PROGRESS REPORT ON A SUBSURFACE STUDY OF THE PERSHING OIL AND GAS FIELD, OSAGE COUNTY, OKLAHOMA.

By W. W. Rubey.

INTRODUCTION.

The Pershing oil and gas field lies in the east-central part of Osage County, Okla., and includes the area around the common corner of Tps. 24 and 25 N., Rs. 9 and 10 E. The small station of Pershing, which is in the field, is about 4 miles southwest of Nelagoney, 7 miles west-northwest of Bigheart, 4½ miles northeast of Wynona, and 6 miles southeast of Pawhuska. The Missouri, Kansas & Texas Railway right of way passes through the field in a general southwesterly direction. The area considered in this report is bounded by the rather arbitrarily chosen limits of the "drainage area" of the North Cochahee and South Cochahee domes as indicated in U. S. Geological Survey Bulletin 686.[1] (See Pls. VII and VIII.) As thus outlined, the area is greater than that of the field itself, at least in a northeast-southwest direction,[2] but because of the relative scarcity of deep wells in the outlying parts of the area, the study of underground conditions was confined almost entirely to the part of the area in which oil or gas has been produced.

The field work was done in parts of January and February, 1921, by W. W. Rubey, with the assistance of Mrs. Rubey. The locations and elevations of all wells were determined by plane table with telescopic alidade; samples of the oil, gas, underground waters, and formations penetrated in drilling were collected; and copies of the logs, statistics of production by months, and other well data were made from the files of the Osage Indian Agency at Pawhuska and of several oil companies operating in the field.

[1] Bowen, C. F., Structure and oil and gas resources of the Osage Reservation, Okla., T. 24 N., R. 10 E.: U. S. Geol. Survey Bull. 686–D, pl. 5, 1918; Heald, K. C., T. 25 N., R. 9 E.: Bull. 686–E, pl. 7, 1918; Winchester, D. E., Heald, K. C., and others, T. 25 N., R. 10 E.: Bull. 686–G, pl. 10, 1918; Heald, K. C., Bowen, C. F., and others, T. 24 N., R. 9 E.: Bull. 686–P, pl. 32, 1919.

[2] The area lying about the Saucy Calf anticline, in secs. 25, 26, and 35, T. 25 N., R. 9 E., is sometimes included within the Pershing field. See Snider, L. C., Oil and gas in the Mid-Continent fields, p. 212, 1920.

The writer wishes to acknowledge his indebtedness to the office personnel of the Osage Indian Agency and to the individuals and the oil companies who so generously supplied assistance in obtaining information. He is also indebted to his colleagues of the United States Geological Survey, especially to K. C. Heald, for many valuable criticisms and suggestions.

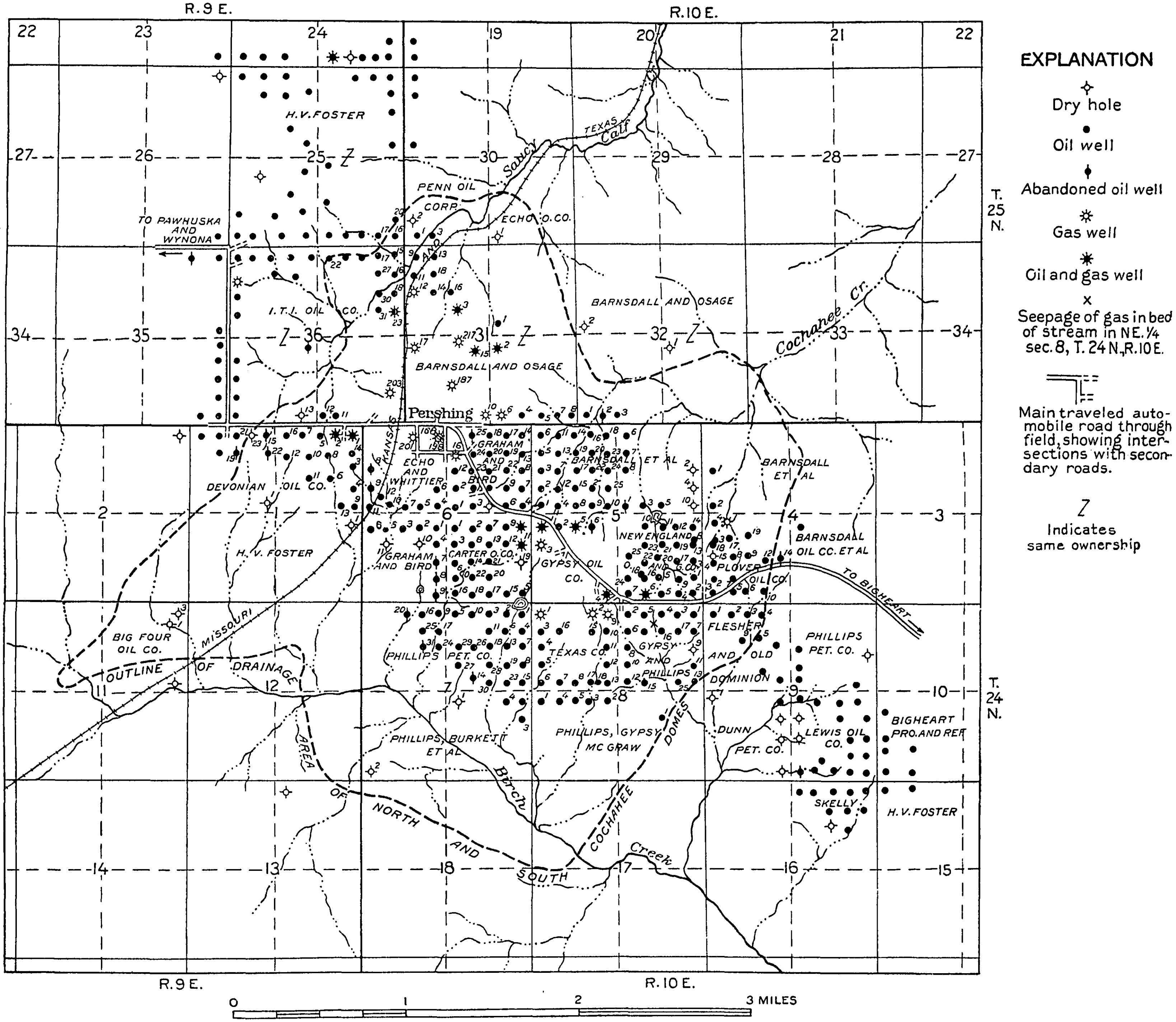
The purpose of the study was to point out to oil and gas companies the advantages that may accrue from a free interchange of information, to examine in a quantitative manner the importance of many factors bearing on structure, stratigraphy, and production, and to discover, if possible, relations of facts that might be of value in the future development of more or less analogous areas. Except in the orientation of the fault that cuts the surface beds, the Pershing field seemed to be a fairly typical Osage County oil field, and this fact, together with its central location and relative completeness of development, led to its choice as the object of this study.

This report is merely a preliminary statement of some of the more firmly established results thus far obtained and does not purport to be final in any particular. Many of the findings of the investigation are not yet coordinated with one another, but it is felt that a series of comprehensive explanations made while a study is incomplete might unduly affect interpretations to be made later. Work now in progress and to be done in the future may be expected to show that some of the relations here suggested should be modified and to throw additional light upon or add confirmatory evidence to many of the conclusions here tentatively set forth. In addition, the partial but unproved results of incomplete studies and the methods developed in attacking other problems are herein briefly discussed, so that those now engaged in similar investigations may have access to the information obtained and may have an opportunity to suggest other lines of study that would make the final report more nearly complete and more accurate.

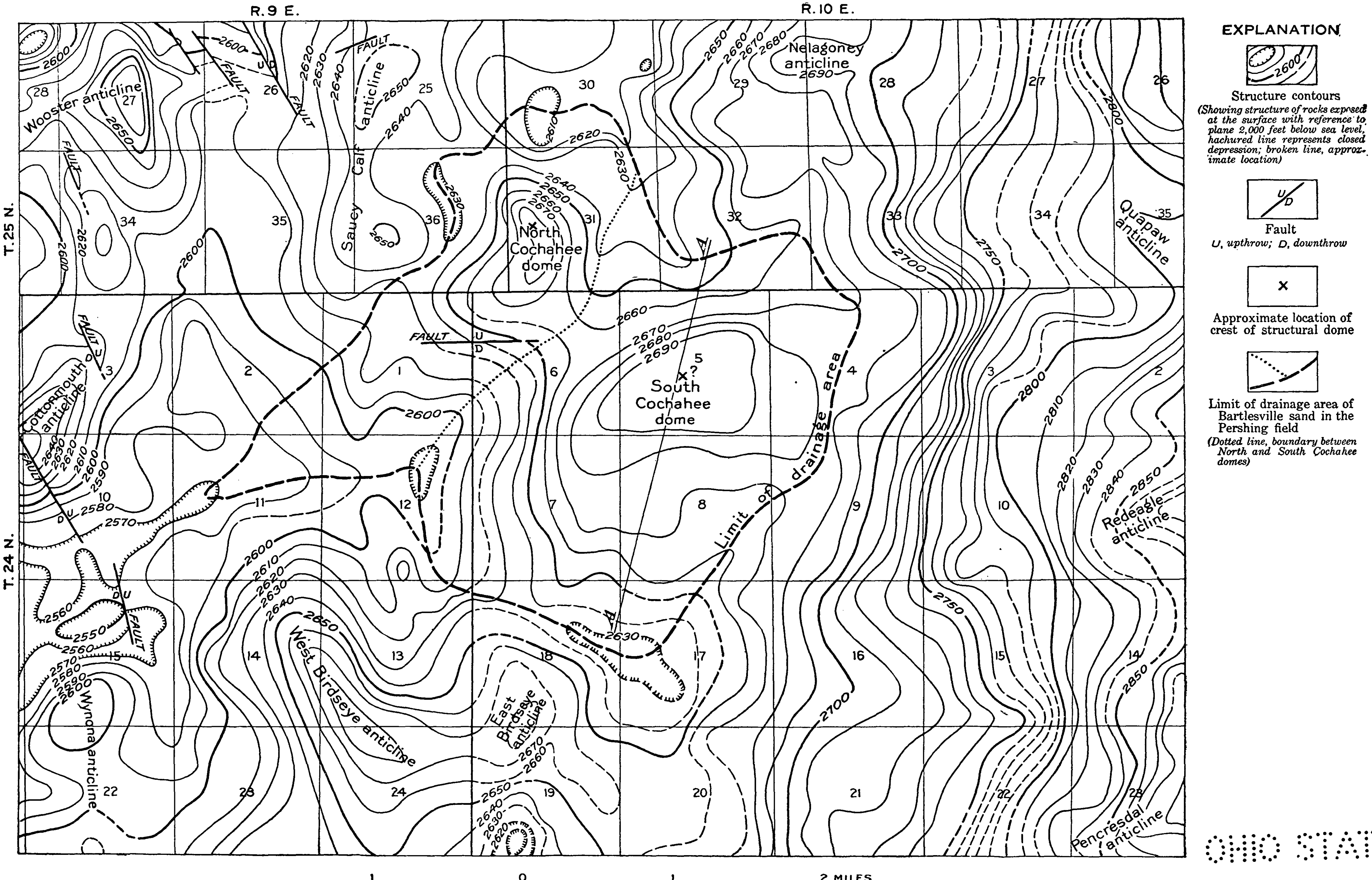
METHODS OF STUDYING WELL RECORDS.

The preparatory work that was done to put the information obtained into convenient form for use consisted of plotting graphically the logs of all the wells in the field and assembling important well data, such as elevation, location, distinguishing name and number, date of completion, and initial production. The blank forms on which the logs were plotted are drawn on the scale of 100 feet to the inch, and each 10 feet is represented by a horizontal line.

Strata that were recorded by the drillers as lime, sand, and coal were marked in ink on the graphic log with the conventional symbols for limestone, sandstone, and coal, respectively. "Shells" were



MAP OF PERSHING OIL AND GAS FIELD, OSAGE COUNTY, OKLA.



STRUCTURE CONTOUR MAP OF THE ROCKS EXPOSED IN THE PERSHING OIL AND GAS FIELD, OKLA., AND VICINITY.

usually interpreted as calcareous beds and were so shown. The parts of the logs for which the drillers reported shale, slate, and "breaks" were left blank of lithologic symbols to save time, but any beds whose colors were recorded were indicated with suitably colored crayon, for it is felt that this information is of much value in correlation. Records of occurrence or traces of oil and gas were indicated by green crayon and of water by yellow crayon on the right-hand sides of the logs, to avoid the confusion which might arise, for example, between yellow sandstones and water-bearing sandstones. The reported depths to the tops and bottoms of the strata were placed opposite the bounding lines drawn in the graphic well records, and the full drillers' descriptions (including, for instance, the hardness) of the beds were written in the appropriate positions.

Further data, such as company and lease names, well number, location (direction and distance from section corners, quarter section, section, township, and range), date of drilling, and elevation, were written on the well logs in the spaces provided. From the determined elevation of the well mouths horizontal lines representing mean sea level were drawn on the plotted logs.

Practically the entire procedure as just outlined is that unofficially adopted by the Geological Survey for work with well logs and closely follows in detail the methods that have been used in office work for previous reports on Osage County, Okla. It is thought that this method, although somewhat more laborious at the outset than some other methods which are used, furnishes a more satisfactory means of graphically recording complete data of the type used in geologic work and gives a finished product that may be more readily referred to at a later time.

In correlating the beds shown in some of these graphic well logs several cross sections were constructed through parts of the field where wells are closely spaced, and lines connecting all the strata that could be traced from one well to another were drawn. The upper surface of the "Oswego lime" (an easily recognizable bed), being used as a reference horizon, an average or composite log (see fig. 5) was constructed by choosing what were considered normal intervals to all the beds above and below it. Obviously, as the data from all the wells were not considered in preparing this average section, it is subject to minor revisions, but it served as a valuable guide in recognizing beds in the other well records.

