sand, and therefore greatly reduce the ultimate recovery from it.

Effect of Height of Fluid Level

Accurate knowledge of the height of the fluid level in the well is valuable aid in establishing the best depths to which to lower the tubing and working barrel. A change of fifty or sixty feet or less will often obtain increased production. The proper level at which the working barrel should rest should be ascertained by alternately raising and lowering the tubing through regular intervals, keeping daily production records in the meantime, so as to be able to closely estimate the value of the change. After various trials, some depth will be found at which the well makes a greater daily production, either because production has really increased while pumping or less time is lost because of parted or broken sucker rods. In addition to increasing daily production, the height at which the fluid level is maintained will greatly influence the rate of enroachment of edge and bottom water. This may mean the sacrifice of the increased daily production in order to prolong the life of the well.

Water exclusion is a matter of vital importance throughout the productive life of an oil property, as well as during the development period. And in order to secure the highest possible ultimate recovery, no little time and precaution should be used in preventing the development of water trouble, as well as in combating it after it has developed during the decilning years of productivity. The question of water in oil sands will be discussed under a separate topic in this bulletin.

Therefore, in summarizing, the economic life of an oil well may extend over a period of many years, or it may be quite brief, indeed. Such factors as the porosity and saturation of the sand, rock pressure, resistance to movement, volume of gas occluded in the oil, as well as the cost of operation and the selling price of the oil, all play an active part. The rate of decline of oil well production is rapid during the early months of production, known as the period of flush production. With settled production, the rate of decline frequently becomes much slower each year.

Law of Equal Expectations

The future life of an oil property is often predicted by the use of decline curves which are plotted on graphic or logarithmic paper, covering periods of week to week, month to month, or year to year. According to Lewis[46], the law of equal expectations is as follows: "If two wells, under similar geologic conditions, produce equal amounts of oil and gas during any given period of time, the amounts they will produce thereafter, on an average, will be the same, regardless of their relative ages."

46. Lewis, J. O., Methods of increasing the recovery of oil from oil sands: U. S. Bureau Mines, Bull. No. 148, 1917.

CONDITIONS RESULTING FROM METHODS OF DRILLING AND COMPLETING

Manner and Methods Used in Finishing the Well

The manner in which the well is "drilled-in" and completed will materially affect the amount and character of its initial production, as well as influence the economic life and ultimate recovery. The manner of completing a well will depend largely upon the type of drilling equipment used while drilling-in.

If cable tools are used, a control casing head should be placed on the top of the casing, and the drilling should be done slowly and carefully. The hole should be bailed out frequently in order to examine the cuttings, and to prevent drilling into water that may be carried in the lower part of the sand. Many good wells have been ruined "by drilling out the screw" before pulling the tools to bail the hole. If the sand carries no water, and there is an impervious stratum beneath it, it may be best to drill through the sand 10 to 50 feet into the non-porous stratum. This will afford a sump into which the loose sediment and cavings may fall, thus prolonging the intervals between cleaning out jobs.

The depth to which one may drill into the sand will depend upon other conditions, also. The upper few feet of the sand may be very shaly, thus permitting only the gas to escape, but after drilling a little deeper a more porous sand is usually encountered and produces oil with the gas. Also, the upper part of a sand that carries mostly gas may be separated from the part that carries most of the oil by a thin shale streak or a stratum of calcareous material; in which case, it will be necessary to deepen the hole beyond this level. On the other hand, in deep wells where the rock pressure is great, it may not be possible to drill more than two or three feet into the sand during the initial flow period. Such wells usually drill themselves in. When tight sands, sands of fine and close grained and low porosity, are encountered, it is often necessary to shoot them with variable sized shots of nitro-glycerin. This is especially true when the reservoir rock happens to be a limestone.

If the sand is hard and consolidated enough to stand up; that is, it will not cave or sluff, no perforated liner or "oil string" need be used. That is, the hole is left "open," and the oil is permitted to flow through the water string until it becomes necessary to install tubing. Most wells in Pennsylvania and many in Oklahoma have been finished in this manner.

But where the oil sand is loose and unconsolidated, it is necessary to use means to prevent cavings from obstructing the flow of the oil into the well, which will necessitate frequent cleaning out or the premature abandonment of the well. To overcome the difficulty, operators frequently use an "oil string," which extends to the bottom of the well. The lower joints that pass through the producing formation are perforated to admit the oil, or one of the several types of screen pipe is used.

This may be done by carrying the casing as the well is being drilled, under-reaming as the hole is deepened. Then the casing is pulled and replaced by an oil string, the part to be placed opposite the oil sand being perforated, or perforated casing may be carried as the drilling progresses. However, this method often results in the clogging of the perforations, making it necessary to run a wash-pipe assembly inside of the perforated casing, and then flush out the clogged perforations. Some operators still perforate the casing while in the well by use of various types of casing perforators.

When it is impractical or unsafe to pull the casing, a perforated liner small enough to pass down inside of it may be used. When a liner of this type is used a casing adapter or swaged nipple should be placed over the upper end of it to help guide the tools or bailer into the smaller string of pipe. This type of liner need not extend to the surface, but should be only long enough to extend about 50 to 60 feet above the shoe of the adjacent string of casing. If the sand caves or heaves, a heaving plug may be lowered and set near the bottom of the perforated pipe. This will prevent heaving sand from rising in the casing.

To prepare the well to produce when there is not much gas pressure, it is either bailed down or swabbed until it flows. If it does not flow through the casing it may be tubed. Some wells will flow through the tubing when they will not flow through the casing. If the well does not flow through the tubing, it must then be "placed on the pump." If it is bailed, it is bailed first from the bottom until the oil is free of mud and sand; then it is bailed alternately from the top and bottom of the fluid level until it flows. If the perforations are clogged, it must be swabbed, either in the usual manner or by special types of "swab washers," which are lowered on tubing, the lower end of which is perforated and plugged. A stream of oil or water is then pumped down the tubing under pressure, and is forced out at the perforations, at the upper and lower limits of which a packer is used which directs the spray directly against the perforations of the liner, thereby blowing or washing them free of mud and sediment.

Effect of Mudding Oil Sands While Drilling

When the well is drilled-in by using rotary tools, methods differing somewhat from those discussed above are used. While rotary equipment has a distinct advantage over drilling-in with cable tools where high gas pressure are encountered, it has a marked disadvantage in that the walls of the oil sand must be washed free of all mud plastered there by the mud circulating system during the drilling-in process. This is done by using wash-pipe equipment and assembly, which is described in detail by Wagy[47]. After the washing operation has been completed, the wash-pipe is pulled out, and the well is bailed down. If bailing should not bring it in, it is swabbed or pumped.

When a liner is needed, it is equipped with the wash-pipe assembly and run in on a string of drill pipe with a left hand thread coupling, which may be backed off after the hole has been washed, thus placing the liner. A casing adapter is then lowered and placed over the upper end of the liner. Other methods of placing liners and washing the sand in rotary wells are described by Jeffery[13].

Although the use of mud fluid as used in rotary-drilled wells is practical in loose and unconsolidated sands, it occasionally does more harm than good, so far as prospecting and testing for oil and properly finishing wells is concerned. Profitable oil and gas horizons may be mudded-off and passed up by using this method of drilling unless the driller, geologist, and engineer are always alert as to the drilling procedure. Thick mud under high pressure can easily do this unless all sand or other possible reservoir rocks are frequently sampled by coring devices. When rotary mud is used to mud-off an unprofitable upper sand or to "kill" a similar sand containing gas, neighboring wells may be injured as a result of using too high pump pressure and thin mud fluid. This will not occur as a usual consequence, but if the sand is loose, coarse, or fractured, such injury may result.

Also, in wells that have been drilled with rotary equipment, or in rotary-drilled wells where it is later decided to plug back and try to produce from an upper sand that was mudded-off during early drilling, it is usually impossible to wash off the mud-plastered walls to the extent that the sand is as free to produce as it might have done if the drilling had been done with cable tools.

Drowning Oil Sands

Drowning an oil sand with water may occur in several ways: by drilling too far into the sand, by shooting the bottom of the hole into bottom water, by water leaking into the casing or around a poorly-cemented shoe, by migrating waters coming from adjoining wells in which the casing strings have been improperly landed or cemented too high, and by the encroachment of edge water, any one of which, if permitted to continue, will either ruin the well or ma-

47. Wagy, E. W., Perforated casing and screen pipe in oil wells: U. S. Bureau Mines, Tech. Paper No. 247, 1920.

terially reduce the amount of oil recovered. And, an oil sand that is once flooded with water can never be rejuvinated; that is, so far as present engineering methods are applicable. It is an easy matter to "plug back" a well that has been drilled into bottom water[13], but a well that has been shot into bottom water constitutes a more complicated job because of the fractures produced or because the bedding planes are loosened. In a bottom water job of this sort it is best to resort to the McDonald process described by Tough[48]. The other causes of drowned oil sands mentioned above will be discussed under another topic.

Conditions Resulting from Redrilling and Deepening

Certain troubles may arise within the well that will necessitate a redrilling job in order to bring the well back to its former production. Large quantities of heaving sand may suddenly flow up through the bottom of the casing or through the perforations which may cover the pump, and fill the lower part of the well. Such sand may become so tightly packed that the bailer will not pick it up, and then the drilling tools, and a sand pump must be used. Collapsed, corroded, or parted casing and liners may have to be pulled and repaired. When this is done, the well usually caves, necessitating the use of drilling tools or the use of a sand pump or combination bit and mud-socket. After redrilling, wells often resume their production with increased vigor, due in part to the accumulation of oil and gas about the well during its period of idleness, and also to the removal of sand and sediment from about the perforations and in the bottom of the hole. If, during the repairing and redrilling job, the gas pressure is materially wasted the well may show a loss in production. Washing the walls of the well with oil may help to correct this reducted production, however.

Production is frequently stimulated by deepening the well. This may not be necessary until many months or several years have elapsed. Frequently a well drilled into a high-pressure oil sand must be permitted to produce for a time before the gas pressure is sufficiently reduced to permit proper completion. It may happen that the well was drilled only a foot or two into the sand, when high pressure gas made it unsafe to attempt to drill deeper because of the possibility of losing control of the well. Also, wells may be deepened when a lower producing horizon has been discovered.

Controlling High Pressure Wells While Drilling-in

When drilling into a stratum containing oil or gas under high pressure, precautions must be taken to prevent loss of control of the well, which usually results in waste of much oil and gas, and serious

48. Tough, F. B., Methods of shutting off water in oil and gas wells: U. S. Bureau Mines, Bull. No. 163, 1918.

damage to the well and its equipment, and perhaps to adjoining wells. Lack of control at such times often permits large amounts of sand to heave into the well, or the walls may cave or the casing collapse, necessitating redrilling or even the abandonment of the well.

Control casing heads, blow-out preventers, and gate valves are devices that are widely used as precautionary measure on wells drilled in a high-pressure area. They are intended to temporarily restrain the expulsive forces by closing in the outlets at the well mouth until such measures can be applied that will make the control permanent; such as, securely anchoring the casing, and installing master gate valves, pressure relief valves, etc. However it usually is within "wildcat" areas that such disastrous conditions develop; that is, they occur at times when they may be least expected. Jeffery[13] quite completely reviews the various methods and equipment used in handling high-pressure wells.

Millikan Pressure Records

When a flowing well is being drilled-in it is difficult to ascertain when an additional streak of pay sand is being drilled. Recently the Amerada Petroleum Corporation has carried out some interesting experimental work along this line under the direction of C. V. Millikan, Petroleum Engineer. Mr. Millikan[49] says:

> By placing a gas meter on the gas release line from the oil and gas separator, any increase in volume of gas that comes with oil production is recorded. In addition to the better knowledge of sand conditions, these data are a valuable aid in determining the size and depth of shots, plugging off water, and estimating ultimate production. The meter also gives a record of operation while the well is drilled-in; and if allowed to remain on the well after completion will give information that may lead to more efficient recovery of the oil from the sand.
>
> All gas from the well is recorded by the meter except that absorbed by the oil going into the stock tanks, which is too small to effect any results obtained. The orifice meter is very sensitive, and any change in the rate of flow of gas during drilling is recorded instantly. After the well starts flowing and another pay stratum is drilled into, there is an increase in the volume of gas recorded by the meter, and a constantly increasing volume of gas is shown until the entire thickness of the pay streak is drilled, when it will show a constant rate of flow again. By determining the depth of the well when the increase is first shown by the meter and again when the rate of flow becomes constant, the thickness of each pay streak can be determined as accurately as the driller can determine the depth of the well and amount drilled.

49. Millikan, C. V., Use of gas meters for determination of pay strata in oil sands: Amer. Inst. of Mining Engineers, Pet. Devel. and Tech. p. 183, 1925.

The meter registered many other details of well conditions and operations just as quickly and definitely as it did the penetration of pay strata. This was especially true of the well on the Bruner lease at Cromwell. The wells on the Goltry lease were flowing such a large volume of oil and gas that the great pulsation prevented the recognition of small effects caused by certain conditions of changes in the well. The meter on Galtry No. 38 on April 17th showed signs that the well was about to stop flowing, and it "went dead" on May 6th, nineteen days after the first indication by the meter. On Bruner No. 4, each operation or condition of the well had a characteristic effect on the rate of flow of the gas, which was recorded by the meter. Perhaps the most important of these is the effect when the bit drilled through the sand into shale; the meter recorded this fact instantly.

In addition to the information obtained on the sand and operating conditions of the well, the actual measuring of the volume of gas gives data on the relation of gas and oil as the production declines, and on normal operating conditions that tend to reduce or increase the gas ratio. It is hoped that a study of these methods will indicate the best method of attack of the problem of increasing the efficiency of explusion of oil from the sand, a problem in which much work is now being done.

WATER IN OIL WELLS AND OIL SANDS

As the art of drilling and developing properties has progressed, increased thought, labor, and money have been expended on various methods, devices, and equipment for arresting the migration of water from its normal subsurface position into the porous strata containing valuable oil or gas accumulations.

Underground losses of oil and gas probably far exceed all the waste at the surface; but of course, these losses are not visible. There seem to be no parallel cases where oil fields have been saved by corrective measures as compared to the many oil fields that have been ruined by lack of such measures. There is plenty of evidence, however, that underground wastes due to water incursion have lost forever thousands of barrels of oil. The principal losses are probably due to large quantities of oil unnecessarily remaining in the sand, by oil being trapped off by water, or by dissipation of gas pressure.

When a new well is being drilled in undeveloped or slightly depleted territory, little water will migrate into the oil-bearing sands, and the small volume that may so enter is readily ejected by the gas or is pumped out. The greater the degree of depletion of the oil contained in the sand in the vicinity of a well, the more readily will the sand take water, and likewise, the more difficult is the removal process. The dominating factor is the greater surface tension of water as compared to that of oil which is in the ratio of about 3 to 1. Another important factor is the decrease in the expulsive force incident to the exhaustion of the gas pressure. After water is once admitted into a partially depleted oil sand, it hangs tightly in the interstices, thus retarding or trapping the flow of oil.[50]

Types of Water

The various types of oil field waters are as follows: Top water, which migrates downward into the producing horizon; intermediate water, which has its source in a water sand between two oil sands; bottom water, or water that is encountered in the lower part of the oil sand, or in a sand below the oil sand; and edge water, found in the oil sand down the dips or near the edges of the structure where the oil and salt water are in contact. In addition to these, water may be encountered locally in small sand lenses, which may occur any place in the productive zone. However, such water should be termed top, bottom, or intermediate, depending upon its relative location to the well.

Drilling Precautions

In drilling oil wells it is good practice to keep accurate records of the various natural water levels and their characteristics; such as, sulphur content, salt, alkalinity, temperature, etc. In addition to this, an accurate casing record is important. If such water samples and casing data are preserved, they will be of much benefit in locating and combating future water incursion.

A sample of each water stratum drilled through should be labeled and filed away in some suitable container; such as a Mason Jar. It may never be necessary to analyze these samples unless future water troubles develop. By comparing the analyses of these samples secured while drilling with those that are taken from the producing well, the source of the water trouble may be readily located.

Unless the driller and engineer properly finish the well, water incursion may soon develop, and cause trouble throughout the life of the well. When inaccurate records are kept, casing is often landed too high. Also, if the hole is not well-reamed, or if, when rotary tools are used, the space behind the casing is not thoroughly flushed out, the cement placed behind the casing may not make a good water shut-off.

In determining the source and movement of oil-field waters, dyes or other flow indicators have been used. They will aid in determining whether the water is coming into the well through a leak in the casing or around the shoe of the water string, or whether it is migrating from one well to another. Fluorescein and Venetian red

50. Slichter, C. S., Field measurements of the rate of movement of underground waters: U. S. Geol. Survey, Water Supply Paper, No. 140.

have been used successfully in this work. The dye should be dissolved in a bucket of water, then poured around the outside of the casing and washed down with a hose. In studying water migration from well to well, the dye solution is put in a glass container and lowered to the bottom of the hole where the container is broken with the bailer or tools. It is placed in the well that seems to be flooding the other well or wells. Production from this well should be suspended, so that the dye will not be pumped out. The neighboring wells should be pumped vigorously, and the water content closely watched for traces of the dye.

Top water may gain access to the oil sands by: a leaky water string, either through a leak in the casing or by water moving down around the outside of the casing shoe; the water string may be landed above the bottom of a water sand; or an oil or gas sand may be flooded by migrating waters from a neighboring well.

Remedying Water Incursion

Before any repair work can be done to exclude top water, its source must be definitely known. The well log, casing and cementing record, fluid level record, and production record are consulted. If the well has shown a sudden increase of water, the source is likely due to ruptured casing, or the water has broken in around the lower end of it. A casing tester[2] should be run to locate the place within the casing that is leaking. If this proves futile, the hole should be bailed to the bottom, then let stand, in order to watch the fluid level.

The problem of shutting off top water may be attacked from various angles; Canvas or oakum packers may be used; the casing may be screwed up tighter; the water string may be driven farther into its landing base; a liner may be run in and cemented; the casing may be removed, the hole drilled deeper, and a smaller string of pipe run in to a greater depth; or the casing may be pulled up, and cement forced behind it. All these methods of shutting off top water are fully discussed by Tough[48].

In testing for intermediate water a bridge may be used to test the casing at any desired depth. Using a bridge eliminates a great deal of needless plugging. In bridging up from the bottom, the well should be plugged by stages; that is, one sand should be tested at a time. Such water present can best be located by testing each successive sand as the well is being drilled. But this cannot be done very easily if rotary tools are used. However, if the mud fluid is functioning as it should, there will likely be no future water troubles.

If intermediate water is present, the operator must use great care in prospecting the upper oil sands while producing from the lower sands. In this case thick mud fluid or cement should be placed behind the water string, extending up above the upper limit of the upper oil sand. Packers have been used on intermediate water jobs, but their use is not to be recommended if the wells are long-lived. Cement can be readily placed between two water sands by using the recently patented cement barrel.[13]

If the bottom of the hole is suspected of producing bottom water, the hole may be plugged in successive stages with cement. Cement will frequently shut off bottom water when bottom hole packers, lead plugs, lead wool, etc. have failed to do so. The cement may be lowered in dry sacks or the McDonald[48] process may be used.

The procedure in making a plugging test for edge water depends upon its location in the well. That is, edge water may be from an intermediate oil stratum or from the lower part of the oil sand. In making a bottom hole plugging test, there is a possibility of shutting off the edge water upon which the oil is floating.

Water in a local lenticular sand should not be mistaken for edge water. Enroaching edge water ordinarily entraps large quantities of oil. This may be partly eliminated by forcing compressed air into those wells nearest the edge water, thus holding back the water, at the same time trying to increase the production in the wells up the dip. Or, all edge wells may be kept pumping so as to remove the water from the sand as rapidly as it encroaches. Thus a barrier can be created which will protect the rest of the field. This method might run into excessive costs, however. Also, the wells may be plugged as soon as edge water comes in, and other wells drilled on up the dip in order to withdraw the trapped oil, but frequently the cost may not warrant such procedure.

Water Analysis

Operators in many fields have recognized the importance of chemical analyses of the underground waters encountered at various depths during the drilling process, and they have made profitable use of the results in solving the source of the waters that have caused trouble in wells. On the other hand, many operators look upon water analyses with indifference. A reliable method of studying the chemical relations of underground waters has been worked out by Palmer[51] and Reistle[52]. By this method different waters can be accurately and rapidly compared. To make such work valuable, and unmixed or uncontaminated sample should be obtained from each sand. The Halliburton sand tester[39] is ideal for this work.

51. Palmer, Chase, The geochemical interpretation of water analysis: U. S. Geol. Survey, Bull. 479.

52. Reistle, C. E., Identification of oil field waters by chemical analysis: U. S. Bureau Mines, Tech. Paper, No. 404.

Acid Waters

Acid waters and certain alkaline waters associated with oil field waters cause rapid deterioration and corrosion of metal equipment used at the wells. The magnitude of this destruction is proved by the huge waste of iron and steel pipe, tubing, casing, and pump valves, and sucker rods that occurs each year.

The corrosion of the field equipment in wells is largely an electro-chemical process, caused by the various chemicals dissolved in the water which produce galvanic action on the well equipment. Also, carbonic acid and sulfuric acid are formed in the water, and "eat out" underground equipment. For example, iron carbonate combined with water and oxygen will produce carbonic acid; whereas, hydrogen sulfide and oxygen or calcium sulfate and carbon dioxide and water will both produce sulfuric acid.

However, not all ground waters are corrosive. In general, natural saline waters, acid waters, and waters whose dissolved constituents break down readily to yield carbonic acid, hydrochloric acid, or sulfuric acid are corrosive, in the sense that they either induce corrosion or afford conditions favorable to its occurence; whereas, most strongly alkaline waters are non-corrosive. Waters that contain magnesium chloride are especially corrosive, but those that contain sodium carbonate are generally non-corrosive in oil wells.

Certain gases absorbed in water influence corrosion. This is especially true when carbonic acid gas (CO_2) and hydrogen sulfide gas (H_2S) are carried in solution with the waters in contact with oil field equipment.

This question of corrosion of oil and gas field equipment is very well discussed by Mills[53].

Danger of Improper Plugging

When a producing well ceases to produce at a profit, or if it is producing much water, it should be plugged, and abandoned.

Certain precautions must be used to prevent the incursion of edge or bottom water into the well which may cause migration of water to adjoining wells. It is the best practice to fill the bottom of the well with cement before beginning to pull the casing. This cement plug should extend up the hole to a point above the cap rock. The hole should then be filled with thick mud fluid, after which the casing should be salvaged if possible, as casing left in a well increases the corrosion hazard, and thus hastens the time when water may percolate into the abandoned hole.

53. Mills, R. Van A., Protection of oil and gas field equipment against corrosion: U. S. Bureau Mines, Bull. No. 233, 1925.

One well improperly plugged may cut off or materially influence the production of several adjoining wells, as water may migrate into it and then flood an upper or lower producing sand. However, if the casing has been pulled, a hole left full of cement and thick mud offers little opportunity for the mingling of fluids from different horizons.

RELATION OF TYPE OF SAND TO RECOVERY

While the amount of oil a sand may contain depends primarily upon the relative amount of pore space and the extent to which that pore space is filled or saturated with oil, it does not necessarily follow that the highest per cent of recovery will be obtained from sands that have high porosity and saturation. Sands of low porosity may ultimately produce relatively more oil than those of high porosity if the expulsive forces; that is, gas pressure, hydrostatic pressure, and rock pressure are high and the sand is of coarse grain. In the other hand, sands of high porosity will yield relatively more than those of lower porosity when the oil is of low gravity and high viscosity.

The most porous sands are those that are made of comparatively uniform grains and free from clay. Cementation by silica, lime carbonate, iron oxide, or other substances will reduce the effective porosity. If the sand is loose and free from cementing material or clay particles, its porosity is likely to be high. Clay particles fill the pore spaces, and some clay is in a jelly-like colloidal state which is relatively impervious.

These so-called "tight" sands are occasionally saturated with oil, but they will not yield it readily unless the expulsive forces are very great. This is because adhesion and capillary attraction are greater in the smaller pores, thus making it more difficult to drive out the oil. In this connection it has been demonstrated[30] that water will flow about 2,500 times as fast through a stratum of fine gravel than it will through one of very fine sand, though the per cent of porosity may be the same in both strata.

Slichter[30] has demonstrated that the amount of oil retained in a sand by adhesion and capillarity is greater in fine sands even if porosity is practically the same. The fine sand used was composed of angular grains of irregular size, averaging about 3/254 inch in diameter with a porosity of 28.5 per cent; whereas, the coarse sand consisted of well-rounded grains of uniform size, averaging about 6/254 inch in diameter with a porosity of 37 per cent. Both samples were saturated with crude oil of 41.2° Baume″ gravity, then were placed so as to drain or filter out for a period of 26 days. After this period. the coarse-grained sand retained 15 per cent of the original amount of oil, and the fine grained sand retained 21 per cent. By using oil of 14° gravity over a period of 73 days, the coarse sand retained 30.5 per cent; whereas, the fine sand retained 53 per cent. In this experiment the expulsive force was due only to gravity, however; but the results may give some idea as to the lowest possible limits of ultimate recovery in fine- and coarse-grained sands, as well as show the effect of texture upon recovery when the expulsive force is constant.

SECURING THE MAXIMUM ULTIMATE PRODUCTION

In the older oil fields, the question of securing the maximum production is largely a question of rejuvenation, and in the newer oil fields, it is largely a question of efficient operation; such as, proper well spacing, suitable completion, conservation of natural gas occuring with the oil, intelligent regulation and methods of production, attention to the individual well, and cooperation between operators in the same field.

In most of the older oil fields of the country, the history of the average well has been as follows: The well is allowed to flow as long as it will—for a few days, weeks, months, as the case may be. By this method it produces only a small part of the oil in the sand without any attempt to conserve the natural gas occuring with the oil. The well is then "put on the pump." By this method it usually produces for a much longer period, often extending over a number of years, until the production declines to a point where operation is no longer profitable, and the well is either plugged or abandoned, or some of the methods of rejuvenation are tried out in order to prolong its life. At this time, when the well or group of wells can no longer be pumped at a profit, most authorities agree that often as much as half of the oil originally in the sand still remains unrecovered. In some oil fields part of this oil still remaining in the sand is recovered by one of the methods of rejuvenation. In fact, for the past fifteen or twenty years, the operation and production of many of the oil fields of Pennsylvania, West Virginia, and Ohio, has been the direct result of the application and constant use of rejuvenation methods.

Rejuvenation methods consist of: Cleaning out with tools or compressed air and water to remove accumulated sediments and cavings; heating, shooting, reaming or adding chemicals to remove paraffin and clean the sand face; repairing casing or plugging to shut off water entering the well, which is flooding the sand; introducing water to the sand in one well or row of wells to drive the oil ahead of the introduced water to other wells; introducing air or gas under pressure at one well or row of wells to drive oil towards other wells; the use of vacuum at wells; and the use of back-pressure at wells.

REJUVENATION

Cleaning-out With Tools to Increase Production

The drilling tools are frequently used at flowing wells to aid in cleaning-out the sand and sediments. The tools, which may consist of a small bit, short stem, and drilling jars, are clamped to the temper screw and then spudding up and down in the hole just off bottom. This process is called "agitating." By this method the well can be made to flow faster, because the gas is mixed and churned through the oil, and the lifting action of the tools and wire drilling line tends to boost the upward movement of the oil. Any sand and sediment that may be caving or slumping off is not permitted to settle, and most of it is carried out in suspension with the oil.

In wells where the producing sand has a tendency to cave or heave, such sediments may rise up into the perforated liner, and may completely fill it. Usually a bailer or sand pump will remove such material; but if they are of such a character as to cause rapid settling it may be necessary to re-drill the bottom of the hole before bailing. This process of re-drilling and cleaning-out frequently causes the well to resume production with a larger volume of oil.

Cleaning Out with Compressed Air

The Dunn-Lewis method is an adaptation of compressed air for increasing the production of oil wells by its use at high pressure for cleaning-out purposes. This method has been used to date in various fields of the United States to depths exceeding 2,800 feet.

The Tidal Oil Company was first in experimenting with this process and, in cooperation with the inventors, perfected the equipment. The equipment consists of a tractor having a winch attached, which is used for hoisting the sucker rods and tubing; a high speed, two-stage portable compressor, capable of developing 500 pounds pressure; and an air tank about 3½ feet in diameter and 14 feet long. The compressor and the tank are mounted upon separate motor trucks or wagons. In addition, some type of pulling mast is required.

On some leases the Dewey Friction Wheel Pulling Machine has been used, which eliminates the need of the tractor and winch. It consists of a mast and two "dished-faced" wooden wheels mounted upon the ends of a short spooling shaft, which is the same length as the rear axle of a motor truck, and upon which the cable used in pulling is wound. The power is supplied by backing a truck up against the wooden wheels until the tires of the rear wheels of the truck fit into the dish-faced wheels. Then by jacking up the rear end of the truck, the truck engine supplies sufficient power for pulling the tubing. A clutch is used to disengage the shaft from the motor power.

The receiving or air tank is equipped with two discharge pipes, one taking the compressed air from the top of the receiver and the other from the bottom. The former is used when compressed air is to be released into the well for cleaning or blowing out purposes, or until all loosed sand, mud, and sediment have been blown from the well. The lower discharge pipe is used when water is to be blown into the well ahead of the compressed air. In this latter case, the lower third of the receiver is filled with water; and, when released into the well ahead of the air, washes down the face of the oil sand and removes any sediment still clinging to it.

After the sucker rods and tubing have been pulled, a heavy shoe is fitted to the lower end of the tubing, replacing the customary perforated pipe. The shoe serves to clear the way through sediment, and to break the larger pieces of rock. A rotary swivel with hose is connected to the top of the tubing, and it is then lowered back into the well. The other end of the hose is connected to the receiver or compressed air tank. The compressor is then run until the tank is charged with air at 400 to 500 pounds pressure, after which the charge is turned into the tubing, which is lowered as the well is cleaned out. When the air pressure in the tank is depleted to about 150 pounds pressure, the tank must be recharged. This requires about 35 to 45 minutes. Any rocks small enough to pass upward between the tubing and the casing will be ejected, and the larger rocks can usually be crushed by means of the heavy shoe on the bottom of the tubing, which can be raised and lowered by the pulling machine.

Before the equipment is disconnected and pulled out, the casing should be washed. This is done by introducing the pressure into the casing. This will force all the remaining loose or floating sand and fluid out through the tubing.

After the well has been cleaned, the rods, tubing, and working barrel are replaced, and the well put back to pumping. The tubing shoe may be left in the well, so as to simplify subsequent cleaning-out.

By this process the loose sand, rocks, shale cavings, paraffin, and other substance can be blown out in a much shorter time than is required when drilling tools and sand pumps are used. The average time needed to clean a well and place it back "on the pump" is three days when the wells are about 1,400 feet deep. The average cost of cleaning such wells is about $240.00; Whereas, the average time required for cleaning with cable-tool machines in the same district is 51 days per well, involving an average cost of $1,000.00 per well.

Paraffin Troubles and Methods of Treatment

Mills[54] has discussed in a recent publication of the U. S. Bureau of Mines, "The Paraffin Problem in Oil Wells," which the writers quote, in full, as follows:

"**Introduction**.—This preliminary paper is intended to answer briefly some of the inquiries coming to the Bureau of Mines regarding the so-called "Paraffining" of oil wells, and methods of preventing and remedying that trouble. The increased difficulties in operation and the losses of production caused by the deposition of gummy and waxy hydrocarbons, commonly called paraffin in the wells, tubing, other pumping equipment, and in the pores of the productive sands, have long been recognized, but the trouble has not been overcome. The nature and causes of the trouble, together with some of the possible methods by which it may be diminished or overcome, are outlined below:

"**Character of the Paraffining Materials.**—The so-called paraffin that collects in oil wells and in the pores of the oil-producing sands immediately around the wells, is generally made up of amorphous wax or uncracked paraffin, asphalt, or other gummy hydrocarbons mixed with more or less waters, oil, and inorganic silt. Some of the samples of this "paraffin" collected from oil wells in different fields and examined by the Bureau of Mines contains as much as 20 per cent by weight of water and inorganic silt; whereas, other samples are composed entirely of waxy hydrocarbons and oil. The inorganic silt accompanying this "paraffin" is mostly fine sand, clayey materials, common salt, and finely disseminated precipitates of calcuim and maguesium carbonates. Sulphates of calcium, barium, and strontium are less common constituents of the "paraffin."

The "paraffin" material from oil wells varies in consistency from soft, grease-like material resembling vaseline to hard, wax-like masses resembling the natural wax ozokerite. The melting points and solubilities have a wide range of variation, depending upon the composition and consistency of the paraffin. The relationships are illustrated by the results of preliminary laboratory tests (determinations of approximate melting points and solubilities) presented in Tables I and II.

54. Mills, R. Van A., The paraffin problem in oil wells: U. S. Bureau Mines Investigations, No. 2550, 1923.

Table I—Relative solubilities of different "Paraffins" in different solvents at 85° F.