The remainder of the correlating was done by "matching up" logs of wells near together and thus identifying the more important strata reported in each well. The lines represented by these "log to log" correlations were arranged to pass near wells in which the formations had been previously recognized, and these lines invariably started from and ended with logs of wells represented in the cross sections, so that the danger of one inaccurate correlation causing all subsequent ones to be erroneous might be lessened. It was found advisable to bear in mind the elevation of the wells that were being correlated and to restudy carefully records that indicated large relative variations in the elevation of key beds. It was also found to be helpful to prepare a structure contour map of one of the deeper-lying beds while the correlations were progressing, as this drew attention to apparent discrepancies between the structure of the surface beds and that of the bed contoured and demonstrated the advisability of corroborating conclusions that had been reached. The correlation work was thus spread from the cross sections until the entire field had been covered. The elevation of certain beds was then determined, and structure contour lines were drawn.

GENERAL FEATURES OF THE REGION.

History of development.—The first attempt to find oil or gas in this region was an unsuccessful well drilled late in 1906 to a depth of 2,162 feet by the Pochequette Oil Co. in the NW. ¼ sec. 1, T. 24 N., R. 9 E. The next development work in the region consisted of the drilling of several small oil wells in 1914 near the common corner of secs. 25, 26, 35, and 36, T. 25 N., R. 9 E., in the area about the Saucy Calf anticline, outside the area here discussed. Late in 1915 and during 1916 other small oil wells and a few gas wells were drilled in this same locality, and dry holes near the crest of the Saucy Calf anticline and in the SE. ¼ sec. 7, T. 24 N., R. 10 E.

In 1917 four gas wells were drilled in the Pershing field on and near the North Cochahee dome, with initial production ranging from 5,500,000 to nearly 20,000,000 cubic feet. The first of these—the Echo & Whittier No. 1 (now Indian Territory Illuminating Oil Co. No. 168)—in the NW. ¼ sec. 6, T. 24 N., R. 10 E., was completed March 23, 1917, with an initial production of 5,500,000 cubic feet of gas from a depth of about 800 feet. The other wells found additional gas reservoirs at depths of about 1,600, 2,000, and 2,400 feet. In this year also several successful oil wells were drilled in the Saucy Calf area, a few of which showed initial 24-hour yields of 1,000 barrels or more.

In the first half of 1918 a few gas wells yielding small amounts of oil were drilled in the Pershing field, but important oil production was not obtained until June 22 of that year, when the Echo & Whittier No. 4, in the same quarter section as the "discovery well" of gas, was completed with an initial daily production of 390 barrels of oil and 10 barrels of water from a depth of about 2,050 feet. Many successful wells with initial production of as much as 2,000 barrels were drilled during the later part of 1918, most of them near the center of sec. 6, T. 24 N., R. 10 E., although both oil and gas were found at this time farther south on the South Cochahee dome. Field work for the parts of United States Geological Survey Bulletin 686 covering this region was done late in 1917 and in the spring and summer of 1918, and these reports were published late in 1918 and early in 1919.

The year 1919 witnessed the rapid expansion of the field. About 175 wells were drilled, and the outlines of the field were then roughly determined. The largest oil producer in the field—the No. 8 well of the Carter Oil Co., in the SE. ¼ sec. 6, T. 24 N., R. 10 E.—was completed in January of this year with an initial yield of 5,500 barrels a day.

During 1920 the field was extended very nearly to its ultimate limits. The extension of the oil-producing area northwest of the North Cochahee dome and the renewed drilling activity in the Saucy Calf area were the important features of the year.

In 1921 but few wells were drilled before the general retrenchment program of the petroleum industry virtually stopped oil-field development everywhere.

About 250 wells in the Pershing field and 75 in the Saucy Calf area have produced oil, and 15 or 20 wells, most of which are in the Pershing field, have produced only gas. The average initial production was slightly less than 200 barrels of oil in both fields and about 4,000,000 cubic feet of gas in the Pershing field and 1,500,000 cubic feet in the Saucy Calf area.

Topography.—An irregular, partly dissected ridge traverses the field from northwest to southeast and is bordered on the southwest by the Birch Creek valley and on the north and northeast by the valleys of Saucy Calf and Cochahee creeks, respectively. The hill slopes are fairly gentle, and the relief between the uplands and the larger valleys is 125 to 150 feet. The country is largely treeless, although the lower land in the western part and scattered points on the ridge throughout the area are wooded.

General geology.—The shale, sandstone, and limestone exposed at the surface are all of upper Pennsylvanian age, and Pennsylvanian rocks of similar character underlie the region to a depth of more than 2,000 feet. The strata have a regional westward dip of about 25 or 30 feet to the mile, but this dip is interrupted and broken by numerous folds. The general attitude of the beds in northeastern Oklahoma is shown in a map compiled by J. H. Gardner.[3]

Detailed information as to the stratigraphy and structure of other parts of Osage County may be found in the several township reports

[3] Gardner, J. H., Mid-Continent geology: North American oil and gas, a supplement to the Oil and Gas Journal, May 30, 1919, p. 11.

of Bulletin 686 and in the reports on the Foraker and Pawhuska quadrangles.[4]

STRATIGRAPHY.

EXPOSED ROCKS.

The rocks exposed in the area considered consist chiefly of shale, sandstone, and a few inconspicuous beds of limestone. They include

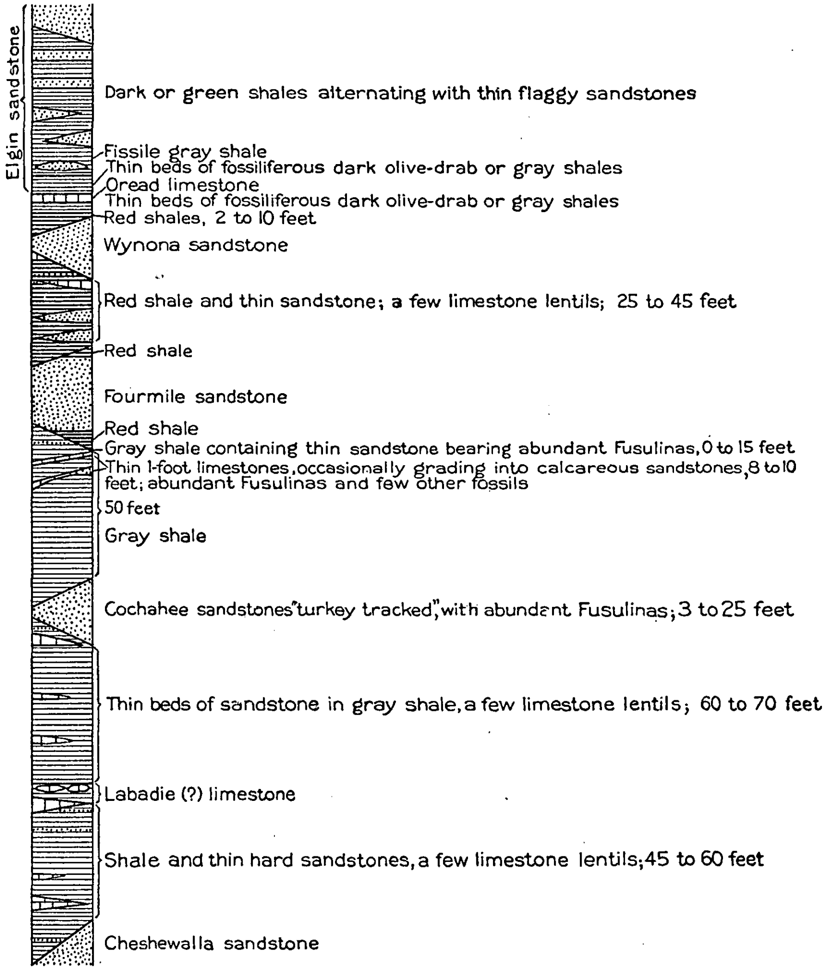


FIGURE 4.—Columnar section of rocks exposed in the Pershing oil and gas field, Okla.

at the top some of the beds in the base of the Elgin sandstone and at the bottom beds just above the Cheshewalla sandstone, and their aggregate thickness is between a maximum of 300 feet and a minimum of 170 feet, the average being probably about 235 feet. Shale forms approximately two-thirds of the section, and sandstone makes

[4] Heald, K. C., The oil and gas geology of the Foraker quadrangle, Osage County, Okla.: U. S. Geol. Survey Bull. 641, pp. 21–41, 1917; Geologic structure of the northwestern part of the Pawhuska quadrangle, Okla.: U. S. Geol. Survey Bull. 691, pp. 61–87, 1919.

up nearly all the remainder. The most conspicuous beds included are, in descending order, the Wynona sandstone, the Fourmile sandstone, and the Cochahee sandstone. (See fig. 4.)

Elgin sandstone.—In Tps. 24 and 25 N., R. 9 E., the Elgin sandstone has a thickness of 135 to 145 feet, the lower half of which consists of green or dark shales with interbedded thin flaggy sandstones. About 25 feet of the lower beds of this formation is exposed in secs. 1, 2, and 11, T. 24 N., R. 9 E. Thin beds of gray or olive-drab shale, which at some places is very fossiliferous, occur at the base of the greenish shale of the Elgin sandstone.

Oread limestone.—Where exposed in Tps. 24 and 25 N., R. 9 E., the Oread limestone consists of a few feet of orange-red limestone, which on fresh surfaces is gray and shows much milky-white calcite. However, it is rarely exposed as a ledge and is to be identified by the limy concretions and fossils that weather out of the shale with which it is associated. Thin beds of dark fossiliferous shale similar to those above the Oread limestone immediately underlie it and are in turn underlain by 2 to 10 feet of red shale.

Wynona sandstone.—The Wynona sandstone is a massive bed 7 to 25 feet thick underlying the red shale. It was used as a key bed in mapping the structure of the southwestern part of the area. Beneath the Wynona there are from 25 to 45 feet of red shale, thin beds of sandstone, and a few scattered limestone lentils.

Fourmile sandstone.—The Fourmile sandstone is a massive bed from 20 to 40 feet thick, with thin beds of red shale at its top and bottom. Its basal bed is coarser than other sandstones with which it might be confused. The Fourmile was the key bed used in determining the structure of the southeastern part of the field. It overlies 35 to 50 feet of a gray shale that contains in its upper half several thin beds of fossiliferous limestone and sandstone. These beds, however, are rarely exposed.

Cochahee sandstone.—The Cochahee sandstone, the type locality of which is in secs. 32 and 33, T. 25 N., R. 10 E., is from 3 to 25 feet thick and ranges from a thin flaggy to a thick massive bed. A peculiar weathered surface suggesting turkey tracks and the great abundance of *Fusulina* in some places are its most characteristic features. The Cochahee was used in mapping the northeastern part of the area. It is underlain by 45 to 55 feet of gray shale containing thin beds of sandstone and a few limestone lentils.

Labadie (?) limestone and lower beds.—The Labadie limestone has not been recognized as outcropping in the area, although limestone lentils occur at about its horizon. Beneath the Labadie (?) limestone and above the Cheshewalla sandstone are 45 to 60 feet of shale, thin beds of sandstone, and limestone lentils similar to the beds between the Cochahee sandstone and the Labadie (?) limestone.

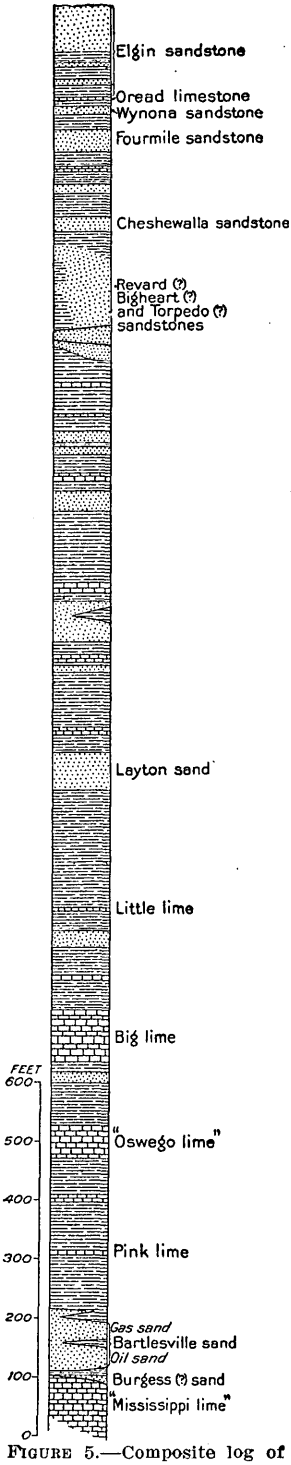


FIGURE 5.—Composite log of wells drilled in the Pershing oil and gas field, Okla.

Much of this lower series is exposed in parts of secs. 31 and 33, T. 25 N., R. 10 E.

Age.—The Elgin sandstone, which lies above the Oread limestone, constitutes the lowermost formation of the Shawnee group of Kansas, and the exposed rocks from the top of the Oread to the base of the section correspond to approximately the upper half of the Douglas group of Kansas.

ROCKS NOT EXPOSED.

Character.—The unexposed rocks to a depth of about 1,450 feet below the base of the Fourmile sandstone are similar in character to the outcropping beds. From this depth to the "Mississippi lime," about 625 feet deeper, limestone is more abundant. The "Mississippi lime" has been penetrated about 475 feet in one well, but it appears that other wells have reached beds that are lower stratigraphically. The upper 150 to 300 feet of these rocks are recorded in the drillers' logs as an unbroken series of limestones, a few of which are sandy. The deeper-lying strata are reported as thick alternating beds of limestone, sandy limestone, and sandstone and thin beds of shale, sandstone, and limestone.

The accompanying columnar section (fig. 5) is intended to represent only approximately the thickness and character of the beds penetrated in drilling. Data for its construction were taken largely from one cross section of the wells through the field. More of the "Mississippi lime" is not shown because the exact equivalencies in that part of the section have not yet been worked out to the writer's satisfaction. In addition to the beds which are labeled with the names commonly used by drillers in the Pershing field, several others can be more or less clearly recognized as the equivalents of strata to which drillers have given names elsewhere in Osage County, but because of the confusion that exists regarding the exact position of the beds to which many of these names should apply, it is thought best not to include them here.

Age.—It is regrettable that with the great wealth of data from deep wells which has been accumulated no adequate study or thoroughly satisfactory correlation of the surface and underground formations in northern Oklahoma with the standard Pennsylvanian section of Kansas has been made. Such a correlation is made difficult by the change in lithology from the type localities in central eastern Kansas, where limestone forms a large part of the beds, southward into the thicker section of Oklahoma, where the rocks comprise chiefly more or less discontinuous beds of shale and sandstone. Moreover, few of the well records give precise information, and this tends to discourage any painstaking attempts to make refined correlations over the necessary distances. A carefully constructed cross section along a line that would pass near many deep wells and through areas where the outcrops and configuration of the surface beds have been mapped in detail might be expected to show underground relations that would help to interpret the stratigraphy. With the development of new methods for the study of well cuttings and microscopic fossils (for instance, those worked out by Goldman[5] and Roundy[6]), it may be hoped that in the future it will be possible to make fairly definite correlations between these two areas. A valuable paper, giving much information on the subsurface stratigraphy of eastern Osage County, by Greene,[7] was published in 1918.

The age of none of the beds underlying the Pershing field has been determined, but it is hoped that a study of the cuttings from wells in the field will furnish lithologic evidence and yield fossils that will be of valuable assistance in recognizing the formations.

It may be provisionally stated that in this field the Douglas group of Kansas is represented by about 400 or 425 feet of strata below the top of the Oread limestone, or from the top of the section probably to some point in the basal part of the sandstone series recorded as Revard (?), Bigheart (?), and Torpedo (?) sandstones in figure 5. The Lansing group of Kansas may be represented in this area by about 300 feet of material recorded as alternating thin beds of sandstone, limestone, and shale. The Kansas City group of Kansas, according to commonly accepted interpretations of the well sections, would be the equivalent of about 500 or 550 feet of beds and would include near its base the Layton sand of the drillers, although by some its contact with the Pleasanton group would be drawn lower in the section. The Pleasanton group of the United

[5] Goldman, M. I., Lithologic subsurface correlation in the "Bend series" of north-central Texas: U. S. Geol. Survey Prof. Paper 129, pp. 1–22, 1921.

[6] Roundy, P. V., unpublished data.

[7] Greene, F. C., A contribution to the geology of eastern Osage County: Am. Assoc. Petroleum Geologists Bull., vol. 2, pp. 118–123, 1918.

States Geological Survey (the upper part of the "Marmaton group" of the Kansas Geological Survey) would be represented, according to the same interpretations, by 350 or 425 feet of strata. The Henrietta group (the lower part of the "Marmaton group") probably would be equivalent to the 175 or 200 feet of limestone, shale, and sandstone between a theoretical horizon somewhere in the Big lime and the base of the "Oswego lime" of the drillers. The 375 feet, more or less, of shale, sandstone, and thin beds of limestone between the base of the drillers' "Oswego lime" and the upper surface of the "Mississippi lime" probably corresponds to the Cherokee shale of Kansas, although formations that lie between the Cherokee shale and the Boone limestone farther east may be represented here.[8]

The age of the rocks penetrated below the upper surface of the "Mississippi lime" is so uncertain that it is not thought advisable to make even tentative statements as to their age at this time. A paper on this subject by Aurin, Clark, and Trager[9] has been published recently.

CHARACTERISTICS OF THE OIL SAND.

In the study of the well logs a number of important stratigraphic features of some of the underground formations were brought out. It is safe to predict that many other interesting points will be disclosed, especially in reference to the beds above the Bartlesville sand, as the work proceeds. Several of the observations that can be more easily demonstrated are discussed in the sections on the relations of stratigraphy to structure and production (pp. 45, 60).

Correlation of the logs supplemented by other studies forces the writer to the conclusion that the different beds making up the Bartlesville sand are extremely variable and laterally discontinuous. In cross section this group of sandy beds is strikingly similar to the sandstones tentatively correlated with the Revard, Bigheart, and

[8] For bases of the correlations given above see Greene, F. C., A contribution to the geology of eastern Osage County: Am. Assoc. Petroleum Geologists Bull., vol. 2, pp. 118–123, 1918; Shannon, C. W., and Trout, L. E., Petroleum and natural gas in Oklahoma: Oklahoma Geol. Survey Bull. 19, pt. 1, pp. 82–90, 1915; Ohern, D. W., The stratigraphy of the older Pennsylvanian rocks of northeastern Oklahoma: Oklahoma Univ. Research Bull. 4, pp. 10–34, 1910; Moore, R. C., and Haynes, W. P., Oil and gas resources of Kansas: Kansas Geol. Survey Bull. 3, pp. 84–102, 1917; Goldman, M. I., and Robinson, H. M., Structure and oil and gas resources of the Osage Reservation, Okla., T. 28 N., Rs. 11 and 12 E.: U. S. Geol. Survey Bull. 686–Y, pp. 360–381, 1920; Snider, L. C., Geology of a portion of northeastern Oklahoma: Oklahoma Geol. Survey Bull. 24, pt. 1, pp. 20–51, 1915; Heald, K. C., Geologic structure of the northwestern part of the Pawhuska quadrangle, Okla.: U. S. Geol. Survey Bull. 691, pp. 72–77, 1918; Siebenthal, C. E., Mineral resources of northeastern Oklahoma: U. S. Geol. Survey Bull. 340, pp. 189–195, 1908; Hinds, Henry, and Greene, F. C., The stratigraphy of the Pennsylvanian series in Missouri: Missouri Bur. Geology and Mines, 2d ser., vol. 13, pp. 1–190, 1915; McCoy, A. W., A short sketch of the paleogeography and historical geology of the Mid-Continent oil district and its importance to petroleum geology: Am. Assoc. Petroleum Geologists Bull., vol. 5, No. 5, pp. 543–550, 1921.

[9] Aurin, F. L., Clark, G. C., and Trager, E. A., Notes on the subsurface pre-Pennsylvanian stratigraphy of the northern Mid-Continent oil fields: Am. Assoc. Petroleum Geologists Bull., vol. 5, No. 2, pp. 117–153, 1921.

Torpedo sandstones (see fig. 5), which at their outcrops in the eastern part of Osage County are rarely persistent. Supplemental data, which also point to the lenticular character of the oil sand, were the irregularities resulting from attempts to contour the upper surface of the oil-bearing strata in the Bartlesville sand and to draw lines showing equal gross thicknesses of the oil sand and of the interval between the upper surfaces of the gas sand and the pink lime. Although drillers' logs are not highly trustworthy if unaccompanied by drill cuttings from the well, it is thought that they are likely to be more nearly accurate in the portions representing the sandy beds and beds near by, where the expectation of oil leads to careful observations, than they are in the portions representing the upper barren strata.

If the lenticularity of the Bartlesville sand is accepted as a fact, many anomalies, such as differences in productivity and in the gravity of the oil and even in the elevation of the sand in near-by wells, may be more easily understood, but inasmuch as by the nature of the records the extent, at least, of this lenticularity can not be definitely proved, it is thought advisable to consider alternative explanations of equally far-reaching consequence for these apparent anomalies.

The presence of coal interlaminated in the Bartlesville sand frequently recorded in well logs and the authenticated occurrence of fragments of bituminous coal associated with particles of the oil-bearing strata, blown from the wells by explosions, furnish interesting evidence bearing on the conditions under which the oil sand was deposited. Widespread coal deposits are known in the approximately contemporaneous Cherokee shale sediments of Kansas, Missouri, and elsewhere, but the rather sharp topographic relief which it is thought existed at the time of deposition of the beds containing the coal in the Pershing field, as discussed under the heading "Interpretation of buried escarpment" (p. 48), is not entirely in accord with the prevailing conceptions of the configuration of the adjacent land surface at the time coal was being formed. A map showing the distribution and thickness of these coal beds, in conjunction with data on the intervals between them and the underlying "Mississippi lime," might conceivably throw much light on the problem.

STRUCTURE.

PREPARATION OF STRUCTURE CONTOUR MAPS.

After the beds penetrated by the wells had been correlated in the manner described under the heading "Methods of studying well records," it remained only to compute the elevation of the datum beds and to plot the figures thus obtained on a map in positions representing the location of the wells, in order that contour lines showing the configuration of the strata might be drawn. These two processes are so simple and so thoroughly understood that they will not be discussed here.

In regions of relatively flat-lying strata, such as characterize the Mid-Continent oil fields, it has come to be the almost invariable rule for geologists to show the structure by means of structure contour maps—that is, maps that show the configuration of a certain bed by lines drawn through points where its elevation is the same. These maps possess many advantages, for they not only show much more than can be brought out by other methods, but the type of data needed for their construction is the only sort available where the rocks have very low dips.

In general two distinct ways of constructing structure contour maps may be recognized. One is a strictly mechanical process in which the computed elevations are exactly followed and which is based entirely on the axiom that three points determine a plane; the other is a method that permits the worker to incorporate his interpretation of the conditions into the finished map. The first method is simple and requires no further explanation, and where the points at which the elevation of the bed to be contoured has been computed are closely spaced this method is usually adopted. The second method is more or less complex, according to the amount of supplemental information regarding the beds possessed by the worker, his knowledge of the physical laws that control the deformation of strata, and his opinion, based upon acquaintance with peculiarities in near-by regions, of what the conditions should be in the area examined. As a matter of actual practice, of course, the two methods are combined in preparing most structure contour maps, but their fundamental difference remains.

The second method is unquestionably superior for a map constructed by a well-trained and attentive geologist to show the structure of the exposed rocks in an area with which he is thoroughly familiar. This method is probably the most accurate for any map depicting the attitude of the surface beds, for their inclination once seen is not commonly subject to a gross misinterpretation. In areas where the points at which the elevation of the key stratum can be computed are widely spaced interpretations by a competent observer are doubtless of greater value than mechanically drawn contours, even for a map representing the structure of beds not exposed at the surface.

For the ordinary "substructure" maps of oil fields, however, especially of fields where most of the wells are closely spaced, the writer believes that interpretative contouring is quite as likely to obscure the real conditions as to furnish enlightening explanations of the apparent relations. Erroneous correlations or faulty records may give elevations that could be easily interpreted in such a manner as to remove all doubt from the worker's mind as to the accuracy of the information, whereas like errors on mechanically contoured maps would intrude so conspicuously as to demand restudy. The fact that the actual inclination of the deeper-lying strata is almost hopelessly hidden from view is frequently disregarded, and if interpretation is permitted, the temptation to "discover" evidence favorable to any preconceived idea whatsoever is indeed great.

The mechanical method has serious disadvantages, it is true, for by this method the structure between widely spaced points of observation is necessarily made unduly smooth, and where more data are available probably greater irregularities are shown than are actually present. The very obviousness of these errors, however, is a point in favor of the method, as it shows clearly by its strict conformation to all the data available the generally recognized fact that drillers' well logs are not infallible and permits each geologist to make his own interpretations without befogging in a haze of theories the records that might be essential should later developments necessitate a restudy of a region.

In a very few areas in the Pershing field meager data regarding some beds made it necessary to use the interpretative method, but in each of these areas the simplest explanation conceivable to the writer was used, and the interpretation is shown by dotted lines.

In order to avoid the confusion caused by a mixed use of elevations above and below sea level, it was thought advisable to refer all the beds contoured to a datum plane 2,000 feet below mean sea level. All figures of elevation are therefore "plus" figures, the higher figures indicating high points on the surface of the key bed and the lower figures indicating low points. Consistency demanded the conversion of the elevations given on the maps of the exposed rocks to the same reference plane.

FEATURES SHOWN BY THE STRUCTURE CONTOUR MAPS OF THE PERSHING FIELD.

Structure of the surface beds.—As previously stated, the structure of the strata that crop out in the four townships that include the Pershing field was mapped by several geologists of the United States Geological Survey, and the maps were published in chapters of Bulletin 686. A theoretical bed about 300 feet below the middle bed of the Oread limestone, which would fall near the top of the sandstones called Revard (?), Bigheart (?), and Torpedo (?) sandstones in figure 5, was used as the datum plane for contouring over all of the area except T. 25 N., R. 9 E., where the middle bed of the Oread limestone itself was used. In preparing Plate VIII the contour lines of the four maps were made to coincide by reducing them to the datum plane used over three of the four townships, and the elevations were then referred to a datum plane 2,000 feet below sea level instead of sea level.

The North Cochahee and South Cochahee domes are the controlling structural features in the Pershing oil field. These domes, as shown in Bulletin 686, have, respectively, more than 10 feet and less than 30 feet of "closure" (the vertical distance between the crown of the upfold and the highest point in the bounding synclines). Their "drainage area" or "gathering ground" is represented in Plate VIII; that of the South dome is roughly twice as great as the other. The area of the South Cochahee dome, in comparison with its small amount of "closure," is much greater than is common in the domes of Osage County. The dips throughout the area are gentle, ranging from about 20 feet to the mile in secs. 4 and 5, T. 24 N., R. 10 E., to 200 feet to the mile near the west quarter corner of sec. 31, T. 25 N., R. 10 E. Another area of steeper dip (in places more than 100 feet to the mile) lies along the south line of sec. 6, T. 24 N., R. 10 E.