(Solubilities expressed in Percentages)*

KIND OF PARAFFIN	BENZOL (90% grade) Spec. Grav. 0.880 at 60°F.	GASOLINE (Motor grade) Spec. Grav. 0.753 at 60°F.	NAPTHA (Comm. grade) Spec. Grav. 0.759 at 60°F.	KEROSENE (Water, white) Spec. Grav. 0.800 at 60°F.
Commercial paraffin (Melting point 123°F.)	92	36	46	30
Soft "paraffin" from oil-well tubing, Salt Creek oil field, Wyo., (Melting point 127°F.)	3	5	4	3
Waxy paraffin from oil-well casing, Garber oil f.eld, Okla. (Melting point 179°F.)	12	12	11	9

*A solubility of 12 per cent means that 12 pounds of the paraffin will dissolve about 100 pounds of the solvent.

Table II—Relative solubilities of different "Paraffins" in different solvents at 122° F.

(Solubilities expressed in Percentages by Weight)*

KIND OF PARAFFIN	BENZOL (90% grade) Spec. Grav. 0.880 at 60°F.	GASOLINE (Motor grade) Spec. Grav. 0.753 at 60°F.	NAPTHA (Comm. grade) Spec. Grav. 0.759 at 60°F.	KEROSENE (Water White) Spec. Grav. 0.800 at 60°F.
Commercial paraffin (Melting point 123°F.)	1044**	1016**	780**	330**
Soft paraffin from Oil-Well tubing, Salt Creek oil field, Wyo., (Melting point 127°F.)	70	58	73	43.3
Waxy paraffin from oil-Garber oil field, Okla. field, Oklahoma, (Melting point 179°F)	8	10	12	4.6

*Same as Table I.

**At this concentration, lowering the temperature a fraction of a degree caused paraffin in the solution to solidity.

The "paraffins" from oil wells are generally less soluble and have higher melting points than commercial paraffin. At temperatures above their melting points, indefinite quantities of these materials liquify and combine with the solvents or with crude oil. Under such conditions where hot solvents or crude oil contains high concentrations, when the temperature falls below its melting point a large part of the paraffin tends to congeal immediately heat.ng the solvents to temperatures slightly below the melting points of the oil-well "paraffins" generally increased the dissolving action, but with the waxy paraffin from the Garber field, the solubility decreased as the temperature was raised. The low solubilities of the paraffins at ordinary temperatures and their tendency to separate out when hot solutions are slightly cooled, tend to render more difficult the successful use of solvents for cleaning-out oil wells.

Causes For Paraffining.—The principal causes for the so-called paraffin are:

(1.) The chilling incident to the sudden reduction of pressure and expansion of gas in the wells and in the producing sands close to the wells, (Lowering the temperature only a fraction of a degree often causes deposition of paraffin from oil containing its full capacity of dissolved paraffin.)

(2) The diminishing solubility of the paraffin at the lowered pressures generally prevail in the wells. (Paraffin is soluble in oil and gas at higher pressures.)

(3). The churning action of the pumps and sucker rods which tends to accentuate the emulsification of water, oil, and silt.

(4) The evaporating and drying action of natural gas. The evaporation of the more volatile constituents of the oil leaves behind the paraffin residues to be deposited in the wells and productive sands.

(5) The alternate wetting and drying of the productive sand exposed in a well where the fluid level is repeatedly lowered from the top to the bottom of the sand by pumping. Expanding gas tends to chill and dry the uncovered surfaces of sand. This wetting and drying cycle is comparable to repeatedly painting the exposed faces of the sand with paraffin.

(6) The leakage of certain kinds of water into the wells, especially water carrying mechanically suspended silt, or waters that carry dissolved salts which act chemically with the salts dissolved in other waters in the wells so as to form silty precipitates. The loss of carbon dixoide gas along with other dissolved gases from waters containing bicarbonates also causes the precipitation of silty carbonate, more especially calcium carbonate. The fine particles of silt seem to form the nuclei about which the oil and water emulsify to form some of the so-called paraffin materials.

Effects of Paraffining.—The deposition of the paraffin and associated substances upon the faces of the productive sands in the wells and in the pores of the productive sands immediately around the wells tends to obstruct the flow of oil and gas into the wells. This damage is most common and at the same time most serious in oil pumping fields where the gas pressure has been depleted and the oil has been subjected to long continued evaporation by escaping pas. The plugging effects generally become progressively worse until, in extreme cases, the flow of oil into the wells is practically shut off before the recoverable oil is exhausted.

Casing, tubing, sucker rods, valves, and working barrels also become so badly fouled with paraffin as to interfere with pumping. In some fields, flowing wells, especially those flowing through tubing, become chocked with paraffin deposited in the tubing and casing, or even in the flow lines that conduct the oil from the wells to the field tanks. The deposition of paraffin in a flowing well is generally the worst in the upper part of the well where the pressure is comparatively low and the oil has suffered the full chilling effect of the expanding gas. As the flow of oil and gas is chocked off, the paraffin tends to run together and pack, sometimes completely filling the tubing or casing for several hundred feet. Losses in production followed by expensive pulling and cleaning jobs are the usual accompaniment of "paraff.ng". In extreme cases, especially where improper cleaning methods are used, the productive sands around the wells may become plugged to distances of several feet away from the wells, thus damaging those wells beyond repair.

Damage Erroneously Attributed to Paraffining.—Hard inorganic salts, commonly termed "gyp", composed primarily of carbonates and sulphates of calcium, magnesium, barium, and strontium, as well as common salt, frequently encrust the pumping equipment and walls of the wells or accumulate in the pores of the productive sands around the wells. Waters leaking into the oil and gas wells frequently deposit enough inorganic salts to plug the pores of the productive sands for considerable distances from the wells. Inorganic deposits in the wells may or may not be accompanied by paraffin. The damage they cause and more especially the plugging of pores of the productive sands, is often erroneously attributed to paraffining.

Determining the Cause of the Trouble.—Before applying methods for stopping or remedying paraffining and related troubles, it is desirable to determine the nature and causes of the trouble. So-called paraffin or mineral salt will be recognized at once when one or the other is removed from a well, but the different kinds of mineral salts plugging the pores of the sands, and also the mixtures of paraffin, oil, and water, with different kinds of silt, are not so easily recognized. Possible methods of cleaning such deposits from wells and methods of preventing further deposition depend largely upon the composition and mode of formation of the deposits. A chemical examination of the paraffin should indicate whether or not it is an emulsion of paraffin and oil with water and silt. The composition of the silt and its probable mode of formation can also be determined by chemical study. If the paraffin proves to be an emulsion, the exclusion of the water from the well is one of the problems confronting the operator.

Calcite or other mineral salts plugging the pores of the oil sand generally appear as chalk-white patches between the sand grains. This trouble should be suspected if mineral crusts are found coating the equipment and walls of the well. To detect calcite or other carbonates, drop a piece of the crust or plugged up oil sand in hydrochloric acid. Calcite or other carbonates will effervesce in the acid, whereas insoluble sulphates fail to effervesce in acid. Some of the so-called paraffin deposits in southeastern Ohio contain such large proportions of silty carbonates that they effervesce and melt away in hydrochloric acid, yielding clean oil after the foreign matter has gone into solution. Most of the so-called paraffin troubles in oil wells are caused by the deposition of hydrocarbons comparatively free from water and silt, but the fact is emphasized that some of these paraffin troubles are, in part at least, water troubles that must be met on that basis.

Method of Preventing Paraffining, Regulation of Fluid Level—Recognizing the causes and effects of paraffining outlined in the preceding pages, the following methods have been used or suggested in order to eliminate the causes and to prevent or overcome their damaging effects. Probably the most common method of preventing or retarding the paraffining of a sand in a pumping well is to tube the well high enough for the sand to always remain covered with oil. This prevents to some extent the chilling effect of expanding gas, and it is believed that the solvent action of the oil helps to keep the face of the sand clean.

Should the well make water, it can be tubed with the working barrel a short distance above the top of the sand and the perforation set near the bottom of the hole with a flood nipple immediately under the working barrel. This enables the operator to pump down the water which collects each day and prevents him from pumping the well below the flood nipple. By this method the sand will always remail covered.

Regulation of Back Pressure.—By maintaining as high back pressure on the wells as is possible without interfering with the recovery of oil, it should be possible to diminish the chilling by diminishing the expansion of gas in the wells. At the same time the paraffin would be more soluble on account of the higher pressure. The back pressure in pumping wells might best be held by tubing the well high, and thus maintain a column of oil in the hole rather than by pumping the well down and holding the back pressure by a closed casing head. By keeping a column of oil in the hole the operator gains the two advantages of maintaining back pressure and keeping the sand covered. The problem is different in flowing wells where the productive sands remain covered by oil most of the time. The chilling and drying effect of the expanding gas at the bottom of the well being thereby diminished, and the gas pressure being sufficient to help dissolve or blow off the paraffin that might otherwise plug the sand. Paraffin troubles with flowing wells generally result from the plugging of the upper parts of the tubing and casing, as well as the flow lines.

Paraffin that plugged the two-inch tubing in a flowing well in the Salt Creek oil field. Wyoming, in one to two weeks was overcome by closing in the well for 24 hours, thus raising the pressure to 450 lbs. per sq. inch, and then allowing the well to flow wide open through the tubing for the next 24 hours, and repeating these changes over 24 hours. So long as this cycle was repeated, the tubing remained practically free of paraffin. The Bureau of Mines is conducting an investigation of the effects of regulated back pressure upon oil production.

Use of Heaters.—Another possible method to prevent or diminish paraffining is to heat the interior of the well while it is in operation. This would afford the advantages of continually washing the face of the sand w.th the inflowing fluid, while at the same time maintaining a temperature high enough to prevent the deposition of paraffin while it is being pumped from the well along with the oil. Steam and electr.c heaters may be developed for this purpose. Several companies have experimented with the electric heaters, but numerous electrical and mechanical difficulties have interfered with the success of this method. Up to the present time electrical oil well heaters have not come into general use, although favorable progress and some successful results are reported by companies engaged in developing and testing this type of heater.

Steam introduced between two inch tubing which is run inside of 3-inch tubing, as described elsewhere in this report, might prevent paraffining but the method is costly both in equipment and operation. It should work best in shallow wells, because in deep wells the excessive condensation of steam is a serious drawback. The practical value of the method should be determined by adequate trials preferably in shallow fields.

Method of Removing Paraffin From Wells—Classification of Methods.—After the paraffin has accumulated in a well sufficiently to cause trouble, it can be removed by the usual pulling and cleaning job, by the paraffin auger, by reaming the oil sand, by shooting, by the introduction of solvents like gasoline or benzol to dissolve the paraffin, by the introduction of chemicals to heat, melt, and oxidize the paraffin with steam, hot water, or hot solvents and by burning out the paraffin. The pulling and cleaning job is too well known to require comment at this time. The paraffin auger for removing paraffin from tubing without a pulling job, is too little used to warrant further description here. Several different devices for reaming oil sands to remove paraffin have been patented and widely advertised. Favorable results are claimed for these devices but mechanical difficulties are involved in their use. They have not come into general use.

Shooting.—Engineers of the Bureau of Mines have made some preliminary investigations into the matter of removal of paraffin and similar residues from wells, and it has been found that the most successful and positive method of removing these residues from the face of an oil sand is by shooting. This probably gives the combined effect of melting and burning the paraffin and breaking down the face of the sand, accompanied by more or less fracturing. Ordinarily squib shots are placed in the hole in 1½ inch shells, which are in reality so-called anchor shells for full sized shots. From 5 to 10 quarts of nitro-glycerin is about right for sands from fifteen to forty feet thick. Generally as much glycerin would be placed opposite the producing sand as would be contained in a 1½ inch shell, having a length of about 3-4 of the thickness of the sand. If the well is drilled below the oil sand, the shot should be anchored so as to be opposite the sand, or the hole bridged and the shot placed on the bridge, in either case the hole should be filled with water at least to a level above the shot so that the force of the shot will not be wasted. It is also necessary that the operator use care in shooting, lest he damage his casing.

Too heavy and too frequent shooting hastens the enlargement of the shot cavity and causes the excessive caving of soft sand that must be cleaned from the hole. The continued enlargement of the shot cavity renders further shooting ineffective except as it causes more caving. In some fields shooting tends to damage the wells by tightly packing the sands. Again, casing seated close to the top of the oil sand may render shooting impracticable. Conditions such as these call for other methods of removing paraffin.

Use of Solvents.—The introduction of one to three drums of gasoline to dissolve the paraffin has given only partial success, because the paraffin is not readily dissolved by gasoline. Benzol is a more effective solvent than gasoline for some of the so-called paraffins. Both crude oil and kerosene also exert a selvent action on the paraffin, but none of these solvents have the cleansing action that is desired. Generally, these solvents are most effective when hot, especially if they are hot enough to melt the paraffin, but they are apt to deposit paraffin back in the productive sand when slightly cooled, thus complicating the trouble. A hot solvent, saturated with dissolved paraffin, will deposit some of this paraffin as soon as the solvent begins to cool. Hot solvents, with their dissolved paraffin, should therefore be bailed or pumped from a well before cooling causes the redeposition of the paraffin.

Some common methods of introducing a solvent are:

(1) Run down through tubing.
(2) Run down between tubing and casing.
(3) Pour down open casing from which tubing has been pulled.
(4) Lower in dump bailer.

The dump bailer should be especially useful for introducing hot solvents and for introducing chemicals to heat the solvents according to the methods described in the succeeding paragraphs.

The washing of a well with gasoline once every three or four years has been tried at Bradford, Pennsylvania, with moderate success, but to wash a well with gasoline or benzol more often than that may not be profitable, particularly if the well is relatively small. The use of solvents by present methods is costly to apply on a large scale at frequent intervals, and the results are not commensurate with the cost.

Steaming.—Steaming to remove paraffin from the faces of the productive sands has been attempted in many fields. Steam has commonly been introduced through a single string of tubing. Probably the best arrangement for steaming is to use two-inch tubing inside of three-inch tubing, the three-inch tubing being open at the bottom and extending down to a point just above the working barrel on the two-inch tubing. Steam can then be put down the well between the two-inch and three-inch tubings, and allowed to rise freely between the three-inch tubing and the casing. In this way, it may be possible to heat a well sufficiently to melt and pump off the paraffin without interrupting production. The ideal condition is afforded where there is sufficient pressure in the sand to cause a fluid movement into the well while it is being steamed. The melted paraffin is then washed from the sand into the well and pumped out. In steaming a well it is imperative not to confine the steam under pressure in the well, because that tends to melt the paraffin and drive it back into the sand where it will congeal again to form a so-called "paraffin ring," plugging the sand around the well. This damages the sand worse than before. In general steam treatment is costly and the results are not uniformly satisfactory.

Use of Chemicals, Calcium Carbide.—The use of chemicals to remove paraffin and associated deposits from oil wells is only in the experimental stage. The practical value of these methods depends upon cost, as well as increased production. High cost is one of the principal obstacles to success. Calcium carbide is one of the chemicals reported to have been tried in the shallow fields of eastern Kansas. In this method, from 100 to 200 pounds of this reagent were placed in cylindrical wire gauze containers of the proper size to be lowered to the oil sand. Water occurring in the hole, or put in for the purpose, reacted with the carbide, thus generating the heat which melted the paraffin. The effect of this treatment is said to have been beneficial.

Caustic Soda and Aluminum.—A patented process wherein a mixture of caustic soda (sodium hydroxide) and metallic aluminum is dumped down the wells, or is lowered in a dump bailer, also depends upon the generation of heat to melt the paraffin when the mixture comes in contact with water. The water occurs naturally in the hole or is put in for the purpose. Successful results are claimed for this process. It has been applied extensively in the old Pennsylvania fields.

Sodium Peroxide.—The Bureau of Mines has been experimenting with the use of sodium peroxide for the removal of paraffin from oil wells. From 100 to 200 pounds of the reagent are introduced into the well either by dumping it in at the top or by putting it down in wire cloth, tin, or glass containers. One or two barrels of water are also run in, if the well does not already contain water, for water is essential to the action. Although the experimental work is not complete, the results of these preliminary experiments indicate favorable possibilities. Experiments by individual operators in different parts of the Appalachian and Mid-Continent fields afford further encouragement in that the rates of production of several wells were increased from 50 to 100 per cent by cleaning them out with sodium peroxide.

Upon immersion in water, this reagent generates intense heat and liberates oxygen which supports combustion. Hydrogen and oxygen which are liberated through the decomposition of the water also burn. The paraffin is probably removed from the face of the oil sand both by melting and by burning.

Sodium peroxide is dangerous in that it sets fire merely upon contact with water or damp objects. The use of this reagent would be especially dangerous around wooden derricks or other inflammable structures. In shipping and handling, extreme care must be taken to keep it from contact with water or inflammable substances that are moist. The cost of the reagent is approximately 30 dollars per 100 pounds.