One fault, which shows a maximum displacement of less than 10 feet, cuts the beds in the Pershing field. The orientation of this fault is strikingly dissimilar to that of the great majority of the faults mapped in Osage County and adjoining parts of the Mid-Continent oil fields.[10]

The North and South Cochahee folds are called domes to emphasize their difference from the commoner, more definitely elongated anticlines of Osage County. It is possible that this distinction is significant of the origin of the folds, the anticlines indicating folding by lateral pressure or being an expression of deeper faults, and the domes, in some places, suggesting settling of the sediments about a buried core of firmer rocks. However, the complete gradation between the two types and the associated presence of basins (the inverse of domes) seem to the writer to make such a relation improbable.

The Pershing field lies but a few miles east of a pronounced area of deformation extending in a southerly direction through the central parts of Tps. 25 and 24 N., R. 9 E.[11] Quaquaversal folds are

[10] For a compilation of the major structural features of the region see Fath, A. E., The origin of the faults, anticlines, and buried "granite ridge" of the northern part of the Mid-Continent oil and gas field: U. S. Geol. Survey Prof. Paper 128, pl. 12, 1921; also Kansas Geol. Survey Bull. 7, pp. 149–166, 1921.

[11] U. S. Geol. Survey Bull. 686–E, pp. 40–41, pl. 7, 1918; Bull. 686–P, pp. 197–198, 211, pl. 32, 1919; Prof. Paper 128, pl. 12, 1921.

common near the extensively faulted areas but are rare in Tps. 24 and 25 N., R. 10 E., where the modifications of the regional westerly dip are almost all such minor structural features as noses and terraces. Attempts have been made to discover some definite arrangement of the faults and folds but have been admittedly only partly successful. The writer is of the opinion that one large factor contributing to the difficulties of such a task is the confusion resulting from the effect of the regional dip upon the configuration of the folds as shown by structure contour maps. Elimination of the regional dip, by a method comparable to the use of "convergence sheets"[12] and the delineation of structure as it would appear if the region were tilted to an approximately horizontal position, in some places yields surprising results, as by this method barely perceptible flattenings in a regional dip may assume proportions that dwarf by comparison the previously conspicuous folds. In general, it may be said that such a treatment brings out more forcibly those axes which approximately parallel the regional strike and by showing the relative magnitude of the different lines of deformation presents a fairer picture of actual conditions. It is the belief of the writer that if the general inclination of the strata in Osage County were determined by means of numerous cross sections drawn on lines at right angles to the strike, and if these data were applied to the existing structure contour maps, information of much value regarding the origin of the folds might be derived.

Structure of beds above the pink lime.—Before the completion of work on the Pershing field it is planned to draw structure contour maps of the Layton sand, Big lime, "Oswego lime," and probably some bed nearer the surface than the Layton sand. Contours drawn on these strata will be useful in furnishing justification for eliminating absurdities which may appear on other maps, and they are expected to furnish valuable data on conditions suspected from other studies.

Structure of the pink lime.—The pink lime is thought to be the most satisfactory bed in the Pershing field for showing the attitude of the deeper rocks. Not only is it the first persistent lithologic unit above the oil sand and thus is penetrated by practically all the wells, but its slight thickness (about 8 feet), its persistence, and its commonly distinctive color (which has caused it to be generally recognized and carefully looked for) and the fact that its depth was determined with a steel measuring line by many of the drillers give it great value as a bed for contouring. On the other hand, several thin limestones that occur in the shale interval between the

[12] Griswold, W. T., and Munn, M. J., Geology of oil and gas fields in Steubenville, Burgettstown, and Claysville quadrangles, Ohio, West Virginia, and Pennsylvania: U. S. Geol. Survey Bull. 318, pp. 23–25, 1907.

base of the "Oswego lime" and the top of the oil sand may in carelessly prepared well logs be confused with the pink lime. In such logs, however, the position of the pink lime can usually be determined by comparison with the records of adjoining wells.

The map showing the attitude of the upper surface of the pink lime (fig. 6) undoubtedly contains some errors. As explained above, the method employed in constructing the map brings out these errors clearly. By reference to the map showing the location of the wells

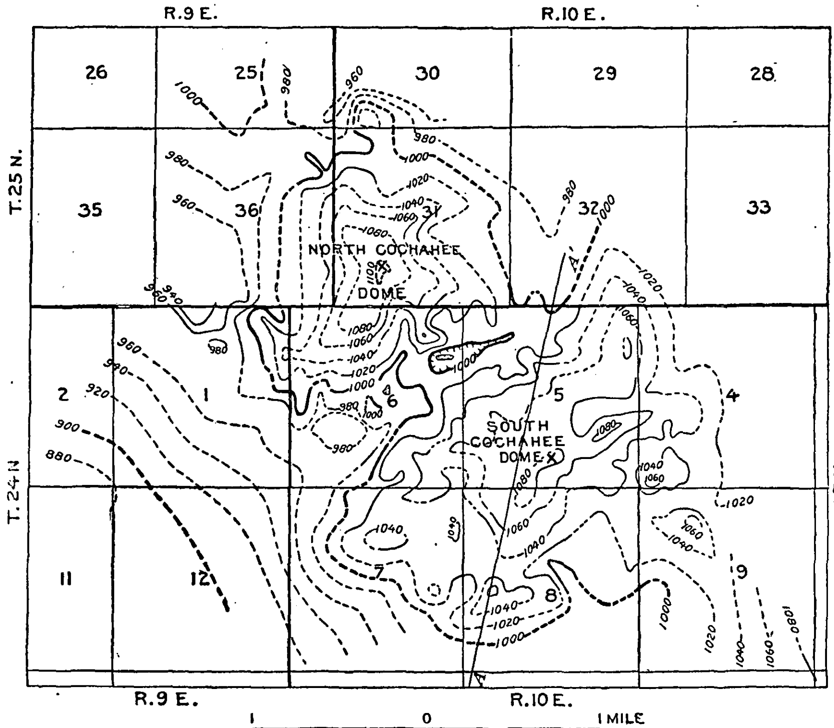


FIGURE 6.—Structure contour map of the upper surface of the pink lime in the Pershing oil and gas field, Okla. Elevations above a reference plane 2,000 feet below sea level. Broken lines indicate that position of contour lines may be somewhat in error because of doubtful identification of upper surface of pink line or because of a greater distance than 850 feet between the wells. Crosses indicate the approximate position of the crests of the domes. *A–A'*, line of cross section, figure 8.

in the field (Pl. VII), which gives a general idea of the distance between points used in determining the elevation of the pink lime (the "control" of the datum plane, as it is commonly called), and observation of the agreement of the isolated irregularities with the larger features, the degree of accuracy of the contour map may be properly judged. The dotting of the lines where datum-plane elevations are doubtful and where the points at which such elevations were determined are more than 850 feet apart attempts to show this degree of accuracy. Because of the lesser relative accuracy of the data available and the greater inclination of the pink lime and the more numerous irregularities in its surface, which tend to obscure the major features, the configuration of this bed is shown on figure 6 by a contour interval of 20 feet instead of the 10-foot interval used in delineating the structure of the beds at the surface shown by Plate VIII.

Most of the significant facts brought out by a study of this map showing the attitude of the pink lime are discussed under the headings "Relations between beds at different horizons" and "Relations [of production] to geologic and other conditions." However, it is pertinent to call attention here to certain features.

The highly irregular but nevertheless often repeated double series of axes of both the major and minor folds would seem to indicate cross folding, the two series crossing each other approximately at right angles. It would hardly be worth while to call attention to the detailed evidences of the continuity of such northwest and northeast axes, even though they might be of some significance, because their very presence is admittedly not susceptible of definite proof.

The occurrence of areas of relatively steep dip (in several places as much as 500 feet to the mile) and the marked lateral extension of the strike of the beds in certain places are somewhat suggestive of faults. Such an area of steeper dip is in the NE. ¼ sec. 6, T. 24 N., R. 10 E., and is associated with a small apparent extension of the strike eastward into sec. 5. Other more marked northeast-southwest alinements are to be noted on the northwest and southeast sides of the South Cochahee dome, and, particularly on the southwest end of the same dome, there are alinements of the strike with a northwesterly trend, approximately at right angles to the trend at the other localities mentioned.

Structure of the oil sand.—A structure contour map of a horizon in the Bartlesville sand is not presented in this report. An attempt by the writer, made before the concept of the extreme lenticularity of this sand was developed, to draw contour lines on the upper surface of the sand was decidedly unsuccessful, but another attempt will be made, for some questions pertaining to the accumulation of oil in this region can not be adequately answered without such a map.

Contours were drawn to show the upper surface of the beds from which the oil is recovered. The result made it quite clear to the writer that either the depths given in the well records are greatly in error or else the oil comes from different horizons in different parts of the field. Both explanations may be in part true, but the writer inclines to the belief that the pinching out of layers of sandstone accounts for at least the larger irregularities. For instance, he is of the opinion that two or more beds, which are separated by an interval greater than 50 feet, yield the oil in the southern part of sec. 6 and the northern part of sec. 7, T. 24 N., R. 10 E., respectively.

Not only do the major differences in elevation of the "pay sands" indicate the lenticular character of the sandstone, but the minor irregularities also suggest just such an uneven surface as would normally be developed in strata of this nature.

Some facts of structural significance, however, may be ascertained from a study of the apparent attitude of the sand. In general the oil was found some 20 feet higher up on the flanks of the South dome than on the North dome, a difference which is in accordance with the apparently larger amount of gas in the North dome. Another generalization that can be made is that on the edge of the field oil was found at a lower level on the southwest side than elsewhere, its greatest depth being at the southwest end of the saddle that separates the two domes, slightly more than 1,200 feet below sea level. Elsewhere along this side of the field it was found at depths of 1,180 and 1,190 feet below sea level, but on the eastern and northern edges the margin of the oil-yielding portion of the sand was found at 1,170, 1,160, and even only 1,130 feet below sea level.

Attitude of the upper surface of the "Mississippi lime."—Comparatively few of the wells in the Pershing field have been drilled deep enough to reach the "Mississippi lime," and it is therefore impossible to construct an accurate contour map of any of the beds in it. Similar difficulties in other regions have been surmounted by some geologists by means of "convergence sheets," which show the stratigraphic interval between the deeper bed and a bed whose structure is known; such a sheet can be superimposed upon the previously prepared contour map, and the elevations of the deeper beds thereby computed.[13] Studies by the writer have led him to believe that in many regions the interval between given strata varies so greatly within short distances that this method is likely to give highly misleading results unless a great many well records are available. In the map showing the configuration of the upper surface of the "Mississippi lime" (fig. 7) the mechanical contouring and not the "convergence sheet" method was used, and all the points where the elevation of the datum plane could be determined are shown.

The apparent smoothness of the surface and the entire absence of any suggestion of northwest-southeast axes seem to be significant. These features may be due in part to the considerable distance between the wells and the method of contouring used, although the map of the southeastern part of sec. 5, T. 24 N., R. 10 E., where the wells that reach the "Mississippi lime" are closely spaced, shows a smooth surface and does not show axes trending northwest.

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[13] Griswold, W. T., and Munn, M. J., Geology of oil and gas fields in Steubenville, Burgettstown, and Claysville quadrangles, Ohio, West Virginia, and Pennsylvania: U. S. Geol. Survey Bull. 318, pp. 23–25, 1907.

The line of steep dips extending from a point near the center of sec. 6, T. 24 N., R. 10 E., to a point near the northeast corner of sec. 11, T. 24 N., R. 9 E., and the abrupt change in strike along this line are notable features. They are discussed with the results of another study, which seem to give them some significance, under the heading "Unconformity between the 'Mississippi lime' and the pink lime" (p. 46).

Structure of beds below the upper surface of the "Mississippi lime."—It is planned to contour the structure of one or more beds

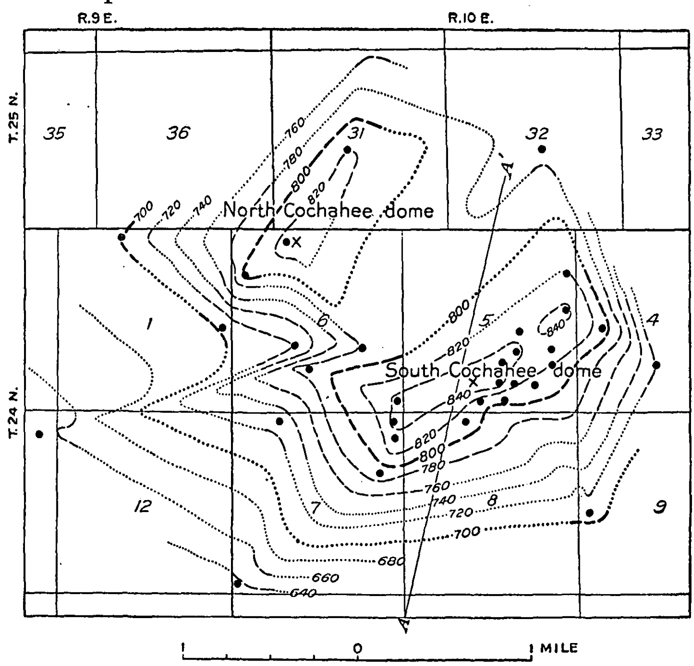

FIGURE 7.—Structure contour map of the upper surface of the "Mississippi lime" in the Pershing oil and gas field, Okla. Elevations above a reference plane 2,000 feet below sea level. • Point where elevation of upper surface of "Mississippi lime" was available. Broken lines indicate that position of contour lines may be somewhat in error; dotted lines that position is inferred. Crosses indicate the approximate position of the highest points on the domes. *A—A'*, line of cross section, figure 8.

below the upper surface of the "Mississippi lime." Such a map or maps would be extremely valuable in the interpretation of certain conditions that have been found to exist, but the paucity of information available on these deep-lying strata and the consequent difficulty of accurate correlation have thus far prevented the writer from making a satisfactory map.

RELATIONS BETWEEN BEDS AT DIFFERENT HORIZONS.

A comparison of the attitude of the several strata shown by the structure contour maps reveals a number of interesting relations. It is readily apparent, for instance, that the deeper-lying rocks are more steeply tilted than the surface beds. An analysis of this divergence, based on determinations made at points far enough apart to lessen the effect of local irregularities, shows that the pink lime has dips from 1.3 to 3.7 (normally 2.4) times as great as the exposed strata, which on the average lie about 1,850 feet above it, and that the upper surface of the "Mississippi lime," which is in general about 250 feet deeper, has dips from 1.5 to 5 or more times as great as those of the exposed strata. It can be further demonstrated that the dip of the pink lime is in general almost exactly the same as that of the oil sand (as represented by the contours on the top of the oil-yielding beds), but that the "Mississippi lime" dips from 1.4 to 2.2 (normally 1.9) times as steeply as the oil sand. This relation, taken in conjunction with the fact that the "top of the oil" usually lies at about two-thirds of the distance from the pink lime to the "Mississippi lime," is strongly indicative of the presence of an unconformity between the oil sand and the "Mississippi lime." Further evidence that such relations exist is discussed under the heading, "Unconformity between the 'Mississippi lime' and the pink lime" (p. 46). Figure 8 is drawn to show this increase of dip downward and certain other features.

All the evidence available indicates that in this field the axes of folding are much farther to the south in the lower beds than in the upper ones. The axis of the syncline between the North Cochahee and South Cochahee domes, as shown on the structure contour maps, is from 700 to possibly 3,000 feet farther southeast in the pink lime than in the surface beds, and from 900 to more than 3,000 feet farther southeast on the "top of the oil" than in the surface beds. The divergence as shown is progressively greater toward the northeast, but the greater differences may be in large part only apparent, being possibly the result of errors in contouring. In considering the amount of offset of axes it is to be borne in mind that the average interval between the surface beds and the pink lime is about 1,850 feet and that the upper surface of the oil-yielding beds is in general 165 feet below the pink lime. (See fig. 8.)

Similar offsets may be noted by comparing the locations of the crests of the larger domes, but as the wells are not as closely spaced in those places as in the synclines the evidence is not so reliable. By extending upward the known dips it appears that the crests of the North and South domes in the pink lime are approximately 950 and 1,500 feet, respectively, farther south than in the surface beds, and in the "Mississippi lime" 2,500 and 1,550 feet, respectively, farther south. (See fig. 8.) Attention should be called, however, to the facts that wells have not been drilled on either dome at points which the outcropping beds indicate to be on the crest, that according to Bowen[14] the highest point on the South dome is about 1,500 feet farther south than the point here assumed, and that the well data on the attitude of the upper surface of the "Mississippi lime" are very meager.

It is thought that the results here presented show at least qualitatively that the axes incline to the south. The angle of inclination is such that the crest of a dome or the trough of a syncline in a bed some distance below the surface is usually from one-half to nearly as far to one side as it is below the crest or trough of the equivalent fold in the rocks that crop out at the surface—that is, the inclination of the axial planes from the vertical is generally between 25° and 40°. No explanation of this inclination has been attempted by the writer. According to Heald,[14a]

> It is to be expected that the axes of domes and anticlines in northeastern Oklahoma will be inclined to the vertical, but it is doubtful if any general rule may be applied to forecast in advance of drilling the direction in which the axes will be inclined. In fact, such data as are available indicate that the inclination in many contiguous domes and anticlines is dissimilar, in some being almost opposite, and a single anticline may show an inclination to the east at one end and to the west at the other, as in the Dropright dome of the Cushing field.[14b]

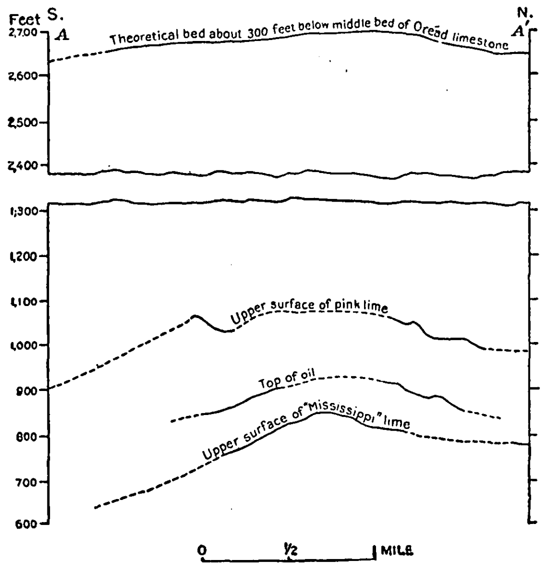

FIGURE 8.—Cross section along line *A*—*A'*, figures 6 and 7, showing the relation of the surface beds, the pink lime, the " top of the oil," and the " Mississippi lime " in the Pershing oil and gas field, Okla. Shows the greater inclination of the deeper-lying strata, the presence of small isolated domes beneath structural terraces, and the lateral shifting of axes. Vertical exaggeration about 13 times.

The inclined axes of anticlines and domes are but reflections of the stresses that have caused folding in the Mid-Continent region. These stresses originated in depth as a result of regional readjustment and their primary effect was the sharp folding and strong faulting of the competent basement beds. This deformation in turn caused stresses that acted on the overlying sediments. The principal component of the movements was in most places vertical, but there were also strong horizontal components. Exceptionally, the principal component was horizontal.

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[14] Bowen, C. F., U. S. Geol. Survey Bull. 686–D, p. 23, 1918.

[14a] Heald, K. C., unpublished manuscript.

[14b] Beal, C. H., Geologic structure in the Cushing oil and gas field, Okla.: U. S. Geol. Survey Bull. 658, pls. 7, 9, 1917.

The most striking evidence of the regional readjustment is afforded by the belts of parallel, en échelon faults, and these faults may furnish a clue to the probable direction of inclination of the axes of anticlines close to the faulted belts. For example, anticlines and domes in eastern Osage County, particularly in the western part of R. 9 E., should have their axes inclined at least slightly eastward, owing to intense stresses originating west of them. Also, as the evidence of the faulted belts indicates that the block to the east of them moved northward as a result of tangential stresses in the competent beds,[14c] a component of this force should, in many places, have modified the stresses that bulged and folded the sediments upward, resulting in axes inclined to the south. Conversely, folds on the west of the faulted zone should have axes inclined to the west and north, and folds within the faulted zone should show little or no regularity in the direction of the inclination of axes.

Structural terraces and noses as shown in the surface rocks appear to overlie more or less isolated folds in the lower strata, but proof of this relation depends in large part upon the establishment of the southward shifting of axes. One apparently clear case of this relation is shown in the line of the cross section (fig. 8) in sec. 8, T. 24 N., R. 10 E. On the structure contour map of the pink lime two small isolated domes are shown to underlie the terrace in the surface beds in this vicinity, but the mapping of the small dome in the eastern part of sec. 7, T. 24 N., R. 10 E., is based upon evidence furnished by one well only and therefore is not entitled to the same degree of credence as that of the other. Additional evidence that axial planes in this field are generally inclined to the south may be found in the east end of the South Cochahee dome and elsewhere.

The writer believes that the upper surface of the "Mississippi lime" is much smoother than that of the pink lime, even where the data are most complete, although the evidence is inadequate to afford conclusive proof. No explanation is offered here aside from noting that the greater irregularities of the pink lime may be more or less local to that bed and possibly caused by unequal settling of strata, perhaps modified by inequalities of deposition, although the linear arrangement of the minor folds suggests that they were formed by lateral compression. The second set of axes in the pink lime (if actually present) may also be represented in the structure of the "Mississippi lime," even though it is not conspicuously apparent.

RELATION OF TOPOGRAPHY TO STRUCTURE.

Viewed in the large the relation of the topography of the region near the Pershing field to the structure of the surface rocks is strikingly close. The main traveled automobile road through the area (shown in Pl. VII) in general follows the divide between Bird Creek, to the northeast, and Birch Creek, to the southwest, although

[14c] Fath, A. E., The origin of the faults, anticlines, and buried "granite ridge" of the northern part of the Mid-Continent oil and gas field: U. S. Geol. Survey Prof. Paper 128, p. 79, 1920.

the ridge is higher and extends over 1,000 feet northward from the road in the SW. ¼ sec. 31, T. 25 N., R. 10 E. It will be seen that the divide as shown by this "ridge road" closely follows anticlinal axes (see Pl. VIII), running southward along the Saucy Calf anticline, eastward near the highest part of the intervening saddle to the south end of the South Cochahee dome, thence southeastward across the saddle to and over the top of the South Cochahee dome, and finally running out of the area over a terrace on the east side of the South dome and a minor structural nose in the monocline to the east. The upper part of Cochahee Creek in secs. 5 and 6, T. 24 N., R. 10 E., and secs. 31 and 32, T. 25 N., R. 10 E., and a northern tributary of Birch Creek in secs. 1 and 12, T. 24 N., R. 9 E., and sec. 6, T. 24 N., R. 10 E., likewise approximately coincide with the axis of the syncline separating the North and South domes. Similarly, Saucy Calf Creek closely follows the axis of the syncline that separates the North dome from the Saucy Calf anticline. The approximation of Birch Creek to the position of the syncline between the Cochahee domes and the East and West Birdseye anticlines, to the south, and of other tributary streams and smaller ridges to minor synclinal and anticlinal axes is not so close but is nevertheless significant.

It is not to be inferred from the foregoing statements, however, that the topography closely indicates the details of structure of even the uppermost beds. The resemblances are to be found only in the larger features, and the configuration of the surface of the ground is not a reliable indication of the oil or gas yielding possibilities of an area.

RELATION OF STRUCTURE TO STRATIGRAPHY.

THICKNESS OF FORMATIONS.

Comparison of the attitude of different buried strata demonstrates conclusively that the intervals between some beds are very irregular and suggests the presence of unconformities. For the purpose of studying more closely evidence of this nature maps showing by contour lines the areas of equal thickness of certain intervals were constructed. It is thought that maps of this sort may be of great value to the geologist, for they enable him to reconstruct the configuration of the rocks or the topography as they must have been at the time the overlying beds were deposited. Such information is not only of value in a strictly economic study of an area but adds materially to our knowledge of geologic history.[15]

[15] For an example of work of this sort on a large scale see Berger, W. R., The relation of the Fort Scott formation to the Boone chert in southeastern Kansas and northeastern Oklahoma: Jour. Geology, vol. 26, pp. 618–621, 1918.

In the work on the Pershing field the intervals between the upper surfaces of the Big lime and "Mississippi lime," the pink lime and the gas sand (upper part of the Bartlesville sand), and the pink lime and the "Mississippi lime" and the total reported thickness of the sandstone group between the pink lime and the "Mississippi lime" were contoured. Many other intervals and thicknesses remain to be contoured—for instance, the intervals between the Layton sand and the Big lime and between the "Oswego lime" and the "Mississippi lime" and the thickness of the lowest sandstone (Burgess sand?) above the "Mississippi lime."

The map of the interval between the Big lime and "Mississippi lime" is so closely similar to that of the interval between the pink lime and "Mississippi lime," except in the degree of changes, that it need not be discussed more fully here.

A map of the interval between the upper surfaces of the pink lime and the gas sand shows so great irregularities within short distances that it strongly suggests the lateral discontinuity of the layers of sandstone that form the upper surface of the gas sand, a suggestion which is entirely in harmony with other results that have been obtained.

INTERVAL BETWEEN THE UPPER SURFACES OF THE PINK LIME AND THE "MISSISSIPPI LIME."

The equal-thickness map of the interval between the pink lime and "Mississippi lime" (fig. 9) was constructed entirely from the intervals shown by well records and not by computation from the two structure contour maps (figs. 6 and 7). As these three maps were made independently of one another, exact agreement among them exists only where the wells furnishing the necessary data are closely spaced.

Unconformity between the "Mississippi lime" and the pink lime.—A marked thinning of the interval over the South dome is apparently not paralleled by a similar decrease of thickness over the North dome, although this difference may be explained by the fact that the data in the northern area are much more meager than in the southern. Assuming that the pink lime was virtually horizontal when it was deposited, we can reconstruct the configuration of the upper surface of the "Mississippi lime" (and consequently the topography) before the pink lime was laid down. Such a reconstruction indicates the presence of a hill or elongated ridge of the Mississippian (?) rocks at the present site of the South Cochahee dome when the lower Cherokee (?) sediments were laid down. It is worth noting that this ridge is approximately parallel to the long axis of the existing South Cochahee dome in the upper surface of the "Mississippi lime" (fig. 7) and that the valley or syncline lying north of the ridge exactly coincides with the suggested line of steep dip in the western part of the field shown in figure 7. Although information in regard to the northern part of the field is scanty, a general southward inclination of the old Mississippian (?) surface there is indicated. This inclination is repeated southward from the ridge. (See fig. 10.)