Hydrochloric Acid.—The Bureau of Mines has experimented with the use of hydrochloric acid following the treatment of a well with sodium peroxide. The purpose of this acid treatment was to dissolve calcium carbonate which, together with paraffin plugged the pores of the sand around the walls of the hole. Several carboys of concentrated acid were dumped into the well by inverting the carboys on top of the open casing head, and allowing the acid to run down the casing. (A dump bailer might be used to keep the acid off the casing). The acid was introduced after the sodium peroxide had stopped its violent reaction. The introduction of the hydrochloric acid which mixes with the sodium hydroxide resulting from the preceeding reaction gives another violent reaction with considerable heat. By adding an excess of acid, the calcium carbonate, silt, crusts, and interstitial matter is cleaned out by being dissolved. The acid may be permitted to stand in the well a few days, but should then be bailed out together with loose sand, stilt, and water.

Sulphuric Acid.—Sulphuric acid should not be used in oil wells because of the danger of plugging the sand with precipitated sulphate salts, more especially calcium and barium sulphate.

Other Possible Reagents.—It is possible that liquid oxygen can be used successfully for the remooval of paraffin from wells. Metallic sodium and combinations of sodium and aluminum, sodium peroxide and aluminum, calcium carbide or powdered carbon and sulphur together with sodium peroxide and numerous other reagents and combinations or reagents designed to produce heat in the oil well may be also found useful for cleaning out paraffin. The subject is one for extensive investigation.

Combined Use of Solvents and Reagents.—The increased solvent action of hot gasoline, benzol, and other solvents has been pointed out. These solvents can be heated by steam or other methods, and lowered into the well by the dump bailer. Possibly a more effective method would be to put the gasoline in the well, and then run in a heat-generating reagent, such as sodium peroxide. For the operation of this method, water with which the sodium peroxide can react should underlie the gasoline. If water does not occur in the well it should be introduced immediately before or after the sodium peroxide is added. Hydrochloric acid and sodium peroxide is another combination of reagents yielding a violent reaction accompanied by heat when mixed. The reactions between sodium peroxide and the water or acid, together with a possible combustion of part of the gasoline should heat the remaining gasoline enough to clean the well. The gasoline should be bailed from the hole while hot, so as to avoid the redeposition of paraffin when the gasoline cools. This method should be given adequate field trials before being extensively applied.

Burning.—A cheap and effective method of removing paraffin from the face of an oil sand is to burn it off. So far as the writer knows this was first tried by tthe Smith-Dunn Co. near Marietta, Ohio, in October, 1920. Oil-soaked waste was lighted and dropped down a well where the Smith-Dunn compressed air process was being used. Air and natural gas coming into the well made a combustible mixture which ignited and burned for 24 hours. The fire which was confined to the bottom part of the well was then extinguished by pouring in a few buckets of water at the top of the well. The well had apparently been thoroughly cleaned. The rate of production was about doubled.

Following this, the Bureau of Mines joined the Smith-Dunn Co., in burning out another well. The well was bailed dry, tubing run to the bottom of the oil sand, and a drum of gasoline poured down the hole. Compressed air was then forced down to the bottom of the hole through the tubing, and the well ignited by dropping down some burning oil-soaked waste. The fire was kept burning for several hours by supplying compressed air through the tubing. The well appeared to have been thoroughly cleaned, and the rate of production was increased several times over what it was before burning.

A burning method used by the Hope Natural Gas Co. has recently been described in one of the oil journals* as follows:

'The Hope Company uses a gas and air mixture for the flame at the bottom of the hole, putting it down with a compressor through 2-inch tubing. At the bottom of the tubing is welded a plug which reduces the orifice to 1-inch, cutting down the pressure of the mixture and preventing back-firing. Below the plug a swage nipple is attached. the belled bottom of the string thus providing the chamber for the flame.

'Still below this is a basket, two feet long and made of common chicken netting' into which a lighted fuse is lowered through the tubing. This being in place, the gas and air mixture is turned in and within a few minutes it is possible to tell by the smoke whether the flame is going.

'Of course, this mixture will ignite the gas, which is coming up through the tubing, but most of the West Virginia oil wells, such as the Hope has been experimenting with. make so little gas that it is readily extinguished, and as the gas will not burn

*National Petroleum News, Vol. 15, p. 91, No. 34, Aug. 22, 1923.

unless mixed with air, the flame will not travel down into the tubing. Enough pressure of the gas-air mixture as it comes through the orifice at the bottom is usually kept at about eight ounces.

'In one instance the temperature at the bottom of the hole was raised to 3,300°F., and general practice is to hold it about 2,300°. Of course, a continuance of this usually results in two or three joints of the tubing being burned loose, but this can be drilled up in a short time and really makes little difference.

'The first criticism that is naturally raised is that a flame will scar the sand, and thus effectually stop all the oil. It is the experience of the Hope Company that on certain sands, particularly conglomerate containing pebbles. the burning of the paraffin with such intense heat has the effect of caving the hole, and thus opening up the pores. A shot, it is true, does frequently fuse the sand, and its effect is irregular. Some of the old wells have been shot and cleaned out so many times that there doubtless is a cavern at the bottom of such size that only an extremely heavy shot will knock off any more of the walls, and this might have the fusing effect.

'For holes that have not been heavily shot, certain patented rotary reamers with horizontal blades have given good results, but where the cavern is large the blades will do little more than fan the air at the bottom of the hole.

'In its experiments, the Hope Company keeps a pilot light burning at the surface, so as to tell whether the mixture is right.'

In order to avoid burning and parting the tubing at the bottom, it would probably be advantageous to use two or three lengths of calorized tubing, which is capable of withstanding high temperatures.

The burning method holds promising possibilities especially in shallow fields. It can doubtless be most easily applied where the Smith-Dunn or Marietta compressed air process is being used, because by that process combustible mixtures of gas and air are often issuing directly from the oil sand into the wells.

Summary.—The suggestions contained in the preceeding paragraphs are based primarily upon present day practice and upon a few preliminary experiments that suggest other favorable possibilities. Present methods for preventing and removing paraffin and associated deposits from oil wells are not all that is to be desired. The cost of cleaning out paraffin is high, and the results seem to be only temporarily beneficial. Wells that have increased their rates of production several hundred per cent upon being cleaned, often go back to their old rates of production within three or four weeks after they were cleaned. The problem then is not only to clean the wells beneficially and economically, but to maintain the beneficial effects long enough to make the operation profitable. The redeposition of the paraffin and associated substances, especially calcium carbonate, must be retarded or prevented. The problem of the effective prevention and removal of paraffin and associated residues from oil wells is one worthy of considerable investigation, and is one which the Bureau of Mines hopes to attack further in the near future.

The Use and Limitations of Vacuum

Back-pressure, or possibly "pressure control" is a better term, is frequently maintained on flowing wells in order to conserve the gas accompanying the oil, and thus prolong the flowing life of the well; to decrease the amount of gas per barrel of oil produced; and to give a greater total ultimate production of oil.

In general there are two methods of applying back-pressure, (1) intermittent application, and (2) constant application. The former, generally known as stop-cocking, consists of closing-in the well entirely for a certain period then releasing the pressure. The latter is usually secured by placing a valve, set for a given pressure, in the lead line or at the gas trap, or by placing a flow nipple or "bean" with an orifice smaller than the internal diameter of the tubing in the lead line at the gas trap, in the lead line at the well, or in the bottom of the tubing.

From the results of experiments of the senior writer with stop-cocking and constant back-pressure at some wells in southern Oklahoma he is inclined to attribute the more favorable results secured with stop-cocking as compared with the use of back-pressure valves to the fact that with the former the wells were entirely closed-in part of the time without the escape of either oil or gas, and when opened there usually resulted a flow of oil with the gas. When using a back-pressure valve at the well, set for a given pressure, much of the time, gas escaped through the valve without being accompanied by a flow of oil. By both of these methods, at the wells tested, the oil flowed by heads.

The writers are inclined to think that the use of flow nipples or the use of smaller tubing of only sufficient internal sectional area to accomodate the oil production by constant flowing should show reasonably lower production of gas per barrel of oil than would be the case when stop-cocking is used.

The results observed at flowing wells in Pennsylvania where 1¼ inch tubing was used, as well as at several large wells in Oklahoma and California where small tubing or flow nipples were used, seem to substantiate the opinion that the flowing life of a well, as well as the volume of oil recovered are materially increased by holding a back-pressure on the well.

In oil field practice, the size of the tubing used in a flowing well invariably has been of the size which the operator expects to use later for pumping the well. This has been the principal consideration in making the installation of tubing at the flowing well, and in most cases has resulted in the use of tubing too large for flowing the well.

Swigart[55] discusses the use of back-pressure at pumping wells. His summary of results, conclusions, and recommendations are quoted in full, as follows:

> The following summary has been drawn partly on the basis of the results obtained during the field experiments on back pressure and partly from data and opinions resulting from a study of oil-well production methods in various fields of the United States which is now being attempted. Since the experiments were confined to two wells in one field, and other data are incomplete, many of the conclusions must be regarded as suggestive rather than definite. A number of the following conclusions will not be applicable to wells under different conditions, but it is believed that most of them may be common to wells in other areas. The wells referred to are wells that produce by gas pressure and not by water pressure.
>
> 1. A differential in pressure between the well and outlying portions of a natural underground oil reservoir is essential for the movement of oil toward the hole. As the rock pressure in the oil-bearing formations declines, the pressure at the well must be lowered 'ahead' of it to insure a flow of oil and gas towards the well. In order to maintain this differential after the rock pressure has declined to a low point, vacuum is put on many wells. The magnitude of the differential will depend upon a large number of variable factors, many of which can not be determined. Therefore, actual field tests on individual wells or some of the wells on a property with fairly uniform conditions, must be made before the most efficient differential can be determined.
>
> 2. Underground conditions, as regards pressures and arrangements of fluids, in oil fields are constantly changing, therefore one set of tests to determine the best differential pressure can not be accepted for the basis of operations over a long period of time. Systematic tests should become a part of the operating routine. The operator after making a few tests will be able to decide upon the frequency with which future tests should be made. It is the writer's opinion that once an operator becomes thoroughly conversant with his wells, the need for tests will not arise often enough to be burdensome.
>
> 3. Both absorbed and free gas, if free gas is present, assist oil in migrating from outlying portions of the reservoir to the well. The greater the rock pressure and consequently the greater the quantity of natural gas in the reservoir. the greater will be the ultimate recovery of oil from a well. Experience has shown that relatively small amounts of oil are recovered from a well after its gas pressure has declined to a very low level.

55. Swigart, T. E., Experiments on back pressure on oil wells: U. S. Bureau Mines Investigations, No. 2420, 1922.

4. If the preceding conclusions hold, it may be said that the methods that will permit the extraction of oil from natural underground reservoirs with a minimum amount of gas per unit for oil, are those which will insure the greatest ultimate recovery of oil. Operating methods that permit or encourage the escape of more gas than the minimum amount required to bring each unit of oil into the hole will lessen the amount of oil which ultimately may be recovered.

5. By holding back pressure on a pumping well, the daily gas production may be reduced appreciably. In general, the greater the back pressure the less the daily gas production.

6. Fairly large back pressures can be held on many pumping wells without cutting down their oil production, and back pressures approaching closely the potential rock pressure of the reservoir can be held on some wells at a sacrifice of only small percentages of their present daily oil production.

7. The back pressures that are most effective in increasing th efficiency in oil recovery (by cutting down the number of cubic feet of gas per barrel of oil), are those pressures which do have a noticeable effect on the present daily oil production. However, the higher the back pressure, the grater seems to be the rate of increase in efficiency of production, (that is, the greater becomes the reduction in cubic feet of gas per barrel of oil with every equal increase in pressure.)

8. By closing in well No. 1 which was in the nature of an isolated well, and permitting only that gas which came through the lead line to escape, it was found that the daily oil production was decreased 7 per cent, and the number of cubic feet of gas per barrel of oil was decreased by two-thirds. Doubtless such a small decrease in present daily oil poduction would be compensated for by the increase in ultimate recovery many times over.

9. A well which was offset on 3 sides at the usual distances by wells producing at atmospheric pressure and which drained a fairly porous sand was sensitive to back pressure. A back pressure of 20 pounds when the potential rock pressure was over 50 pounds caused a loss of 13 per cent in present daily production, while a back pressure of 306 pounds reduces the daily oil production by 37 per cent. High back pressures are not practicable for wells that are closely offset by wells producing at atmospheric pressures.

10. Stop-cocking raised the present oil producing of well No. 1 from 8 to 11 per cent over the normal oil production at atmospheric pressure, and 18.2 per cent over the oil production of the well at a 50 pound back pressure.

The loss in efficiency by stop-cocking due to the production of gas in excess of the amount produced per barrel of oil at 50 pound pressure amounted to more than 23 per cent. Therefore, although the present daily oil production was greatly increased by stop-cocking, the amount of gas used per barrel of oil was 3⅓ times that used per barrel at 50 pound pressure, and such practice no doubt would cut down appreciably the total ultimate production that could be obtained if the back pressure on the well were kept near the potential rock pressure.

11. Stop-cocking injured the production of well No. 7 (offset on three sides) when the well was closed in each night. Prior to stop-cocking the well had been producing at atmospheric pressure for 50 days. Later stop-cocking increased the production of the well 3 per cent when a pressure of only 20 pounds was allowed to build up within the well each night. It is believed that while gas pressure was being established in the sand which had been under low pressure during the run at atmospheric pressure, the daily oil production was injured, and as the new arrangements of fluids took place, the well regained its normal production.

12. Stop-cocking probably will increase the oil production of most wells. If the well is closely offset by wells at low pressure, the overnight pressures should not be permitted to rise too high, else the oil poduction may suffer at the gain of the offset wells. Stop-cocking may or may not be efficient as regards gas production with the oil. In general, stop-cocking will be more successful after the rock pressure has built up in the reservoir near the well. If stop-cocking is started with the pressure near the well at zero pounds gage, the first month of handling will probably cause a decrease in oil production, but continued stop-cocking should increase the oil production.

13. Producing with open casing heads from wells while the gas pressure is still good will result in inefficiency. For instance, well No. 7 averaged 21,546 cubic feet of gas per day during the period from December 18 to 30, 1921 with the casing head open (at atmospheric pressure). Except for about thirty days at odd times, it had never produced at atmospheric pressure during its life of approximately 1⅓ years. After producing at atmospheric pressure from December 18 to February 20, its daily gas production dropped to approximately 10,300 cubic feet, or decreased by 100 per cent, indicating that at atmospheric pressure the well had blown off a considerable part of its "head."

14. Back pressure held on wells that have been producing at lower or atmospheric pressures will reduce the oil production at least temporarily, owing to the decreased rate of flow of gas and oil towards the hole during the time that the pressure is building up in the sand. After a relatively high pressure has been built up in the sand between the well and more remote portions of the reservoir where the maximum rock pressure of the particular locality exists, comparatively high back pressure may be held without seriously cutting down the oil production. Enough time to permit re-establishment of high pressure near the well must be allowed before the true effects of the pressence can be gained.

15. Wells produce casing-head gas at a faster rate when they are pumping and where the fluid is pumped down than when they are shut down and there is a column of fluid in the hole. The fluid column which builds up when wells are shut down usually is effective in materially reducing the rate of flow of casing-head gas.

16. The wells tested did not cut their oil because of back pressure. They did cut their oil, however, because of leaky cups and valves or when pumped after they had begun to "pump-off."

17. The holding of back pressure should increase the flowing of wells. The employment of the back pressure method of handling wells no doubt will bring into prominence flowing devices by which relatively small wells will flow their production with their own gas pressure. Increasing the flowing life of a well is important not only with regard to increased recovery, but also with regard to reduced operating expense.

In this paper data have been presented to show the effects of holding back pressures on two wells. These data for the most part, bear out theoretical conclusions, many of which have been advanced previously by Bureau of Mines engineers. Practically all oil men from the oldest experienced field men to the petroleum engineer agree that "when the gas is gone," the average oil well may be considered as practically exhausted. Experienced oil men agree that if gas could be conserved and therefore the rock pressure in the oil sand sustained above the usual level, oil wells would decline more slowly in daily production. This, of course, would result in a greater ultimate production of oil from each well.

Holding back pressures on pumping wells may afford a method of cutting down the gas production per barrel of oil. However, the back pressure method of handling wells is not recommended for indiscriminate use. In many localities it will be impractical. It is felt, however, that the tests described in this report indicate the possibilities of holding pressure and increasing the efficiency of production and, possibly will serve as a basis for future work in the scientific production of oil. The chances for increasing the ultimate oil production apparently are of such nature as to warrant consideration of this method or other improved methods whiich may be developed.

Lovejoy[56] discusses the effect of back-pressure on wells in the Brock field, Carter County, Oklahoma. Uren[57] discusses methods of applying back-pressure and effects upon recovery.

In most oil fields, gas pressure is the chief cause of oil drainage from the oil sand into the well, because the well serves as an orifice for the release of gas pressure within the oil sand. Other things being equal, the higher the initial gas pressure within the oil sand, the more rapidly will the oil and gas enter the well; and as the pressure within the sand is relieved by the oil and gas flowing into the well and escaping to the surface, the flow into the well will gradually decline until atmospheric pressure is reached.