The discordance of dips, the varying intervals, and the marked differences between the attitude of the upper surfaces of the pink

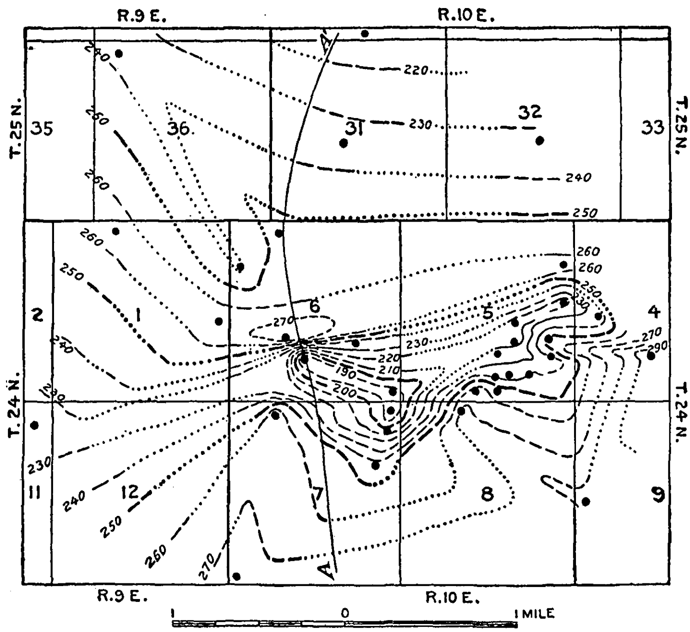

FIGURE 9.—Map showing lines of equal thickness of the interval between the upper surfaces of the pink lime and the "Mississippi lime" in the Pershing oil and gas field, Okla. • Point where thickness of the interval was determined. Broken lines indicate that position of contour lines may be somewhat in error; dotted lines that position of contour lines is inferred. *A–A′*, line of cross section, figure 10.

lime and "Mississippi lime" and the configuration of the old surface all afford evidence of the existence of a stratigraphic break or unconformity between the "Mississippi lime" and the pink lime. The similarity of the steepness of dip of the upper surfaces of the oil-yielding beds and the pink lime indicates that the break lies in the lower 75 or 100 feet of sediments above the "Mississippi lime." The exact position of such a break is of great importance in a study of the occurrence of oil and gas, and although it has not yet been determined definitely, the writer thinks that the distribution and thickness of the lowest sandy bed (the Burgess sand?) indicate that the plane of break is coincident with the upper surface of the limestone beds.

Confirmation of the theory that a pronounced break exists in this part of the section might be looked for in the observed stratigraphic relations of Mississippian and Pennsylvanian strata in areas not too far distant, where their contact is exposed. In all but a few places where the degree of deformation in the two series is greatly different,[16] there is a great erosional unconformity between these rocks. Berger's discussion and map of the interval between the top of the "Mississippi lime" and the "Oswego lime"[17] gave much evidence that these relations exist also at places where the contact is concealed by younger deposits.

The nature of an unconformity between probable Mississippian and probable Pennsylvanian rocks in the Pershing field—whether erosional or angular—would seem to be easily determinable by correlation of the strata below the upper surface of the "Mississippi lime" penetrated in the wells. The lack of details in the lower parts of the logs, however, prevents thoroughly satisfactory correlations, and for the present at least any statement regarding the character of the unconformity must be based largely on inference.

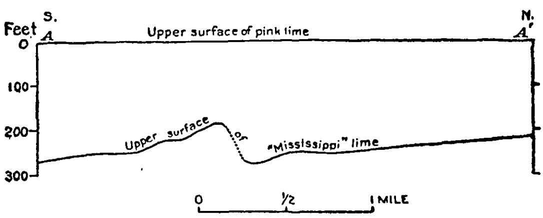

FIGURE 10.—Cross section along line *A—A'*, figure 9, showing the approximate attitude of the upper surface of the "Mississippi lime" at the time of deposition of the pink lime in the Pershing oil and gas field, Okla. Vertical exaggeration about 13 times.

Interpretation of buried escarpment.—The nature of the straight line of sharp change in the interval between the pink lime and "Mississippi lime," which, as has been stated, coincides with the line of steep dips suggested in figure 7, may be subject to various interpretations that would have a bearing on the nature of the stratigraphic relations in the part of the rock column that includes the suspected unconformity. This line might be explained (1) as the result of asymmetric folding, an anticline forming the ridge to the south; (2) as a fault scarp, the southern being the upthrown side; (3) as some form of erosional feature, the southern side remaining as a hill or ridge; or (4) as the result of a combination of two or more of these causes. The processes invoked in any of these explanations would necessarily have been most active prior to the deposition of the strata above the "Mississippi lime."

Little evidence is at present available on which to base an assumption that warping of the beds approximately 10 times as intense on

[16] Hinds, Henry, and Greene, F. C., The stratigraphy of the Pennsylvanian series in Missouri: Missouri Bur. Geology and Mines, 2d ser., vol. 13, p. 209, 1915.

[17] Berger, W. R., The relation of the Fort Scott formation to the Boone chert in southeastern Kansas and northeastern Oklahoma: Jour. Geology, vol. 26, pp. 618–621, 1918.

the north side of an anticline as on the south is the cause of this feature. As pronounced angular unconformity between Mississippian and Pennsylvanian rocks is essentially restricted to areas of major uplifts, and as no adequate source of the compressional stresses necessary to produce folds in Osage County, such as this buried line would indicate, is known, it does not seem probable that this feature is the result of folding, though consideration of the possibility of such an origin can not yet be finally dismissed.

The straightness of the escarpment suggests to a certain degree the presence of a fault. The general downward tilting of the surface southward both to the north and to the south of the line might be considered as contributory evidence indicating the existence of a fault, as such tilting would be the natural result if blocks of competent rocks should be broken and moved. The presence of faults in the deeper-lying more competent strata of the northern Mid-Continent field has been suggested by Fath,[18] but the orientation of this line in the Pershing field is not similar to that of the deep-seated faults postulated by him. The approximate parallelism of this underground scarp to the fault shown in the surface beds (Pl. VIII) and the very fact that the alinement of this fault shown on the surface agrees not with that of other faults that have been mapped in Osage County but with the scarp might seem to substantiate the hypothesis that the scarp is due to faulting. If the area in the NE. ¼ sec. 6, T. 24 N., R. 10 E., where there is a strong suggestion of a buried fault, as noted on the map showing the structure of the pink lime (fig. 6), is connected with the trace of the surface fault (a hardly justifiable procedure, however), a line very closely parallel to the scarp is obtained, but the upthrown side of the surface fault is to the north, whereas the higher side of the scarp is the south side. It seems improbable that if the scarp marks a fault plane along which displacements of a magnitude of nearly 100 feet occurred about the end of Mississippian time, no noticeable movement should have taken place along this fault at times of later deformation; but as a matter of fact evidence of such movement is lacking. The alinement of the wells in the southern part of the field that yield oil from beds above the Bartlesville sand with the strike of the pink lime and the occurrence of a gas seep on this lime are somewhat suggestive of the presence of minor faults, as is discussed under the heading "Oil from shallow sands." The alinement of these features is parallel in a general way to the trend of the subsurface scarp and might therefore be interpreted as evidence indicating its association with faulting.

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[18] Fath, A. E., The origin of the faults, anticlines, and buried "granite ridge" of the northern part of the Mid-Continent oil and gas field: U. S. Geol. Survey Prof. Paper 128, pp. 77–80, pls. 12–13, 1921.

It is the opinion of the writer, however, that the evidence points to the conclusion that the underground scarp is due to erosion and that the younger strata may have been broken by unequal consolidation above this buried scarp. The objections to the hypothesis of a fault origin mentioned in the preceding paragraph and the sharp topographic relief shown where the contact of the Mississippian and Pennsylvanian rocks is exposed seem to warrant this conclusion. Berger's map[19] shows a topographic ridge extending through the field in a southeasterly direction, bounded on the southwest by a supposed stream valley. It is probable that the limestone strata as well as the general surface of the land in eastern Osage County were inclined gently eastward or southeastward when the oldest shales and sandstones above the "Mississippi lime" were being laid down, but a local doming of some sort north of the Pershing area might have given the rocks there a southward dip. Had this been the case, a stream that flowed southeastward through the area, in cutting down its channel, might have encountered layers of limestone that were more resistant to erosion than the overlying beds and so have had its course deflected southward down the local dip. The general southward tilt of the surface, the northwest-southeast trend of the low area in sec. 1, T. 24 N., R 9 E., and the northward-facing scarp are all apparently in accordance with this view. (See figs. 9 and 10.) The configuration of the ridge or hill would also seem to bear out this interpretation somewhat, as streams draining southward from the main upland would probably carve irregularities in its side such as were found and would leave the headland standing as a broken ridge above the general slope of the surface.

The indicated presence of a spur on the north side of the valley in the pre-Pennsylvanian (?) surface (see fig. 9) may bear a close relation to the fault in the surface beds. The southern extremity of this spur apparently falls directly beneath the northern or upthrown side of the fault. On the south side of such a stream valley as is postulated sand and débris from the bluff would make up a large part of the sediments now present, and the later encroachment of the sea would deposit more shaly material on its north side. As wet particles of shale are thought to be subject to greater compression than grains of sand, it seems plausible that settling of the strata, when the overburden had become great, might have been sufficient to cause a break, which was localized by the spur of firmer material on the north side. The absence of evidence of the existence of a corresponding fault in the Mississippian (?) rocks seems to support such an explanation.

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[19] Berger, W. R., The relation of the Fort Scott formation to the Boone chert in southeastern Kansas and northeastern Oklahoma: Jour. Geology, vol. 26, p. 619, 1918.

THICKNESS OF THE BARTLESVILLE AND BURGESS (?) SANDS.

A map showing the thickness of the gas, oil, and Burgess (?) sands combined discloses several interesting relations, which have a direct bearing upon other problems of the field.

The lenticular character of the oil sand has been suggested by the well-log correlations, by the irregularities in it shown by contours on the upper surface of the oil-yielding beds, and by the variations in thickness of the strata between the upper surfaces of the pink lime and the gas sand. The irregular thickness of the sandstones themselves also suggests lenticularity. The conditions of deposition of the sandstones, as indicated by the presence of coal and the nature of the pre-Pennsylvanian topography, probably would favor the formation of such laterally discontinuous layers.

No thinning of beds over the North Cochahee dome but very pronounced thinning over the South dome was detected by maps of the intervals from the Big lime to the "Mississippi lime" and from the pink lime to the Bartlesville sand and the "Mississippi lime." The combined thicknesses of the "sands" fail to show conclusively any thinning over either dome. Such evidence would indicate that the South dome existed as a hill or as a fold in the rocks prior to the deposition of the beds immediately above the "Mississippi lime" but that the North dome was formed somewhat later than the time when the Big lime was laid down. However, the writer is not aware of other evidence to support this conclusion, and the approximate parallelism of the North dome to the South dome in the present attitude of the upper surface of the "Mississippi lime" (see fig. 7) would seem to offer some evidence to contradict it.

INFLUENCE OF COMPACTING OF SEDIMENTS.

Blackwelder[20] and Mehl[21] have attributed much of the deformation of strata in the Mid-Continent oil and gas fields to the effect of uneven condensation of sediments due to the differential compression of beds of sandstone, shale, and limestone. The point of their arguments is that the attitude of the rocks is dependent upon the relative thickness of underlying beds capable of being compressed. For instance, a hill of limestone or sandstone that was surrounded and covered by mud deposits would be reflected in the configuration of the overlying strata by a dome, owing to the greater degree of com-

[20] Blackwelder, Eliot, The origin of the central Kansas oil domes: Am. Assoc. Petroleum Geologists Bull., vol. 4, pp. 89–94, 1920.

[21] Paper read at the St. Louis meeting of the American Association for the Advancement of Science, in December, 1919, also Mehl, M. G., The influence of the differential compression of sediments on the attitude of bedded rocks: Science, new ser., vol. 51, p. 520, 1920 (abstract).

pacting which it is possible for the wet muds to undergo. Evidence that this process has been effective in the Pershing field has not been brought together in such a way as to show its quantitative value, but the fact that some minor features (as, for instance, smaller domes in the pink lime) are, in part at least, to be explained in this manner is scarcely open to doubt, and the writer's interpretation of the pre-Pennsylvanian (?) topography (a stream valley and a hill below a present syncline and anticline) certainly seems to lend itself well to the theory.

THINNING OF STRATA OVER DOMES.

Secondary causes and apparent thinning.—Discussion of the compression of beds naturally calls up the problem of a satisfactory explanation of the general thinning of strata over domes and anticlines which is so commonly observed in Mid-Continent oil fields and elsewhere. As it is hoped that this report will be of some assistance to other investigators of the underground geology of oil fields, brief mention will here be made of criteria to be sought for in a study of this question. All hypotheses to account for this relation must necessarily fall into one or the other of two classes, arguing either that the thinning is the result of circumstances originating after the beds were laid down, or that it was caused by conditions contemporaneous with deposition. Although most geologists hold to explanations of the second class, the postdepositional causes involved in explanations of the first class should be briefly mentioned. In explanations of both of these classes the difference between a merely apparent and a real decrease of thickness over the domes should be recognized.

As an example of apparent thinning the possible effect of strictly parallel folding might be cited. If the rocks involved in folding were sufficiently competent to be bent without much distortion, strictly parallel folds might be formed. In such folds vertical sections taken high on the sides of an anticline would find the deeper-lying rocks (down to a certain depth) more steeply inclined than the surface rocks, because of the parallelism of the strata to the more closely folded rocks about the axis of folding, but near the middle of a syncline the converse (gentler inclinations at lower depths) would be true. The differences in the thickness of a given bed at different points on the fold would be only apparent and would depend upon the angle of inclination of the bedding planes—that is, steeply inclined beds might conceivably underlie approximately horizontal beds, and even though inclined and horizontal beds were of approximately the same thickness the steeply inclined beds would be penetrated for greater distances and so would appear thicker. However, it seems improbable that this explanation applies in the Mid-

Continent fields, for the incompetency of the rocks that form much of the section would have permitted squeezing of the strata, so that the bedding planes would not remain strictly parallel.

If, however, the thinning is in part real its amount might be apparently augmented by the angle at which the beds are penetrated by the drill. The degree of increase thus explained would be very slight, as a dip of 200 feet to the mile would cause an apparent thickening of somewhat less than 0.1 per cent above the thickness of the same bed where horizontal, whereas in some of the fields certain intervals are approximately twice as thick in synclines as on anticlines.

Actual thickening of strata in the synclines and the associated divergence between the dips of the upper and lower rocks might be accounted for by squeezing during folding of the softer beds or by unequal settling of the sediments. According to the generally accepted idea of the squeezing of soft strata during folding, thickening along anticlinal and synclinal axes and thinning on the flanks would be expected, and the softer shale beds would show much greater variation in thickness than the beds of limestone and sandstone. These fundamental characteristics apparently eliminate this explanation as a possible cause of the conditions existing in most of the Mid-Continent fields.

Contemporaneous causes.—The processes that remain to be considered in searching for an explanation of the thinning of the strata over crests of upfolds are those which occurred while the beds were being deposited. As has been stated, geologists in general are inclined to attribute the observed thinning of beds to processes of this nature. They postulate that the anticlines were being continually uplifted throughout long periods of time and either that they existed as islands rising slightly above the sea or that the region was inundated but that the water was much shallower over the anticlinal crests.

The most generally accepted theory is that the hills were covered by the sea and that thicker deposits were formed in the depressions than on the elevated areas. Unless the tops of the hills were subject to wave or current action, however, no satisfactory reason is known why more material should accumulate in the low areas than on the flooded hills. Wave or current action would be expected to transport the lighter particles and to leave behind the coarser sand grains, so that more sandy beds would be found on the crests of anticlines than in the surrounding synclines.[22] This condition is by no means

[22] At the meeting of the American Association of Petroleum Geologists in March, 1922, a paper was presented by Burton Hartley which is reported to have offered evidence that in the Barnsdall field in Osage County ocean currents were divided by contact with such an elevated area and removed the shaly material from its slopes, leaving relatively clean sand.

found to be universal, and in the Pershing field it certainly does not-exist.

The writer thinks that the evidence in the Pershing field points unmistakably to the conclusion that the hill of "Mississippi lime" underlying what is now the South Cochahee dome existed as an island during at least a part of the time that the seas were filling the surrounding valleys with sediments. The similarity of the dips in the pink lime and the oil sand, contrasted to the great divergence between the inclination of these beds and the upper surface of the "Mississippi lime," and the absence of any noticeable thinning of the interval between the upper surfaces of the pink lime and the gas sand over the domes indicate strongly that most of the variations in thickness of the interval between the pink lime and "Mississippi lime" are the result of the break in sedimentation represented by the unconformity.

It seems reasonable to suppose that other unconformities [23] might be of sufficient magnitude to cause corresponding variations in thickness higher in the section and thus account for the remainder of the thinning of the strata over the domes.

PRODUCTION OF OIL AND GAS.

STATISTICS.

Methods of study.—An examination of the relation of geologic conditions to the accumulation of oil and gas in any particular area is necessarily either a rough qualitative comparison or a more or less exact statistical study of the facts available. Much has been written regarding the qualitative relation of various factors to the occurrence of petroleum, but it is one purpose of the study of the Pershing oil field to analyze and determine so far as possible the quantitative importance of each of these factors. Much of this work remains to be done, as it was thought advisable to determine first the outstanding geologic conditions of the field.

To isolate certain sets of facts for individual study, to be freed from the confusion of much detail which is not germane to the subject of the study, and to obtain a broad view of the interdependency of facts, the use of graphs of some sort is essential. In this study the writer has endeavored to follow the plan of first assembling the reported facts into maps and then plotting against one another on coordinate paper the features between which a connection is suspected or shown by the maps. It is thought that only by some such procedure may the significance and value of many relations be determined.

[23] Bloesch, Edward, Unconformities in Oklahoma and their importance in petroleum geology: Am. Assoc. Petroleum Geologists Bull., vol. 3, pp. 257–270, 1919.

Individual well records.—Within the last few years a great deal of information has been contributed to the knowledge of the behavior of producing wells by studies of curves showing the decline of production in individual wells, but the writer is of the opinion that the initial yield of a well and its total production when finally abandoned constitute all the data necessary for a strictly geologic study. Certainly the addition to these facts of the length of time the well is producing is sufficient for such a study. The confusion that arises from introducing into the study irregularities of curves due to the way the wells are managed, accidents, and other incidental causes—factors which can but rarely be so accurately evaluated as to permit a correction of the data to a standard—is so great as to obscure entirely relations that might otherwise be more or less obvious. It is not meant, of course, to imply that decline curves are not extremely valuable for purposes of taxation and various technologic problems, but the production records that have been kept in nearly all oil fields are so meager that a more detailed compilation of the data is unjustified in view of the results obtainable. Very few operators now take and in the past fewer still have taken gages of the production of individual wells, as they are usually satisfied with the measurement of the oil produced by the entire lease, or by groups of wells, before it is carried away by the pipe-line companies.

In the Pershing field, as throughout other parts of Osage County, the available records consist of figures showing the gross monthly amount of oil taken by pipe-line companies from the several leases, regardless of the number of wells that are yielding oil or gas in each month. The customary treatment of such data in the construction of individual decline curves is to divide the gross production for each month by the number of wells producing during the month. This method gives fully as accurate average decline curves as the data warrant, but it shows no differences between the large and small wells in the same lease and does not furnish information that would permit taking into account the unique features associated with certain localities.

A method of working up data of this type which the writer thinks utilizes all the information available and yields the most reliable results that it is possible to obtain when gages of individual wells have not been taken is, briefly, to divide the gross production proportionately according to the reported initial yield of the wells. As not all the wells started producing on the same day, however, it is necessary to take into account the effect of the time element in such a distribution, and as in most fields production does not decrease by the same percentage during equal intervals of time, it follows that a division which is proportionate to merely the initial production would not, even theoretically, yield accurate results. One added refinement to this method therefore seemed necessary. The procedure used was as follows:

On a prepared form the initial production, the dates of completion and of abandonment, and the occasional gages and estimates that were available were written for each well. A generalized decline curve for the region[24] was plotted on a large scale, and from this curve, starting with the reported initial production, the theoretical average daily production for each well by months was computed. For each month in which a gage had been taken or abandonment dates given the theoretical average was corrected to the amount thus shown, and the figures for subsequent months were modified accordingly. These figures, representing the theoretical daily production for each well for each month, were then multiplied by the number of days during the month in which the well produced, and the resulting products for each month were added. This gave the gross production of a lease according to three assumptions—(1) that the initial production as reported for each well was essentially correct, (2) that the decline of the wells was approximately the same as shown by some average curve, and (3) that the average curve used was applicable to this field. It remained, then, to check these sums against the monthly pipe-line runs of each lease and to compute the discrepancies in terms of percentage. This percentage factor for each month was then applied to the theoretical daily production of each well for that month, and the result was accepted as the probable average daily production of the well.

It might seem at first thought that it is needless to continue the computations from the curve after all the wells in the lease have begun to produce, but it must be remembered that large wells generally decline more rapidly than small ones in the same length of time. Therefore, although the chief purpose of the method has been accomplished in the month when the last well in the lease has been completed, it requires but slightly more work to continue the process and obtain results much more nearly correct.

One disadvantage of this method is its inherent tendency to make the behavior of all wells approach an average (the generalized decline curve of the region). No means of obviating this difficulty is known to the writer, but it is a far less potent factor in this method than in any others used. It is true that this method is laborious and that in a large measure it depends for its success upon the reliability of the decline curve of the region. The work entailed, however, is not nearly as great as might be expected, for the use of an ade-

[24] Manual for the oil and gas industry, p. 82 (Pawhuska-Wynona district, Osage County, Okla.), U. S. Bur. Internal Revenue, 1921.

quate form on which to enter the data immensely expedites the procedure. The writer estimates that it required on an average about one hour for him to compute the daily production of twenty wells for twelve months by this method.

After the past daily production of the wells has been ascertained the ultimate (total past plus total future) production of those wells that have not been abandoned remains to be estimated. Two methods of estimating the future production of a well by the use of records of past production are possible. Either the record of the well is plotted and the curve thus described is extrapolated to the vanishing point, or else the average behavior of other wells in the field that have declined to no production is applied, according to Beal's "law of equal expectations."[25] A combination of the two methods probably furnishes the most accurate estimate. The points representing the past production of some of the wells may be shifted on logarithmic paper until they can be extrapolated as a straight line,[26] but better estimates of the future records of wells that do not show so regular a history can be made by comparison with the performance of similar but more normal wells.

Use of well data.—With the finally accepted figures showing initial and ultimate production the writer plans to study the quantitative effect of each of the many factors which are generally thought or which are here suspected to bear a relation to the occurrence of oil and gas by plotting these variables on coordinate paper. This method of analysis consists briefly in plotting the initial against the ultimate production of a well along the abscissa and the ordinate respectively and placing on the point so marked some distinctive symbol representing the third variable. For instance, all wells that are located in areas of essentially the same degree of dip would be represented by the same symbol, and when all the wells in the field are plotted in this manner the effect or absence of effect of the steepness of dip upon the initial yield, the total yield, and the relation of initial to total yield would be clearly shown. For areas where definite relations are not intricately obscured by conflicting factors, it is possible to draw a line on such a completed graph through all points representing the same degree of the third variable.

It is planned to study by this method the relation to oil and gas production in the Pershing field of such possibly important factors as position of wells with reference to structure (including vertical distance below and horizontal distance and direction from the

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[25] For a discussion of methods of estimating future production of oil wells see especially Beal, C. H., The decline and ultimate production of oil wells, with notes on the valuation of oil properties: U. S. Bur. Mines Bull. 177, 1919; also Manual for the oil and gas industry, pp. 72–94, U. S. Bur. Internal Revenue, 1921.

[26] Manual for the oil and gas industry, pp. 78–79, U. S. Bur. Internal Revenue, 1921.

crests of the domes; direction, intensity, and regularity of dip; occurrence of faults and subsurface escarpments; and drainage areas of different parts of the domes), lithology of the beds (including color and thickness of oil sands and associated shales, proximity to the plane of the unconformity, and porosity), chemical and physical properties of the oil, gas, and water, and some of the drilling practices (such as the spacing and date of completion of wells).

RELATIONS TO GEOLOGIC AND OTHER CONDITIONS.

ULTIMATE OIL AND GAS PRODUCTION.

In order to gain a comprehensive idea of the yield of the wells for comparison with other facts it was thought advisable to construct a map of the field that would show these features. A map showing the ultimate production of each well, particularly if the effect of differences of spacing could be evaluated, would unquestionably approach the ideal as nearly as possible, but the writer realizes that even these data would fall short of showing perfectly the location and size of the oil accumulations, because the ultimate production of a well depends upon a great number of factors besides geologic conditions—for instance, the depth drilled into the sand, proximity to other wells and their age and yield, casing leaks, periods of pumping, and general management. Such a map, however, would take into account the varying decline of different wells and would be essentially a map showing the yield of oil and gas to the acre, but as the ultimate production of all the wells has not been estimated and the quantitative importance of differences of spacing has not been determined, the construction of such a map is impossible at this time.

Although no method has yet been worked out by which the effect upon productivity of the distances between wells could be determined, it seems possible that any one of several methods of attack might be successful. Valuable results have been obtained by directly comparing the oil recovery with the spacing of wells.[27] The reliability of the results obtained by this method depends upon the number of wells examined and the diversity of the conditions associated with them, because the other factors that affect production are not separated out to make the results clearer. The total amount of previous production near a new well would throw light on interference between wells, as would also the length of time the older wells had been producing and the effect of new wells upon the older ones. On the assumption that the area drained by a well is essentially circular it would seem justifiable to conclude that, other things

[27] Swigart, T. E., and Schwarzenbek, F. X., Petroleum engineering in the Hewitt oil field, Okla., pp. 31–35, U. S. Bur. Mines, in cooperation with the State of Oklahoma and the Ardmore Chamber of Commerce, 1921.

being equal, surrounding wells would affect the well studied inversely as the square of the distance between them. If some method of bringing these various factors together could be devised it would give data that would show not only the effect of the closeness of drilling but the rate at which the drainage area of a well is extended and would throw light on other problems of similar nature. For instance, these data would probably show for just how long after an area had been first drilled it would be profitable to undertake a program of closer drilling, although the advisability of such a program of course depends also upon such other considerations as rate of interest on capital and the drilling programs of neighboring leases. By comparing the conditions under which new wells in the undrilled areas within the field are likely to produce with the conditions under which similar old wells have produced, it would be feasible to estimate the probable ultimate recovery from the entire field. Estimates thus obtained could be computed to a theoretical standard well spacing, and these figures would furnish information from which such a map could be constructed.

OIL AND GAS PRODUCING BEDS.

The strata that are productive of commercial quantities of oil or gas in the Pershing field are called by the drillers, in descending order, the Layton sand, the Big lime, the "Oswego lime," the Bartlesville sand, and the "Mississippi lime." Indications of oil or gas are reported from beds at many other horizons, and much of the oil and gas credited to the "limes" named actually comes from associated sandstones. By far the greater part of the oil and gas produced in the Pershing field is obtained from the Bartlesville sand, and most of the information available pertains to the petroleum in this bed. However, the distribution and amount of production from other sands are unquestionably important and are to be worked out in as great detail as the information warrants before the completion of this study.

OIL FROM SHALLOW SANDS.

As has been mentioned, the few wells that produce oil from the shallow sands fall into alinements roughly parallel to the buried scarp. In T. 24 N., R. 10 E., the Midland Securities Co.'s well No. 14, in the NW. ¼ sec. 8; the New England Oil & Pipe Line Co.'s wells Nos. 8 and 16, in the SE. ¼ sec. 5; and the Plover Drilling Co.'s well No. 13, in the SW. ¼ sec. 4, all producing oil from the Big lime, and the Midland Securities Co.'s Big lime well No. 17, in the NW. ¼ sec. 8; a small gas seep in the NE. ¼ sec. 8; and the Plover Drilling Co.'s well No. 14, in the SW. ¼ sec. 4, which produced oil from the Layton sand, fall approximately into two parallel straight lines which coincide with the strike of the pink lime at those places. (See Pl. VII.) It is interesting to note that the gravity of the oil from the Big lime is closely similar to that of the oil from the Bartlesville sand in nearby wells (36° to 40° Baumé), but the oil from the Layton sand is reported to have tested 32° Baumé, and the oil from the Bartlesville sand in the adjoining well had a gravity of 41° Baumé. The alinements mentioned might be interpreted as suggesting faults, the oil and gas having migrated along the fault planes into upper sands. As no other evidence indicating the existence of faults in this part of the field has been discovered, and as the distribution of the reported indications of petroleum in these sands has not been worked out in detail, it is not thought that such an assumption is justified at present.