56. Lovejoy, J. M., Effects of back pressure on wells in Brock field, Oklahoma: Trans. of Amer. Inst. Mining Eng., Vol. 70, pp. 1153-1158, 1924.

57. Uren, Lester C., Methods of applying back pressure and effects upon recovery: Nat. Pet. News, Mar. 3, 1927.

The use of vacuum on the well, to the extent of farther decreasing the differential pressure on the sand face in the well to 10 pounds below atmospheric pressure is equivalent to adding 10 pounds pressure to the gas within the sand.

The amount of gas which can be dissolved in crude oil depends both upon the character of the gas and the character of the oil; and it is directly proportionate to the gas pressure, depending upon the same factors. Beecher and Parkhurst[58] have recently discussed this problem, and the writers quote from their paper, as follows:

> The amount of natural gas that will dissolve in crude oil depends upon both the character of the gas and the character of the oil, if both conditions are constant. For example, a natural gas consisting mostly of methane is not as soluble as one in which some of the heavier hydrocarbons, such as ethane, are present. The first gas used contained only 52 per cent methane, while the methane content of the second gas was 82.5 per cent. The amount of gas dissolved in different types of crude is shown in the following table.

Cubic feet of Gas dissolved in barrel of Oil at different pressures

Gage Pressure Lbs. per sq. in.	Oklahoma Crude, 30.2° A. P. I.				Oklahoma Crude 35.4° A. P. I.	
	Gas. No. 1	Gas No. 2	Air	CO_2	Gas No. 1	Gas No. 2
300	57.0	46.5	12.3	161.0	71	54
500	95.0	77.5	20.5	276.0	118	90
1000	190.0	155.0	41.0	563.0	236	180

There are many illustrations of cases where vacuum has stimulated oil production from wells, cases where it has had little effect upon oil production, cases where it has greatly increased the gasoline content of the casing-head gas, either with or without a marked increase in the relative amount of gas to oil produced and with or without marked decrease in the gravity of the oil produced upon the application of vacuum, and still other cases where there has been little increase in the gasoline content of the casing head gas.

A number of factors or variables, both physical and chemical in the oil sand as well as in the oil itself have doubtless been instrumental in producing the great variations in the effect of vacuum on oil wells. The sand porosity, size of sand grains, uniformity of size and shape of grains, whether or not the bedding planes in the sand or shale partings between the strata prevent oil from migrat-

58. Beecher, C. E., and Parkhurst, I. P., Effects of dissolved gas upon the viscosity and surface tension of crude oil: Mining and Metallurgy, Dec. 1926.

ing from one stratum to another, whether or not capillarity or gravity is the main controlling factor within the sand, whether or not the oil sand is channeled, whether the composition of the oil sand is quartz, limestone, conglomerate, shale, granite-wash, or mixed sedimentary material, all have their effects in the results secured. Whether the oil is of high or low gravity, high or low viscosity, asphalt, mixed or paraffin base, occurs in the sand with high or low rock pressure, is warm or hot as it occurs in the sand,—all influence the results secured with vacuum.

By way of illustration, it would seem that when the oil sand is uniformly fine-grained, and at the time of application of vacuum its upper part is no more depleted than its lower part; that is, there is still about the same relative amount of oil in all parts of a vertical section of the sand from top to bottom, as existed previous to the sand being partially drained by wells, then the action of vacuum would be the same on all exposed surfaces of the sand of the well-walls. But in cases where the upper part of an oil sand has been drained, due to the bedding planes within the sand forming no barrier to migration of oil from the upper to the lower part of the sand, then the effect of vacuum will be different on the upper drained part of the sand as compared with its action on the lower partially drained sand. With oil drained from the upper part of the sand and the pore-openings filled with gas, the effect of vacuum on this upper part of the sand might be felt in the sand for hundreds of feet from the well. This would result in a greater relative increase in gas production to oil, and in case that the bedding planes offered no great resistance in other parts of the sand to the movement of gas and oil, then there would also be a resulting increase in the gasoline content of the gas, due to the relieved pressure on the upper surface of the oil within the lower part of the sand. The results would probably be similar in effect to those at different types of oil storage tanks, there being a greater relative amount of evaporation from the surface of the oil stored in broad, low tanks as compared with the same amount of oil stored in high, narrow tanks.

Vacuum has been used in the oil fields of Pennsylvania for more than fifty years. The following quotation from pages 12 and 13 of Bulletin 15 of the Pennsylvania Geological Survey, entitled "Oil and Gas Region," written by John F. Carll,[59] and published in 1890, gives a conception of early theories regarding vacuum and related oil sand conditions, which should be of interest to the reader:

> It is generally understood that the strongest rock pressures obtain in the deepest wells; and the theory of hydrostatic pressure has been applied to account for the fact. No one, however, has yet been able to work out from actual observations of the

59. Carll, John F., Oil and gas region: Pennsylvania Geol. Survey, Bull. No. 15, 1890.

phenomena presented by flowing oil and gas wells, any absolute and uniform correspondence between increasing pressure and increasing depths, as compared with the immediately overlying surface or with distant elevated outcrops of the producing strata.

If an oil well is simply an artesian well, should not its flow be constant while it lasts, and dependent upon the rapidity with which the impelling water invades the oil-rock reservoir; and after displacement of the oil, ought not water to follow into the well and rise to the surface, or at least to the level indicated by the strength of its initial oil flow?

But oil and gas wells do not act in this way. The output decreases gradually and sometimes rapidly from the start; and after production has settled almost to the minimum the wells may be pumped for years and even subjected to the drafts of gas pumps without being flooded with water, provided the abandoned wells in the pool have been effectively plugged above the oil and gas rock.

It is a well known fact that the oil sand in the celebrated Triumph district, (Tidioute, Warren County, Pennsylvania), which has been under the drill and pump for over 22 years, and produced in the aggregate of fully 5,000,000 barrels of oil accompanied by large volumes of gas, is now so voided by the use of gas pumps that a vacuum gage at any of the well heads registers a downward pressure of 12-13 pounds per square inch. This had been the situation for many years, as gas pumps have constantly been in operation in that district since 1869. New wells are occasionally drilled on this exhausted belt, and it invariably happens that when the oil sand is pierced, a current of air commences to whistle down the hole, nor can oil be obtained until the well mouth is closed and a gas pump put in operation. After a few days testing, oil begins to appear, and the production frequently runs from 15 to 20 barrels a day. Then as the slight excess of fluid in the immediate vicinity of the hole drains, and an equilibrium is established, the output gradually shrinks to the level of the old wells in the pool.

The wells at Triumph are from 600 to 800 feet deep, and usually have only about 200 to 250 feet of casing in them. Consequently some four or five hundred feet of the bore hole is bare rock, equally exposed to the draft of the pump as the oil rock itself. In this uncased portion of the well are the first and second sands which also outcrop in the river hills within two miles of the exhausted pool; and one member of the second sand forms a part of the river bed a mile further north; and yet no surface water or air finds access to the wells through these sources.

Many other proofs of the impermeability of the strata above the oil rocks, and of the fallacy of the hydrostatic theory would be adduced, were it necessary. In a practical experience of twenty-three years in the oil regions I have never witnessed nor heard of a single circumstance to support it. The theory as applied to Pennsylvania oil and gas wells is delusive and untenable; and the cause of the great rock pressure witnessed must therefore be sought for in some other direction.

Ben E. Lindsly,[60] Petroleum Engineer with the U. S. Bureau of Mines has made a thorough study of vacuum problems in oil fields. His paper should be read by all persons interested in the use of vacuum on oil well properties.

Shooting to Increase Production

The practice of "shooting" or "torpedoing" oil wells is not general to all of the oil fields of the United States, but is confined largely to wells drilled into and producing from hard, close-grained sandstones and limestones which offer unusual resistance to the flow of oil into the well, as in some of the fields of Pennsylvania, Ohio, West Virginia, Kentucky, Illinois, Kansas, Oklahoma, Texas and Wyoming.

Wells are shot to stimulate production under three general types of conditions, as follows: 1st, as soon as the well is completed, to cause a "dry hole" to produce, or to increase production of a small well by breaking up the sands and creating fissures and channels extending from the well into surrounding sand strata. The shooting of small wells or dry holes in some of the oil fields of Pennsylvania and north Texas has resulted in some cases in the "bringing in" of flowing wells of 500 to 1,000 barrels initial production.

Following the explosion of a large charge of nitro-glycerin in a well, there is the concussion, the vibration of the casing, the rush of fluid, mud, and rock fragments from the well, often accompanied or followed by a flow of oil and gas. These are the observed effects of the torpedo, but contrary to general belief, the explosion does not result in the formation of a large cavity in the oil sand at the bottom of the well, as has often been shown when one of the common type of oil sand reamers has been run into a well following the explosion of a large charge of nitro-glycerin, with the result that the hole is found only slightly larger than the bit used in drilling. There is probably some shattering and cracking of the sand for a short distance back from the walls of the hole, as shown in Fig. 18 at *a*, but probably the greatest expenditure of force is towards the surface, as in most cases this is the line of least resistance. The force of the explosion in this direction would tend to lift and separate the strata at *b*, *c*, *d*, *e*, and *f*, giving opportunity for oil and gas to flow under less resistance along the bedding planes into the well, than would be the case if all of the oil and gas movement were through the sand pores into the well. If however, there are channels and openings in the sand near the well, as is often the case when limestones serve as the reservoir rock, then part of the force of the

60. Lindsly, Ben E., Use and limitations of vacuum in the recovery of oil; Amer. Inst. of Mining Engineers, Pet. Devel. and Tech., p. 158, 1926.

explosion may result in a breaking through from the well into these openings, resulting sometimes in the bringing in of a gusher after shooting. In Fig. 19 this point is illustrated.

Suppose that three wells are drilled, Nos. 1, 2, 3. Well No. 1 may be near enough to the channels in the limestone to produce small amounts of oil. Well No. 2, upon breaking into the openings will probably be a big producer. Well No. 3 may be a dry hole. If wells

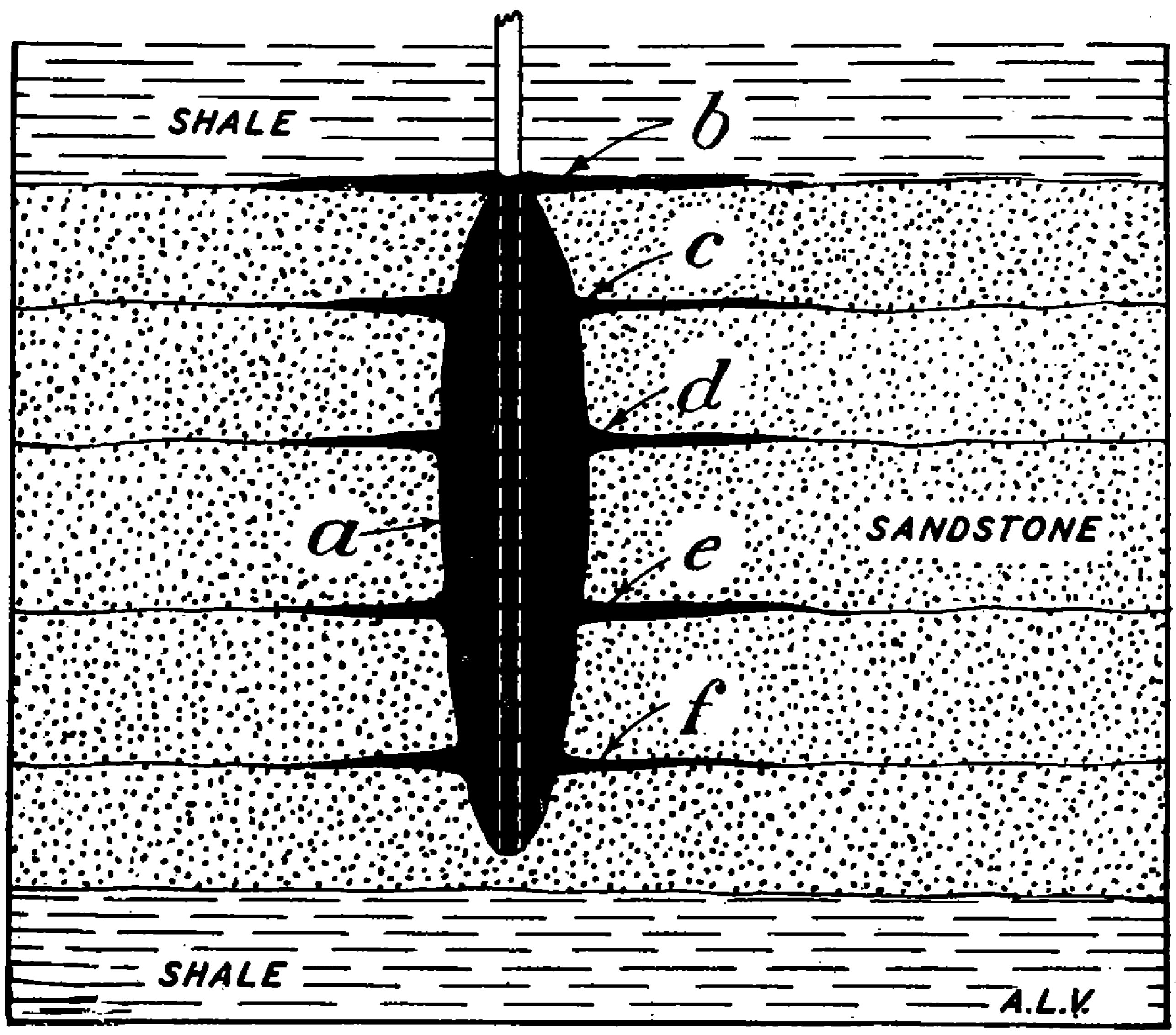

Fig. 18.—Sketch illustrating cracking along the bedding planes of an oil sand as a result of heavy "shooting."

Nos. 1 and 3 are shot they probably will become large producers like No. 2, because of the force of the explosion breaking through into the channels and openings containing oil.

Frequently large natural wells or gusher wells rapidly decline in production after a few weeks, or months, and begin to flow "by heads," with increasing length of intervals between flows. These wells on being "shot," often increase in production sometimes to an amount greater than the initial production. Sometimes wells of this type have been repeatedly "shot" at intervals with good results in increased production.

At pumping wells or wells which no longer flow, small "shots" introduced from time to time will cause the sand to cave, exposing fresh sand surfaces, will enlarge the hole within the sand, permitting of additional space for oil accumulations, and will produce sufficient heat to dissolve and eliminate accumulations of paraffin.

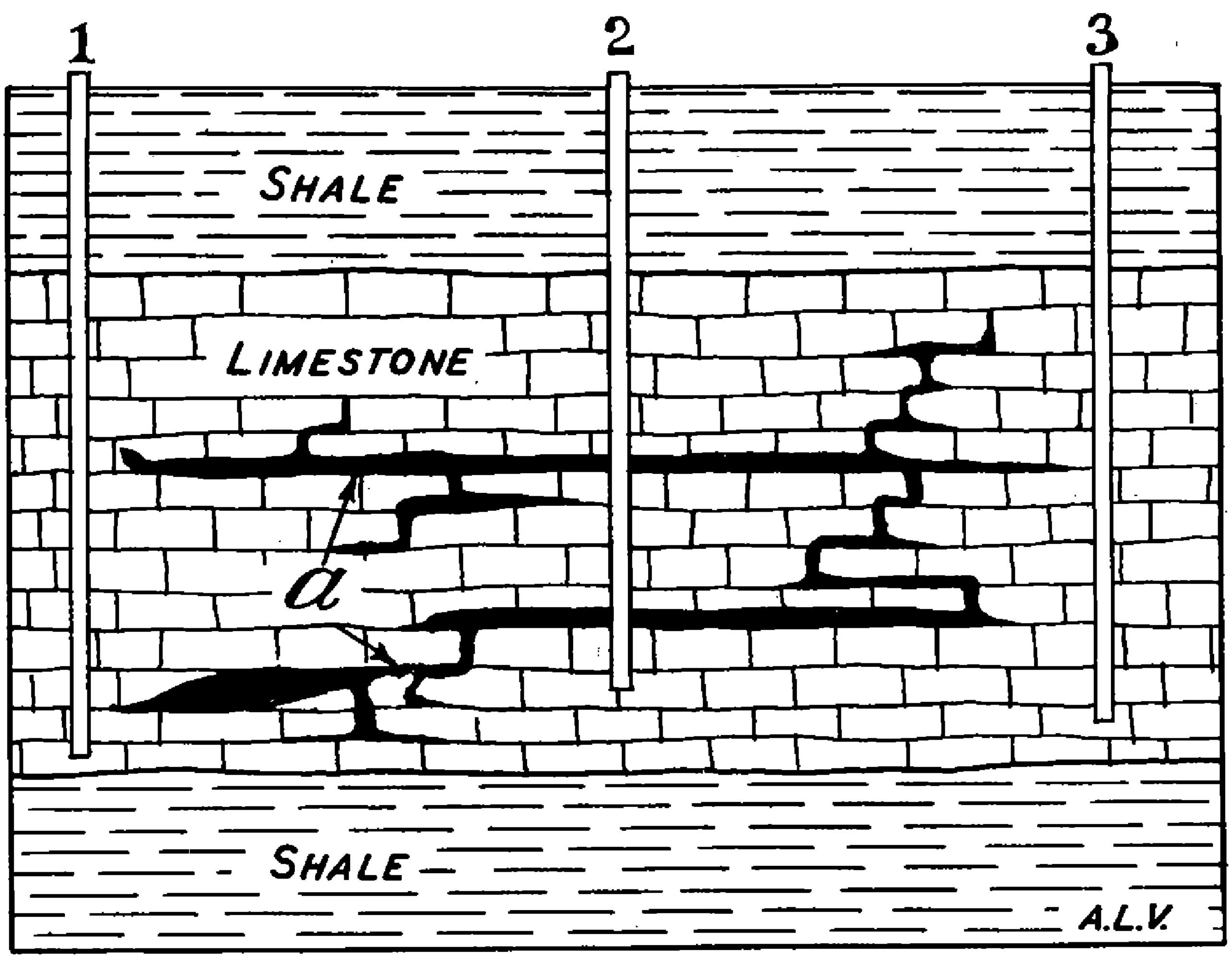

Fig. 19.—Sketch illustrating why channeled limestone "sands" are often shot. Well No. 2 will be a large well naturally, but wells No. 1 and 3 must be shot in order to become large producers.

In loosely consolidated sands, small shots will produce a series of vertical concentric cracks in the sand parallel to the drill hole and at right angles to the bedding planes. Cracks of this type can be observed in sandstone ledges and cliffs in railroad and road "cuts" subsequent to the shooting of churn drill holes. Similar cracks produced in the oil sand generally cause a considerable amount of caving, usually necessitating the cleaning out of the hole with tools. However, a much greater drainage surface is exposed in the well, and a chamber is produced which is frequently several feet in diameter for the full thickness of the sand, and which will hold several barrels of oil. Conditions of this sort are of particular value in some oil fields where the production has declined to only a fraction of a barrel of oil per day, as in many of the oil fields of Pennsylvania where the oil is allowed to accumulate in the wells for several days between pumping periods. In some of these fields the wells are pumped only two or three hours a week. As a matter of fact, the average daily production of the 60,000 wells in Pennsylvania is less than one quarter of a barrel of oil per day.

In "shooting" oil wells, care must be taken in placing the shot, and in judging the amount of explosive used, and the amount of tamping (water) to be run on top of the explosive, so that the casing and other well equipment is not damaged, and so that the formations above or below the oil sand are not shattered.

The placing of the shot too high in the hole may shatter the cap rock and overlying formations, permitting the oil and gas to escape from the sand, or permitting water from above to enter the sand, or causing shale formations to continually cave and cover the oil sand and fill up the hole so that much production is lost and frequent cleaning of the well is required.

Often when the lower part of the sand contains water, a shot placed too low in the sand may shatter the underlying formations permitting bottom water to enter the oil sand. Frequently some of the most difficult bottom water "plugging jobs" are caused in this manner.

Nitro-glycerin is the most common explosive used in shooting wells. A charge may range from 5 quarts to several hundred quarts, depending upon the hardness and thickness of the sand and the results desired from shooting.

Uren[2], Jeffery[13], and H. B. Hill[61] discuss the methods and equipment used in "shooting" oil wells. This paper describes only the purpose and effects of "shooting." For a detailed description of effective methods of shooting, the reader is referred to the Engineering Report on the Davenport Oil Field.[62]

Water Flooding to Increase Oil Recovery

The accidental flooding of oil sands at Bradford and Grand Valley, Pennsylvania by the failure to exclude water by the "formation-shutoff," or by leaking casing or by improperly plugged wells when abandoned, lead to the flooding of the oil sands and the

61. Hill, H. B., Increasing production by shooting: Amer. Inst. of Mining Engineers, Pet. Devel. and Tech. p. 101, 1925.

62. Brandenthaler, R. R., Sclater, K. C., and Kent, H. M., Engineering Report on the Davenport oil field: Report to the U. S. Bureau of Mines, in co-operation with the state of Oklahoma, and the Chamber of Commerce, Bartlesville, Oklahoma, 1926.

driving of the oil in the sand ahead of the "water flood." This discovery lead to the practice of introducing water into some wells to increase the production in others.

Water flooding has been discussed by Lewis[46], more recently in detail by Umpleby[63], and by Bossler[64]. The writers quote from the last mentioned authority as follows:

> Flooding is classed as a pressure restoration method, because the hydrostatic pressure developed by the column of water standing in the well forces the water to penetrate the sand, and to accumulate the oil ahead of it.
>
> **Bradford Pool.**—The Bradford Pool is in McKean County, Pennsylvania, and Cattaraugus County, New York. The area, according to Lewis, is 85,000 acres. These figures will be used for acre yield calculations. Production began in 1869, and to 1915 pool had yielded 230.000,000 barrels of oil, or an average of 2,700 barrels per acre. Estimating an additional production of 21,250,000 barrels to the end of 1920, gives an average yield of 2,940 barrels per acre.
>
> **Bradford Sand.**—The stratigraphic position of the pro- about the same coarseness as the ordinary beach sand of the physical characteristics of the sand Asburner says: "The Bradford oil sand is the most important economic stratum in the northern tier of counties. It consists of gray and white sand of about the same coarseness as the ordinary beach sand of the Jersey coast; compact, yet loosely cemented. The average thickness of the sand is about 45 feet, and from top to bottom the sand strata change but little in their general character. It is only when specimens from successive layers are placed side by side and closely examined that any difference in structure can be noticed. The grains of sand are angular, vary but slightly in size, color, and quantity of cementing material. which holds them together to their rock bed.
>
> The same homogeneousness which characterizes the vertical section is found to exist over a considerable horizontal area. In fact, but little change is found to exist in the sand obtained from wells 15 miles apart, or in the sand from intermediate wells.
>
> The porosity of this sand is reported to average 18 per cent. Structurally, this is one of the flattest oil fields known, dips probably not exceeding 10 feet per mile in any direction.
>
> **First Flooding.**—The first purposeful flooding in this district probably occurred about 30 years ago, and was done with the object of increasing production. The idea probably was conceived from observed results of accidental flooding. When three years elapsed after the water had been let into an old well without appreciable results, the owners sold the property, feeling that their efforts had been futile. The purchaser pumped the wells

63. Umpleby, Joseph B., Increasing the extraction of oil by water flooding; Amer. Inst. of Mining Engineers, Pet. Devel. and Tech., p. 112, 1925.
64. Bossler, R. B., Oil field rejuvenation: Bur. of Top. and Geol. Survey, Commonwealth of Pennsylvania, Bull. No. 56, 1922.

at a small profit for several years; then being alarmed at the rapid increasing production of two old wells, and having the common fear of flood, he sold out at a fair profit. The new owners, for several years, reaped a harvest in the operation of the property. Then, fearing disaster, they sold out at an increase of 25 per cent above the purchase price. This occurred in 1903, since when the property has three times changed hands, and could now be readily sold at a larger figure than was received for it 27 years ago. About one-third of this property remains unflooded.

The history of other leases is similar. Flooding was regarded as an evil until it was shown that a greater quantity of oil could be produced in this way than by ordinary methods in a definite time. However, some producers still regard it with disfavor, and only take advantage of it in self defence. Some producers have been constrained from flooding their wells by the law which requires that abandoned wells and dry holes be plugged to prevent water entering the sand. This law was construed to prohibit flooding. A recent State law, however, removed this restraint.

In addition to intentional flooding, there has been some accidental flooding through improperly plugged holes, leaky casings, etc., as evidenced by the fact that some leases, believed by the purchasers, who were old producers in the field, to be unflooded were found when drilled to be almost completely flooded.

In recent years the practice of flooding has become very general. Fully 80 per cent of the leases are partially flooded, either from within the lease or from adjoining leases. A rough estimate of the area already flooded, including the area watered-out accidentally, would be about 25 per cent.

The flooding of oil sands by water is prohibited by the laws of most states except where permission is secured through the State Corporation Commission or some other State Commission in control of such matters, and even then only after most of the operators within a given oil field are agreed that water flooding should be utilized.

Water flooding of oil sands should only be permitted after a thorough study of the oil sand and field conditions have indicated that good results will probably be secured. To determine this, among other things, it may be necessary to take a number of diamond drill cores of the sand.

In Kansas and some other oil producing states, the injudicious flooding of oil sands has in some cases ruined producing oil properties. At one property in a Kansas oil field, the introduction into the sand of creek water containing mud and silt, plugged-up the sand pores, and practically ruined the property.

Fine-grained sands of uniform texture are the ones which have generally shown the best results with flooding. Also, sands which have only small amounts of the salts of the common earth minerals; such as, the salts of calcium and magnesium, between the sand grains, are the least likely to react chemically with the water introduced to drive the oil, which may cause sufficient precipitation of mineral matter to clog the pore space. However, this is likely to occur only when "hard" waters or sodium carbonate solutions are used.

Several methods of flooding oil sands have been used in the Bradford field—the "straight line," the "five spot," and the "circular drive," the latter one being the most popular.

The "straight line" method consists of drilling a row of oil wells, and pumping them as long as they are profitable; after which another row of wells is drilled on either side of this first row, the wells in the second row being staggered with respect to the position of the wells in the first row. The wells in the first row are then kept full of water, thus driving more oil into the wells of the second row. After the second row of wells ceases to produce profitably a third row of wells is drilled and the second row is then flooded. By this method, usually two rows of wells are drilled each year. This procedure of drilling and flooding is continued until the entire property is depleted.

The "five spot" method consists of simultaneously drilling alternate rows of water wells and oil wells which are staggered with respect to each other. In this way each oil well is in the center of a square of four water wells.

The "circle drive" method has been used most frequently at Bradford. By this method, water is put into a central well, and oil wells are drilled in successively larger circles around this central well as the wells nearest the center well begin to produce water.

Umpleby[63] says that the average rate of migration of the water in the sands at Bradford is 72 feet a year; and that the recovery per acre ranges from approximately 3,400 to 7,500 barrels, depending upon the unequal saturation of the sand in different parts of the field, barren layers in the sand, and the local variation in the texture of the sand.

In some parts of the Bradford field, production has been stimulated by introducing a weak solution of sodium carbonate into the water wells. This has the effect of "cutting" the oil away from the sand grains, thus reducing the tendency for the oil to become trapped and the water to by-pass it.

While water flooding has been successful in the Bradford field, it yet remains to be proven whether it can be applied to oil fields in general. Possibly most Mid-Continent, Gulf coast, and California structures are too steep, the sands are too lenticular and variable, and there has been too much fracturing and faulting of the sands to warrant much success from the application of it. However, there are evidently certain producing areas within these fields where it might be successfully applied. A thorough knowledge of underground conditions is essential, however, because, if an oil sand is once flooded with water that cannot be controlled, the property will be practically ruined forever.

The Marietta or Smith-Dunn Compressed Air Process

Mr. I. L. Dunn, when operating in the Macksburg pool, Ohio, in 1903, observed that when gas at a pressure of 45 pounds was forced into an oil well producing from the 500 foot sand, that after ten days when the gas pressure was released, the well began to pump much oil which continued until the gas had worked out of the oil sand. The results secured in this well finally lead in 1911 to experiments with the introduction of air into a well on the Wood farm near Chesterhill, Ohio. About 150,000 cu. ft. of air at 40 pounds pressure was introduced into the well, and within a week the production of the surrounding wells greatly increased. The process was then employed in many fields in southeast Ohio, the northwest part of West Virginia, and in southwest Pennsylvania with marked success in more than 80 per cent of the places used.

Bossler[64] says regarding the use of the process in Pennsylvania: "This method was once used successfully in Bradford, but was discontinued because the natural gas was spoiled by adulteration with compressed air. The method has been in use in the Third Venango sand near Oil City for a number of years, but no data showing the results obtained were available. Some operators have discontinued its use because the gas was ruined, others because tubing and casing was destroyed. This, they believe, to be due to the pressure of air in the salt water. In most cases, however, the method has been successful with respect to the oil produced."

Lewis[46] has given a detailed discussion of the Marietta or Smith-Dunn Compressed-Air Process, which the writers quote in part as follows:

> The essential principal of the Smith-Dunn or Marietta Process is to replace the natural gas, which originally accompanied the oil, and was the principal agent in forcing the oil into the wells but has been exhausted, with compressed air. The air is forced into the sand under pressures varying from 40 to 300 pounds through some of the wells on the property, which are called "air wells", the oil being pumped from the other wells in the usual way. Any gas which does not combine with the oil chemically under conditions existing underground could be used,

but of these gases only air and natural gas are practically available. On the old, nearly exhausted properties where the process has been employed natural gas is seldom available, or only at excessive cost. And it is seldom practicable to use anything but air.

One of the most important considerations in preparing wells for taking air is to prevent the air having access to any formations other than the oil sands, otherwice large quantities of air may escape into the barren strata, and thus be wasted.

The proportion of air wells to producing wells will depend not only upon the local conditions on each property, but also on the principle on which the process is being operated. If back-pressures are being used, different factors enter into the problem than if no back-pressures are being maintained in the producing wells. Experience with the use of back-pressure indicates that the best practice is to distribute many air wells as uniformly as possible among the producing wells. More recent experience with the use of regulated back-pressures in the manner discussed elsewhere, indicates that fewer wells are necessary, and that the wells so used can be chosen by the capac.ty for taking air rather than because of their central location among a group of producing wells. The operator will decide from the system he is using and from the local conditions which practice to follow.

The three physical principles upon which the compressed air moves the oil through the sand are: first, by direct pressure; second, by the air going into solution under pressure near the air-wells and later expanding near the pumping wells; third, by the carrying of vapors.

Many producers believe that the air displaces the oil, and pushes it ahead in a solid body in the same way that a body of oil appears to be collected and driven ahead of a "water drive" in the Bradford field. At Badford a well in the path of an approaching flood gives no indication of the proximity of the flood until it nearly reaches the well, although it may be very close. The production of oil suddenly increases, and is maintained for a variable period, after which the volume of water increases quickly and ends the life of the well. In the Smith-Dunn process the air reaches the well first and is followed by an increase of production, which takes a few months to several years to reach a maximum; and during the time the process is used, air is passing through the sand continuously. The facts show that there is no "air drive" comparable to a "water drive" in the usual sense of the term, and that the air does not work solely on the displacement principle.

The writer's theory is that the oil is probably worked into a froth by the air, and bubbles are continually forming and breaking in the pores of the sand, all the time moving with the air towards the pumping wells. This condition is indicated by experiments.

In passing through the oil sand the full energy of the compressed air is not expended in actually moving oil. Some of the energy is used in overcoming the frictional resistance in the sand, and much of it is wasted, the air slipping through the sand without moving oil. This waste of energy is comparable to slippage in an "air lift" for pumping oil or water. It is "by-passing" on a small scale, and will be greatest in a coarse, open sand or with a light oil of low viscosity, and increases enormously with the progressive extraction of the oil from the sand; consequently, although the frictional resistance will be higher in a fine, tight sand, or with heavy, viscous oil, the waste of energy will be less and the actual proportion expended in moving the oil may be but little more.

The proportion of energy actually expended in moving oil may, as was previously stated, be conveniently referred to as the "efficiency of expulsion." When the sand is full of oil, the efficiency will be high; but it will become less and less as the sand is depleted, because the slippage will increase. It may be expected that the efficiency of expulsion will decrease with time as the oil is removed, in accordance with experimental results.

This loss of efficiency can be combatted by increasing the volume of the air passing through the sand, or possibly by alternately building up and releasing the pressure. By increasing the volume, the air is forced into new passages through the pores of the sand not affected previously. By building up the pressure it is expected that the oil in the tighter parts of the sand will absorb and become charged with compressed air; and when the pressure is released the air will expand and force the oil in the direction of the pumping well or towards the air passage and lines of least resistance in the formation, where the pressure will be reduced most rapidly. An intermittent building-up and releasing of pressures would tend to cause the oil to move towards the air passages and diminish "by passing" and loss of efficiency.

The passage of air through the oil sands, as previously stated is along the shortest lines of least resistance between the air wells and the pumping wells. If the sand were uniform in character the air would travel directly from an air well to each of the adjacent pumping wells through a comparatively narrow passage, leaving a large part of the sand body practically unaffected; but the variations in the character of the sand cause the air to travel through irregular and devious channels, and thus affect a larger part of the sand body. This would become more and more difficult to accomplish, and sooner or later the practical limits would be reached, although a vast quantity of oil might remain in the rest of the sand.

Because of the solubility of gases under presure and their later expansion upon release of pressure, it becomes possible to affect the oil in all parts of the sand. The air is absorbed by the oil at points of high pressure near the air wells, and moves through the oil towards points of low pressure in the same way that gas, originally dissolved in the oil, flowed towards the wells, when they penetrated the oil sand. It thus becomes possible to recharge the sand so that the oil regardless of its location, is stored with energy once more. This offers a solution for the problems arising from the variations in the sand body and the tendency of the air to follow the channels of least resistance.

It is often contended that the tighter parts of the sand contain only a negligible quantity of the oil, and that practically all production is derived from the thin pay streaks. The author does not hold to this view, for although the greatest production may have come from the pay streaks, especially during the early life of the well, the amount of oil held in the other parts of the sand, when the property has become so depleted that the air process is necessary, may be relatively many times more. Just as a tight-sand well comes in at a lower production, but holds up better than an open-sand well, so in the later life of a well with a thin pay streak, it may be the tighter parts of the sand that yield most of the production. It is often reported that in shooting old wells greater response is gotten from the tighter parts of the sand. The rich pay streak is apt to represent but a small part of the total thickness of the sand, often but 2 or 3 feet in a bed ten or more times thicker, so that although the porosity of the pay streak may be greater than the rest of the sand the total oil content may be much less.

Regulated Back Pressures.—This method is used for overcoming the difficulties caused by the irregular character of the oil sand, by which the variations in frictional resistance in different parts of the sand are more nearly equalized by holding pressures on these wells where the resistance in the sand is slight. The excessive escape of air from wells subject to by-passing is prevented, so that the air is distributed more evenly over the property and is made to do more work. The other principle upon which the use of back pressures is based is the building up of pressure in the whole area drained by the wells until the oil in all parts of the sand is charged with compressed air, so that when the pressure is released the oil will be expelled by the expanding air from the tighter parts of the sand.

The simplest method of maintaining back pressure in a well is to regulate the escape of air-gas from the casing head. A reducing valve is placed on the air-gas line, and is regulated until the excessive escape of air-gas is reduced to the average for the rest of the wells on the property. The back pressure necessary will vary with every change of conditions, and must be determined experimentally; although by closing in the well and noting the pressure, a good index of the back pressure required will be obtained, which should be nearly the same as the pressure of the well when closed-in. Maintaining back pressure by this method in a pumping well is apt to decrease the yield somewhat in the same way that production is usually decreased when back pressures are held on flowing oil wells, but this is more than compensated by the beneficial effect on the other pumping wells, for the air that formerly had passed through the sand without expending much of its energy in moving oil is now forced into other parts of the oil sand and made to do more work.

Use of Gas Pumps (Vacuum) in Connection With the Process.—Gas pumping is not commonly conducted in conjunction with the Marietta air process. Where necessary, the live wells are gas-pumped to protect the property against drainage, especially if the neighboring wells are being gas pumped, or where they are not using the air process and there is movement of air through the oil sand towards the adjoining properties. Gas pumping may occasionally be desirable at wells where the sand is much tighter than the average on the property. The tighter parts of the sand require greater pressure to force the oil through them, and by using the gas pump on wells where the sand is tight the air will be drawn towards these wells, and the movement of the air through the oil sand may be more nearly equalized over the property.

The first effects from forcing the air into the oil sand are shown by the gas. The volume is increased considerably, and the oil produced becomes livelier and shows more of a "head." These results are usually noted soon after the pumping of the air into the sand is begun, but the actual increase in yield of oil occasionally may be delayed for several months. Usually the increase in oil is closely preceded by an increase of water, and sometimes a well will produce water even if it has never before. The time required for an increase in oil production is variable. In one instance the production was increased 3½ times by the third day, but this is exceptional, and in other instances it has taken many months.

The producer should not be discouraged until the process has been given a thorough trial. The texture and thickness of the sand, the size of the field, and whether the oil sand is overlain by a former gas sand, the capacity of the compressor plant and whether it is run continuously or not, the distance between wells and the relative depletion of the oil sand, all influence the time necessary for the wells to respond to the air. Comparatively, tight sands respond more slowly than open sands, but if the sand has a large capacity it may take some time to fill it up and build up a pressure sufficient to influence production. If some wells the volume of water made fluctuates, and instances production; and if the compression plant is not large enough, much time may be needed for it to build up pressure in the sand. It is not necessary that the full quantity of gas extracted from the sand be replaced by air at the same pressure, for ordinarily it is possible to employ the air process at a lower pressure than was originally found in the field. There may be places, however, where the capacity of the former gas-bearing sand connected with the oil sand is so large that it is impracticable to use the process.

Some apprehension has been expressed that the air pumped into the same sand would unfavorably affect the quality of the oil, but repeated inquiries disclosed only one complaint by the producers on this account, and the general opinion held is that the oil is livelier. of better quality and is even claimed to be lighter than formerly. Analyses of oils affected by the air do not show any noticeably unfavorable alterations in the oils.

No increased troubles from the deposition of paraffin in the sands were reported by the operators using the air on their properties; whereas, in many instances it has been reported that the increased pressures from the air have forced much waxy material from the wells. If there is a tendency for the expanding air to cause refrigeration and deposition of paraffin, as feared by some oil men, it appears to be concentrated by the increased pressures which force the paraffin out of instead of letting it accumulate in the pores of the sand as formerly under the weak gas pressure.

The presence of the air under pressure in the sand allows the use of methods for removing the paraffin from the sand about the hole that could not be used before, as it will force out the waxes as soon as melted, instead of letting them seal up the sand, as would happen were there not a strong gas pressure in the sand.

The forcing of air through the sand usually increases the volume of water produced with the oil, but this increase is reported to be proportionate to the increase of oil, so that the ratio of oil and water produced remains approximately the same. In some wells the volume of water made fluctuates, and instances have been reported where a well will produce water almost exclusively for a while, to be followed by a period when little water accompanies the oil. Complaint seldom has been made by the users of the process because of the increase in water, as it has been proportionate to the increase in oil.

The only serious complaint made was where the process was used near Lima, Ohio, in wells producing from the Trenton limestone. Producers in this district report that normally 30 to 40 barrels of water accompany each barrel of oil produced by the ordinary method. When the air was forced through the sand the volume of water became so great in many wells that the users became discouraged and stopped the process. Whether the process will affect other fields similarly, where large quantities of water are present, is not known, because the character of the oil-producing rock, a porous limestone, is not the same as for oil sands.

Mr. Lewis further discusses, "pumping troubles often increased by using the process, effects of the air on the quantity and quality of gas, effects on making gasoline from the gas, precautions in using the air-gas, cost of using the process, fields where Smith-Dunn Process has been used, conditions under which the process has been used, failures of the process, possibilities of employing the process, and using natural gas to increase recovery." The authors refer the reader to the reference[46] for all of these subject heads except the last, which on account of its extensive use recently in many of the Mid-Continent fields, they quote in full, as follows:

Using Natural Gas For Increasing Recovery of Oil (Lewis). —In using the Smith-Dunn Process, results with natural gas seemingly should be effective in forcing oil from the sand as the use of compressed air, and in addition presents some advantages as compared with using air. The principal advantages offered by the use of natural gas are: The gas recovered from the pumping wells would not be diluted with air and the fuel value decreased; dangerous mixtures of air and gas could not be formed; on properties where natural gas was available in sufficient volume and under high enough pressure, no compressor plant would be needed; at times the exhaust gases from gasoline compressor plants could be employed without further compression.

The physical effects of air and natural gas in the sand are much the same. More of the natural gas will go into solution under the same conditions, but whether this fact would prove of importance in practical operations is not known. Apparently the air has not affected the oil unfavorably; and, so far as the writer knows, there would be little choice between air and natural gas from this cause. Theoretically, air or any other gas would carry just as much gasoline vapor as any other gas; and where it is hoped to recharge natural gas by passing it through the oil sand, propably no better results will be gained than with air.

The effect on producing oil wells of admitting natural gas into the oil sand, accidentally or otherwise, has been noted many times in the oil fields. I. L. Dunn states that it was observing such a case that led him to develop the process of using compressed air. An instance in the Cushing field, where the flow of a comparatively new well was greatly increased by natural gas from a deeper sand, getting into the oil sand has already been mentioned. It has been reported that gas under natural pressures has been used at various times to stimulate oil flow, and it is also reported that the exhaust gas from gasoline compression plants has been returned to the oil sands, principally with the idea of recharging it with the gasoline vapors.

The choice between natural gas and air will usually be decided in favor of the latter because the natural gas will not be available, or only at costs relatively prohibitive. The operating method will be approximately the same, and what has been said about operating with air will apply to the use of natural gas. If the natural gas is not already under pressure, it will have to be put through a compressor plant in the same way as air. By carefully gathering the return gas and putting it through the compressor again, it may be circulated in a closed circuit except for the wastage underground and on the surface, and the quantity used for fuel. By careful operation the wastage should not be large. In the early life of an oil field, while much natural gas is still being produced with the oil, it might be profitable to save the gas and put it back into the oil sand, by this means both accelerating and increasing the recovery of the oil.

Ben F. Lindsly[66] of the U. S. Bureau of Mines, in Report of Investigations No. 2778 has discussed the methods of operation, merits, and results of the application of compressed air to the Elliott pool in Nowata County, Oklahoma.

66. Lindsly, Ben E., The application of compressed air to the Elliott pool, Nowata

Regarding the percentage of oil that can be recovered by application of compressed air or gas to oil wells, very little is definitely known. However, the total recovery will vary from one field to the next and even on adjoining leases, since the porosity and character of the sand, the viscosity and temperature of the oil, and the bedding and fracture planes and drainage channels vary in all reservoir rocks.

In this connection, the results of laboratory experiments carried out by the junior writer may be of some interest. However, the percentage of recovery obtained in these experiments are probably higher than those obtained in actual field practice.

The two sandstones used in these experiments were a red, shaley, Permian sandstone having effective porosities of 28.9 and 32.3 per cent. Two blocks, one 12x11x8¾ inches and one 5¼x5⅜x8½ inches, were sawed and measured, so as to obtain their respective volumes. Two holes, about one inch in diameter and located about six inches apart, were drilled in the blocks to within about one inch of the bottom. A ⅜ inch nipple was placed in each hole, and then packed with lead wool to prevent the escape of air or oil. The surface of each sandstone block was given a thick coat of hot tar to prevent the escape of oil, or the incursion of water from the cement in which the blocks were placed. Each block was placed in a wooden box, and neat cement poured around them, and permitted to set for five days. Each block was completely enclosed in from three to four inches of the cement mixture.

Oil was then introduced into the sandstones through one of the two nipples extending through the cement coating into the sandstones, by constructing a three-foot "head" from ⅜ inch tubing, reducers, and a 2½ inch nipple, which could be poured full of crude oil of 42° A. P. I. gravity at intervals. It took approximately five days to completely saturate the small block, and seven days for the larger one.

After the oil had risen to a point near the top of the "recovery" holes, the saturation process was discontinued, and all excess oil in each hole was withdrawn with a pipette and measured. These amounts were deducted from the totals of oil introduced into the blocks, thus obtaining the quantity of oil absorbed in each case.

The smaller block, which had a volume of 3739.0 cubic centimeters, absorbed 1211.0 cubic centimeters of oil, thus showing an effective porosity of 32.3 per cent; while the large block of 18,-336.8 cubic centimeters in volume, absorbed 5330.0 cubic centimeters of oil, showing an effective porosity of 28.9 per cent.

Air was then passed into each stone at one of the nipples, and the oil recovered and measured at the other. A low pressure gage was placed on each in-take air line in order to record the pressure held on the sandstones at all times during the compressed air "drive."

From the small block, 693 cubic centimeters or 57.2 per cent of the oil was recovered under pressures varying from one to twenty pounds pressure over a period of one and one-half hours. From the larger block, 2579.0 cubic centimeters or 48.4 per cent was recovered under similar pressure conditions. Approximately 40 per cent of the oil in each block was recovered under pressure as low as one half to three pounds.

It was noticed that when pressures in excess of 7.5 pounds were used, the air by-passed through the bedding or small fracture planes in the sand, and very little oil was recovered. The gravity of the crude oil recovered was reduced to 41° A. P. I. This was evidently due to the absorption of the more volatile hydrocarbons of the crude by the air, and to the chemical reaction caused by the iron salts present in the red sandstone used.

In carrying out the above experiment the writers are aware that natural underground conditions cannot be produced in the laboratory. However, it is believed that the conditions under which this experiment was conducted are very similar to those generally believed to exist in oil sands; and that the results, while in excess of and more ideal than those secured in actual field practice, should be indicative of what can be expected from natural conditions where compressed air or gas is used. The two holes drilled into the sandstone blocks can be compared to two wells, and the tar and cement covering is comparable to the cap rock of a producing horizon. The wells were finished in a manner similar to commercial wells; and the air pressure represents the natural gas found associated with crude oil, or compressed air or gas as used in the Smith-Dunn or Marietta process.

While the larger per cent of recovery from the small block was due largely to the fact that its volume was many times smaller than that of the larger, thus affording less frictional resistance to the movement of the air, the difference in their effective porosities also evidently reduced the per cent of recovery from the larger block. This may be one explanation of why certain gusher wells under high gas pressure, and which are known to be producing from large-grained, loose, and highly porous sandstones, will more completely drain the reservoir rock, and thus show a higher percentage of recovery, than is usually the case where wells produce from tight sands of lower porosity under similar conditions of gas and rock pressure. Such being the case, it is probable that oil fields of large wells and high initial production secure a much higher percentage of the total amount of oil in the sand as flush production than is the case in tight sands which have much lower initial flows. Also, in such sands the total ultimate recovery will be higher, regardless of the types and methods of more complete recovery that may be applied during the economic life of the wells.

EFFICIENT OPERATION

The manner in which an oil property is operated largely determines the relative amount of ultimate production. After the wells have been properly completed, such pertinent problems as gas conservation and back-pressure, careful regulation of pumping-wells, periodic shooting and cleaning, and the prevention of water incursion are vital to the economic life of the property.

The wells that are completed in accordance with the most efficient engineering methods will ultimately produce more oil at the least expenditure of money. The wells must be drilled to the proper depth, they must be properly cased, and the nature of the local conditions of the sand at each well must be studied, in order to be able to secure the maximum ultimate production.

The engineer must have accurate records and charts which portray, as far as possible, the production history and the underground conditions at each well, so as to know how and when to begin cleaning and repair work, thus keeping the wells constantly at their maximum with the least time lost.

It is possible in many depleted oil fields to clean out old wells and drill to a deeper sand which is known to be productive, providing that the old wells are properly cased and in good general condition. This eliminates the necessity for drilling new wells for deeper sands.

Intelligent Regulation and Variation in Production Methods

The ideal method of operating properties would be to drill only the upper sand wells first; and produce from them until they are depleted, regardless of how prolific deeper production might be, then deepen the well to the next sand. However, under our present practice such a drilling program is hardly advisable; that is, unless neighboring operators agree to follow such a program. This procedure would have two distinct advantages: It would save much unnecessary expense in drilling, and it would offer opportunity to more easily control the future supply, thus reducing surface storage costs.

The drainage of more than one sand into the same well at the same time is not advisable. However, some operators producing from a series of broken sands, as in the Graham oil field of southern Oklahoma, have claimed that the production from any one sand would not pay for the drilling of the well. So the practice in this field has been to produce from a series of sands by means of a perforated liner.

One disadvantage of producing from a series of sands in the same well appears when the area of production is greater in some of the sands than in others. Edge wells will begin to produce water from the first sands drained of oil, and in many cases flood sands still producing oil resulting in the entrapping and loss of much production which would be otherwise recoverable.

Another disadvantage is that the different sands are probably under different pressures, so that a back-pressure suitable for the best production results from one sand, may cause gas and oil from this sand having the higher pressure to enter the other sand or sands. Also, repressuring projects are not so likely to be successful when the well is producing from a series of sands.

Much work is being done by producers in all sections of the country in trying to find the most efficient method of flowing wells, and the method which will cause them to flow for the longest period. This is a difficult task, because no two wells are exactly alike. Sand conditions, volume and pressure of gas present, hydrostatic pressure, per cent of saturation, viscosity of the oil, and position of the well upon the structure may differ from well to well; so that each well and each field presents individual problems.

The usual method practiced is to permit open flow through the casing. The wells are drilled into the sand, and are permitted to make as much oil as they possibly can. As the gas volume and rock pressure are rapidly depleted, the well must be agitated, swabbed, or shot in order to stimulate such flow. Such a manner of flowing a well might be classed as wasteful, since the expulsive force of the gas is soon released, thus hastening the time when the well must be placed on the pump. In most instances it would be much better to hold back-pressure on all flowing wells, thus conserving the gas and rock pressure. This may be done by tubing the well, using back-pressure valves, by stop-cocking, and by flow-nipples or "beans." The amount of back-pressure to be held on a flowing well, however, will depend on the variable conditions at each well. This method of holding back-pressure on wells will be detrimental to those operators using it unless the adjoining lessees are using a similar process of pressure control.

It is common practice to flow the well through tubing after it will not longer flow through the casing. This is done by lowering tubing into the casing, and packing off the space between the casing and the lower end of the tubing with some sort of packer. However, the packer may be placed at the casing head if the well is cased down to the top of the oil sand. Since the tubing affords a smaller conductor, the same expulsive energies will cause the well to flow again. In most Mid-Continent fields the wells will flow through tubing for several months after they have ceased to flow through casing.

Occasionally such wells will not flow through tubing. This is because the gas volume and rock pressure are too completely exhausted during the open-flow period before tubing was installed. This again, is a case where conditions at the individual well or more probably in the individual field are the controlling factors.

Back-pressure and flowing through nipples or "beans" may be used on wells flowing through tubing, the same as on wells that are flowing through the casing. Stop-cocking, however, is most applicable to wells that have been tubed.

The flow nipple or "bean" is simply a restricted opening in a steel nipple that is placed in the flow line leading from the well, or in the tubing. Diameters of various sizes may be used, depending upon the size of the line, volume of oil, gas pressure, temperature and viscosity of the oil. This method introduces friction in the flow line which retards the rate of flow, reduces the velocity of the oil into the casing, and therefore reduces the ability of the oil to carry sand along with it. This process practically eliminates the sanding or bridging of flowing wells, reduces operating costs, and effects a much more beneficial utilization of the gas pressure, so that more of the oil is produced during the flowing life of the well than would be without the use of "beans."

Stop-cocking is a process of alternately closing-in and re-opening a well, permitting enough oil to accumulate during the shut-in period to cover the bottom of the tubing and maintain a steady flow during a short period when it is open. The well should be opened for flow as often as possible, so that the gas pressure will not build up so high as to reduce the flow of oil. Automatic stop-cocking valves will open and permit the well to flow when a certain amount of gas pressure is registered, and then close after the gas and oil have been expelled.

The gas-lift is simply a modified form of the air-lift, which has been used for many years in flowing deep water wells, the principal difference being that natural gas when available is used as the lifting medium instead of air. The process was first used for lifting oil, at Baku, Russia in 1899.

McLaughlin[67], Reid[68], Peterson[69], Brewster[70], and Uren[71] have published some interesting articles on the gas lift.

Bennett and Sclater[72] have discussed the effects of such factors as temperature, surface tension, gravity, and viscosity of the oil, as well as solubility of gas in the oil and pressure within the sand, upon the operation of the gas-lift.

In the Goose Creek field[73] of Texas, the air lift was first successfully used five or six years ago to secure the production of non-flowing wells which were capable of producing much more oil than could be lifted by pumping.

In the Seminole oil field of Oklahoma, as much as 50 per cent of the gross production has been estimated to be due to the use of the gas lift.

Whether or not the use of the gas lift increases or decreases the ultimate production of an oil field is not known, but it is evident that its use has greatly increased the production of many oil well properties, but perhaps at the expense of the production of other properties.

The flowing of crude oil from the sand by means of compressed gas or air, is usually effective under conditions where there is a high fluid level in the well, but insufficient quantity and pressure of natural gas to cause the well to flow naturally.

If a well does not flow naturally, without the use of the gas or air lift, it would be necessary to secure the production by bailing, swabbing or pumping. However, by these methods, the amount of oil that can be produced is a much smaller amount than can be produced by the air or gas lift, if the oil flows freely into the well in sufficient amounts.

The efficiency of the pumping equipment at each well greatly influences the total amount of oil that can be pulled from the wells on the lease or in the entire field. The pump must be of the proper size, the valves must be replaced when worn or corroded, and the barrel must be kept at the proper height in the well in order to

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69. Peterson, Frank, Improving the use of the gas-air lift: Oil and Gas Journal, May 5th, 1927.

70. Brewster, Frank M., Use of air and gas in oil recovery: Oil weekly, May 20, 1927.

71. Uren, Lester C., Increasing oil recovery by conserving gas pressure: the gas lift: Nat. Pet. News, Mar. 23, 1927.

72. Bennett, E. O., and Sclater, K. C., Volume and pressure control for wells on gas-lift: Oil Weekly, Feb. 25, 1927.

73. George, H. C., Surface machinery and methods for oil well pumping: U. S. Bureau Mines, Bull. No. 224, p. 95-97, 1925.

drain the sand uniformly, with the proper amount of fluid resistance to the flow toward the well; that is, the pump should keep proper pace with the well's production. By properly controlling the fluid level in pumping well, the oil may be skimmed off from any bottom water that may exist in the sand.

The length of the pumping stroke must be regulated to be in adjustment with the relative amount of water or gas present, and to prevent as far as possible the slippage and vibration of the equipment which results in broken sucker rods and a minimum of oil produced. Long, slow strokes are better; as short, fast strokes cause greater vibration, and tend to emulsify the oil. Also, it is necessary to use long strokes if the well is producing much water with the oil. It is better to pump a well slowly and continuously, yet maintain a steady drain on the sand than to "pump it off" quickly, which necessitates the well's standing idle for probably half a day or longer.

Uren[45] has discussed "Problems of Pumping Deep Wells." His paper discusses both equipment and methods.

Production Methods of the Future

Many of our oil fields, especially the older ones are operated under conditions of faulty and deficient information regarding structural and sand conditions, and with equipment which has become antiquated in service. To such oil fields which have declined to almost the economic limit of production, there is little probability that the installation of improved methods and equipment which would entail any great expenditure of money, would be warranted.

Certain types of oil sands will respond to repressuring, others will respond to the water drive, and still others may respond to the use of vacuum; but in most cases oil sands which have been exhausted by pumping methods now in use, will probably never make an economical return on further expenditures on new methods and equipment.

The conservation of our petroleum resources lies chiefly in the efficient operation of our more recently discovered fields, which have been developed with the use of more improved equipment and a better knowledge of structural and sand conditions.

The development and operation of these newer fields can only be done efficiently by giving careful attention to the individual well, not forgetting its relation to other wells in the field, and by the closest cooperation among the operators in the same field.

ULTIMATE PRODUCTION

HOW MUCH OIL IS RECOVERED?

A question that is often asked, and yet never satisfactorily answered is, "What part of the oil originally existing in the reservoir rock is recovered by methods now in use?"

Before the geologist or petroleum engineer can estimate how much oil is or can be ultimately recovered from a sand, he must know approximately how much oil a particular type of sand might contain. This is usually calculated in the following manner: In order to obtain the most accurate estimates, representative core samples should be taken at intervals of one foot throughout the thickness of the sand. Enough cores should be taken from the various wells on the property to be able to ascertain the average thickness of the sand under the entire lease, as well as the average porosity of it.

After the average thickness and porosity have been calculated, it is necessary to know the per cent of saturation; that is, what part of the pore space is filled with oil. For the methods used in these procedures, the reader is referred to A. F. Melcher's[26] article entitled "Determination of Pore Space in Oil and Gas Sands."

RECOVERY PER ACRE-FOOT

With the above information at hand, it is then easy to figure the probable amount of oil that is under the lease. This is usually figured in barrels (42 gal.) per acre-foot.

As an example, suppose the average thickness of a sand under an eighty-acre lease has been found to be forty feet, and that the lower ten feet is saturated with bottom water. This would leave thirty feet of sand that contains oil. If the sand has an average porosity of 18.5 per cent, and this pore space (18.5%) is 70 per cent saturated with oil, the volume of oil contained in one cubic foot of sand would be 223.7 cubic inches or .97 gallons [(1,728 cu. in.x18.5%-x70%, ÷ 231 cu. in.]. Then, since there are 43,560 square feet in one acre, there would be 43.560 cubic feet in one acre-foot. Multiply 43,560 cubic feet by .97 gallons, the volume of one acre-foot would be 42,253.2 gallons, or 1,006.0 barrels. If the average thickness of the oil-saturated part of the sand is thirty feet, there would be 30,180 (1006.0x30) barrels of oil under one acre of the lease. Then it would be approximately correct to say that the sand under the entire lease contains 2,414,400 (30,180x80) barrels. Granting that only 25 per cent of this oil will be recovered by flowing and pumping, the property would yield about 603;600 barrels, thus leaving 1,810,800 barrel in the sand.

ULTIMATE RECOVERY

For further information as to the estimation of oil sand capacities and ultimate recovery, as well as the calculation of future decline of production, the reader is referred to "Some Principles Governing the Production of Oil Wells" by Lewis & Beal[74], and to "Estimation of Underground Oil Reserves by Oil-Well Production Curves," by Cutler.[75] "The Manual of the Oil and Gas Industry"[76], also gives some valuable information regarding underground reserves and future production.

It is generally believed by the majority of petroleum engineers and geologists that on the average 50 per cent of the original amount of oil in an oil sand can be removed by our present methods of flowing and pumping. There is, however, a wide diversity of opinion on this question, especially among practical oil men. Their estimates seem to range from 10 to 90 per cent; whereas, laboratory experiments have secured ultimate recovery data ranging from 12½ to 85 per cent, depending upon the texture and bedding of the sand, and the gravity and viscosity of the oils used.

One interesting example is that of Pechelbroon, Alsace[77]. After the wells had been pumped for ten years, shafts were sunk to the oil sands, tunnels driven through them, and the oil still remaining in the sand was permitted to drain into ditches and sumps. The methods of recovery used there proved that 83 per cent of the oil still remained in the sand after pumping ceased.

This large amount of oil retained in the sands at Pechelbroon was doubtless due to several factors. There was very little gas associated with the oil, which was of high specific gravity, and the "sand" or reservoir rock is very fine and contains clay locally.

Melcher[78] found from actual determination of oil and water content remaining in core samples taken from the Bradford sand of Pennsylvania that fully two-thirds of the oil still remained in the sand after pumping was discontinued. Swigart and Templeton[79] state that about 25 per cent of the oil is recovered by flowing and pumping. This estimate was based upon their experience in the Mid-Continent and California fields. It has been estimated that flowing and pumping secure as much as 50 per cent of the total amount of

74. Lewis, J. O., and Beal, C. H., Some principles governing the production of oil wells: U. S. Bureau Mines, Bull. No. 194.
75. Cutler, W. W., Estimation of underground oil reserves by oil well production curves: U. S. Bureau Mines, Bull. No. 228.
76. Manual of the oil and gas industry for 1921: Treasury Dept., U. S. Internal Revenue, Government printing Office, Washington, D. C.
77. Rice, G. S., and Davis, J. A., Mining petroleum in France and Germany: Amer. Inst. of Mining Engineers, Pet. Devel. and Tech., p. 278, 1925.
78. Melcher, A. G., In supply and demand: Report of Amer. Pet. Inst. McGraw-Hill Book Co., p. 101, 1925.
79. Swigart, T. E., and Templeton, R. R., In supply and demand: Report to Amer. Pet. Inst., McGraw-Hill Book Company, p. 101, 1925.

oil in the sands of south Texas and Louisiana. In these areas the sand is coarse-grained, loose and unconsolidated. It is probable that as much as 90 per cent of the oil may be recovered in areas where the production comes from fissured shales and water-channeled limestones.

Frank Haskell[80] of the Tidewater Oil Company, who has had many years experience in the Bradford field where flooding has been used for more than 30 years, states that flooding yields approximately 126 per cent of the yield secured by pumping. Bossler[65] has obtained results of increase in production due to flooding the sands at Bradford, and states that the average increase as a result of flooding is approximately 5,000 barrels per acre on seven properties under observation.

J. O. Lewis[46] estimates the recovery by use of compressed air as 4,000 barrels per acre on 100 different properties; being 50 per cent of the total recovered by flowing and pumping.

However, present methods of applying compressed air to wells will doubtless secure much more than this amount. Bossler[65] states that the application of compressed air to five different properties in Ohio increased the production 14, 61, 71, 71, and 95 per cent respectively above that secured previously by flowing and pumping.

At the present time very little data are available regarding the percentage of recovery obtained from sands where the air-gas lift has been installed.

OTHER SOURCES OF OIL

MINING OIL SHALE AND OIL SANDS

If the present increase in the rate of consumption of crude oil remains practically constant, the time is not far off when it will be necessary to extract oil from the vast shale deposits of the world.

However under the present prices obtained from the sale of petroleum products, the mining of oil shales and sands would not be profitable. Only when the cost of recovery of oil and gasoline from shale, coal, and lignite will permit oils and gasoline from these sources to be sold in competition with similar products from present sources of crude oil supply, will these products be commercially available.

The methods of mining oil sands now in use or advocated are in reality not strictly mining methods, except that a shaft must be sunk to the oil sand and drifts driven and ditches and sumps made

80. Haskell, Frank, In supply and demand: Report to Amer. Pet. Inst., published by McGraw-Hill Book Co. p. 104, 1925.
65. Bossler, R. B., Bulletin No. 36, Dept. of Internal Affairs of Pennsylvania.

in or below the oil sand for the accumulation of the oil draining from the sand. Only such oil sand is actually mined as is removed in the driving of the drifts.

When one considers that a fully saturated oil sand of 10 per cent porosity contains only 10 gallons per ton, one of 20 percent porosity contains only 21 gallons per ton and one of 30 per cent porosity contains only 32 gallons per ton, the absurdity of considering the mining of depleted oil sands which will probably contain less than 10 gallons of oil per ton, is apparent, under present conditions.

The writers are of the opinion that many of our large deposits of oil shale will be mined and oil extracted economically, long before the actual mining of any of our oil sands proves profitable.

The Ranney process of Mining Oil Sands[81] and the Mining operations of Pechelbronn, Alsace[77] are described in "Petroleum Development and Technology for 1925."

The following data regarding the amount of oil shale, coal, and lignites available in the United States have been copied from "Supply and Demand," published by the American Petroleum Institute in 1925:

> The total amount of oil shale is about 394,000,000,000 tons, from which can be recovered about 108,000,000,000 barrels (42 gal.) of crude shale oil. From this crude shale oil, about 25,000,000,000 barrels of motor fuels, including straight run and cracked products, can be obtained.
>
> The quantity of coal within 6,000 feet of the surface is estimated at 3,100,000,000,000 tons. The maximum amount of liquid products that can be secured therefrom is estimated at about 2,000,000,000,000 barrels. The estimated commercial yield of motor fuel from the above liquid products would be about 92,000,000,000 barrels.
>
> The quantity of lignites available is estimated at about 986,000,000,000 tons. From this about 70,000 000,000 barrels of liquid products would be obtained, and of this about 12,000,000,000 barrels could be used as motor fuel.
>
> There is reason to believe that satisfactory lubricating oils will be obtained from shale oil. Regarding lubricating oils from coal and lignite tars, it is not so promising, but future developments will probably show improvement.
>
> There are in the United States several types of rock which do not contain free oil, but which will yield oil when heated. or in other words, when subjected to pyrolysis. These oil-yielding materials may be listed in order of importance, as follows:

81. Ranney, Leo. The Ranney process of mining oil: Pet. Devel. and Tech. p. 315, 1925.

(1) Laminated shale of the Green River formation in Colorado, Utah, Wyoming, and Nevada.

(2) Cannel coal, canneloid lignite, and canneloid shales.

(3) Black shales of the Devonian and Carboniferous formations of the eastern part of the United States.

(4) Black phosphatic shale of the Rocky Mountain region.

(5) Dark shales of the Cretaceous and other formations.

Of these, the shales of the Green River formation are by far the richest and most extensive, and therefore of the most immediate interest.

Oil shales are known to occur, and have been described in 18 states: Indiana, Illinois, Kentucky, Maryland, Ohio, Pennsylvania, Tennessee, West Virginia, Arkansas, California, Colorado, Idaho, Utah, Montana, Missouri, Nevada, Wyoming, and Oklahoma. Of these, Colorado, Utah, and Wyoming are the most important as to quantity, quality, and facility for mining.

The oil content of the shales varies with different beds in the same locality, and also in different places along the outcrop from a minimum of about one gallon per ton to a maximum of 90 gallons per ton. Samples analyzed by the U. S. Geological Survey showed the following results:

42 samples—less than 10 gal. per ton.

71 samples—10-20 gal. per ton.

42 samples—20-30 gal. per ton.

21 samples—30-40 gal. per ton.

18 samples—above 40 gal. per ton.

Regarding the estimated oil per acre, 2,178 tons of shale will cover an acre of ground to the depth of one-foot, and it is estimated that there are 3½ million acres of shale in Utah, Wyoming, and Colorado. Shales covering this area are placed at 2,000 feet thick. and the Green River deposit is of equal thickness, totaling 4,000 feet in all. With 2,178 tons per acre-foot, the oil content per acre is estimated by W. L. Martin[82] as being about 2,178 barrels per acre.

82. Martin, W. J. Montana State Mineral Age, 9, No. 7, 1924.

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