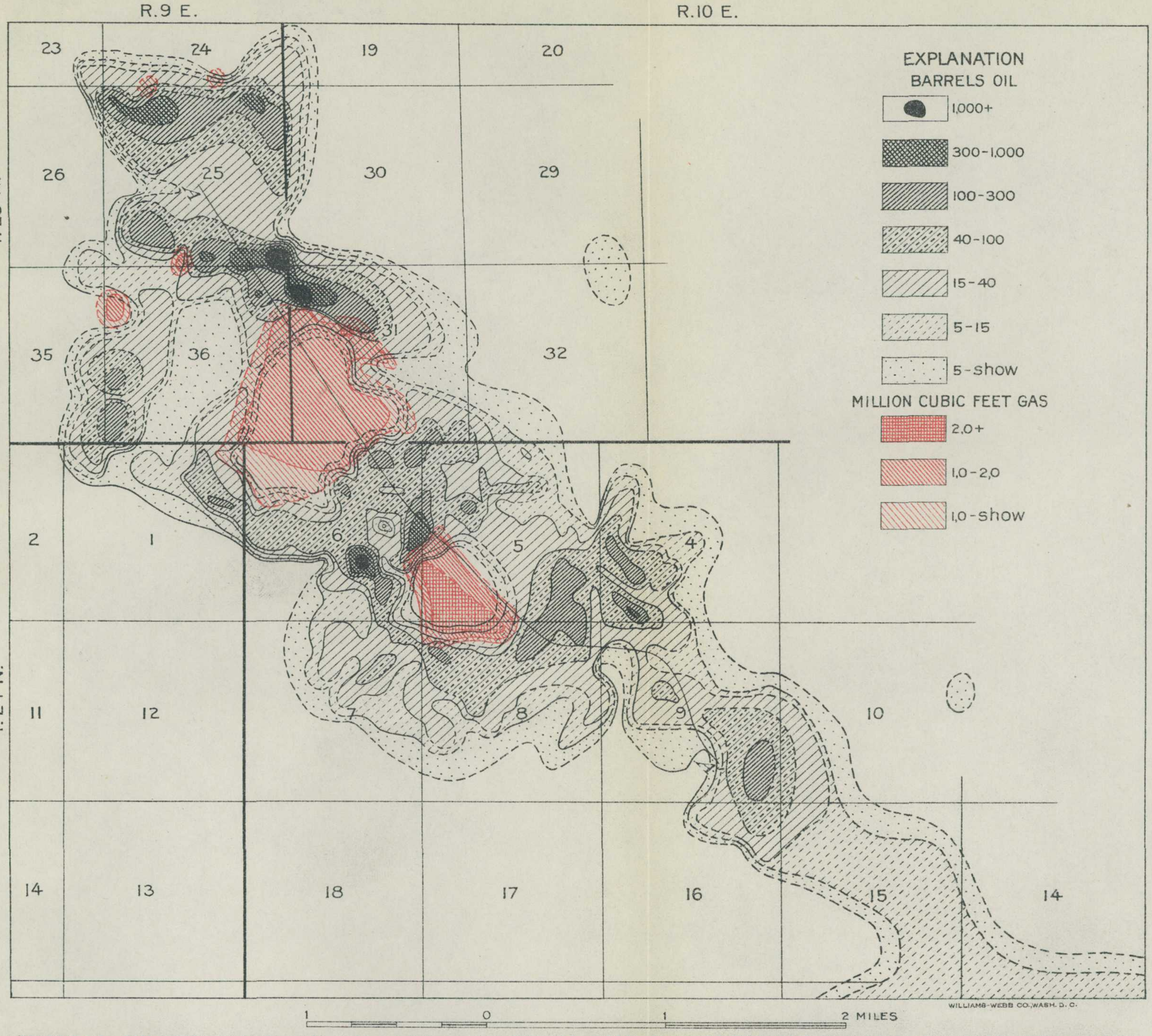
It is likewise impossible to state at this stage of the investigation the probability of obtaining more widespread oil production from the shallow sands. In the light of the unanalyzed evidence it hardly seems probable that these strata will receive serious consideration until the Bartlesville sand is depleted.

PRODUCTION FROM THE "MISSISSIPPI LIME."

Wells drilled into the "Mississippi lime" have in the main resulted in disappointment. With the single exception of the Echo & Whittier well No. 1 (now Indian Territory Illuminating Oil Co. gas well No. 168), in the NE. ¼ sec. 6, T. 24 N., R. 10 E., no wells have found oil or gas in commercial quantities in this limestone series, although it has been penetrated to a depth of several hundred feet in a number of wells in what would generally be considered favorable localities. (See fig. 11.) The data from the Pershing field alone would scarcely warrant enthusiasm over the oil possibilities of these deeper beds, although the fact that oil is obtained in other parts of Osage County from beds below the upper surface of the "Mississippi lime" is encouraging.

INITIAL PRODUCTION FROM THE BARTLESVILLE SAND.

Reliability of map.—In the absence of sufficient data to construct a map showing the ultimate production of wells, the reported initial 24-hour yields of oil and gas from the Bartlesville sand were plotted on a map, and lines were drawn through areas of the same production. It was at once evident that the differences between some adjoining wells were so great that modifications of some sort must be made. The average initial production of the entire field by months was plotted on coordinate paper and found to show a general decrease from the time when the field was discovered. This was to be expected, as the decline of gas pressure would naturally



INITIAL PRODUCTION OF OIL AND GAS FROM THE BARTLESVILLE SAND IN THE PERSHING OIL AND GAS FIELD AND VICINITY, OSAGE COUNTY, OKLA.

Reduced to date of Jan. 1, 1921, by using dates of completion of wells and general decline of initial production in various parts of field.

reduce the yield of later wells, although a part of the decrease might be ascribed to the fact that the more favorable locations were drilled first. Whatever its explanation may be, the decrease furnished data from which a smooth curve representing the average decline of initial production in the field could be drawn. With this curve and the dates of completion of the wells, the effect of the date of drilling upon the yield of the wells could be practically eliminated by reducing all reported initial yields to the same date. This gave a theoretical set

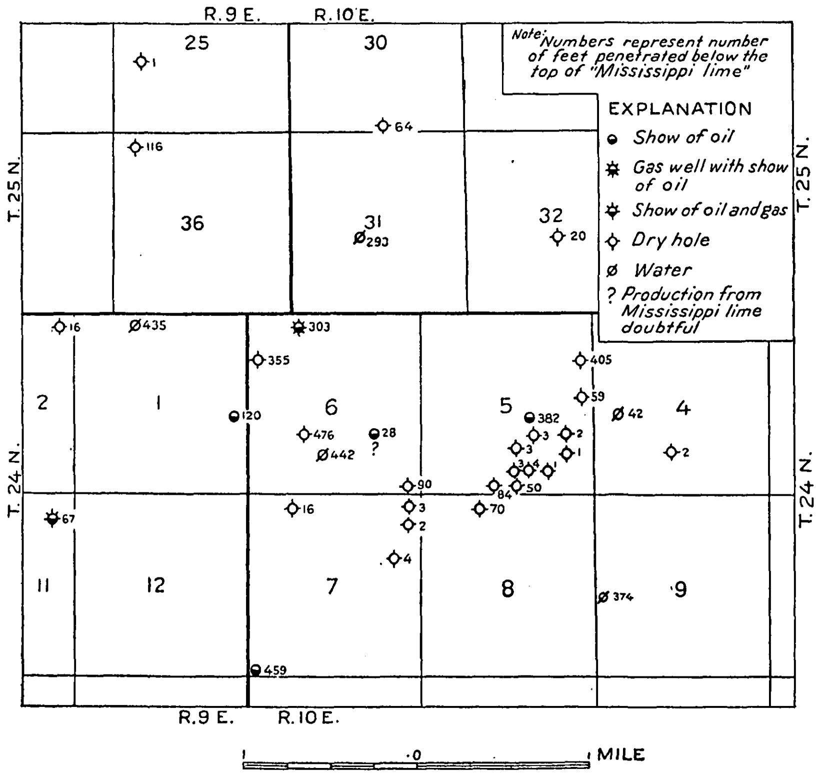


FIGURE 11.—Map showing wells reaching the "Mississippi lime" in the Pershing oil and gas field, Okla.

of figures that still showed the effect of intense local drainage—for instance, the area of low initial production in the east central part of sec. 6, T. 24 N., R. 10 E., which lies between the two areas of larger initial production shown in Plate IX. A varying interval between the lines showing equivalent initial production (1,000 to 300, 300 to 100, 100 to 40, 40 to 15, etc.), which if plotted would be roughly comparable to an average decline curve, tends further to eliminate irregularities.

Features shown by map.—The completed map with these corrections (Pl. IX) shows the major elongation of the oil-yielding beds from northwest to southeast, which is interesting, as it follows a line not suggested by the structure of the beds. This is particularly noticeable in the southeastern extension of the field, where the oil is found in a line that obliquely intersects the monoclinal dip. This alinement in no sense parallels the shore lines of the sea in which the oil-bearing sediments were deposited, as is said to be the case in some fields, at least according to the findings shown in figure 9 of this report, to Berger's map of the Cherokee basin,[28] or to McCoy's paleogeographic maps,[29] and the elongation of the main body of the oil sand in that direction is not suggested by contours of its thickness, nor by evidence regarding the position of possible streams or channels at the time it was deposited.

The occurrence of "edge water" at a higher elevation on the northeast side of the field (p. 40) suggests that possibly the regional movements of underground water might have been a contributing cause of such an arrangement of the oil, but more knowledge of the effect of circulating water on the movement of oil in general and the rate and direction of flow of ground water in Osage County is necessary before the existence of such a process can be recognized. This northwest-southeast line is parallel to the regional strike of the upper surface of the "Mississippi lime" as shown by Gardner,[30] although it does not follow the detailed configuration of that surface within the field itself (fig. 7). Just what connection is signified by this parallelism is subject only to speculation, but it seems possible to the writer that water in the basal Pennsylvanian (?) beds migrating downward away from the nearest outcrop might tend to drive oil before and along with it in lines parallel to the regional strike and that geochemical reactions might take place at a certain general depth which would cause greater cementation in the rocks or greater viscosity of the oil and thus bring about the accumulation.

Plate IX shows other alinements at variance with the major one, some at right angles and others oblique to it. Most of these minor lines follow the strike of the rocks in the immediate vicinity, and no evidence has been found that their orientation is controlled by faults or truncated edges of possibly oil-bearing Mississippian (?) rocks below the unconformity.

The most cursory examination of this map, in connection with the relation of the gas to the recovery of oil, suggests that possibly the greater abundance of large wells on the flanks of the South dome may be due to the conservation of the gas pressure, as fewer gas

[28] Berger, W. R., The relation of the Fort Scott formation to the Boone chert in southeastern Kansas and northeastern Oklahoma: Jour. Geology, vol. 26, p. 619, 1918.

[29] McCoy, A. W., A short sketch of the paleogeography and historical geology of the Mid-Continent oil district and its importance to petroleum geology: Am. Assoc. Petroleum Geologists Bull., vol. 5, No. 5, pl. 4, D, 1921.

[30] Gardner, J. H., Mid-Continent geology; North American oil and gas, a supplement to the Oil and Gas Journal, May 30, 1919, p. 11.

wells have been drilled there than on the North dome. It is also possible that the greater area in which gas wells have been drilled and the lesser number of oil wells on the North dome may be the result of a larger gas reservoir there. Only a detailed study of the records of oil and gas production on the two domes could be expected to solve this problem. Such a study has not yet been made. Proximity to the edge of the pool and consequently probably to "edge water" is usually accompanied by smaller yield, but there are exceptions to this generalization, the most striking of which is probably that in the SW. ¼ sec. 6, T. 24 N., R. 10 E., near the line of the subsurface scarp. It may also be significant that the areas of very large wells in the eastern and southeastern parts of the same section fall on or just to the north of this same scarp.

The association of more productive or longer-lived wells with a thicker oil sand is a widely accepted generalization, and it is somewhat surprising to find that apparently there is no such relation in the Pershing field. The map showing the thickness of the Bartlesville and Burgess (?) sands certainly discloses no consistent relation of thickness to the initial yield of the wells, and it can be definitely stated that no connection whatever is discernible between the initial yield and the depth drilled into the sand. A comparison of the ultimate production of the wells with the thickness of the actual oil-yielding beds (the "pay sands") might show some relation, however.

A close comparison of the maps showing initial production and the structure of the pink lime indicates that in general the oil is found on the flanks of the domes and that the wells are perhaps somewhat smaller on the northeast flanks than elsewhere. Further than this, however, it is difficult to find a connection between the two maps, as the more productive wells are certainly not associated with the smaller anticlines in the pink lime. This lack of association might conceivably be interpreted as evidence tending to substantiate the inference, drawn from a comparison of the structure of the pink lime with that of other beds, that the warping of the pink lime is largely local to that stratum and is not reflected in the beds above and below it.

Nonproductivity of domes.—Another striking fact shown by comparison of these maps is the absence of oil on the crests of the two domes—in fact, the data show that in some places neither gas nor oil is found by wells that have been drilled nearest to the crests. Most cross sections of the domes reveal a gradual increase in the yield of oil wells upward from the edges of the field to points high on the flanks and then an abrupt decrease of oil, which in some places is not compensated by the presence of gas, leaving the tops of the domes barren, at least of oil. (See fig. 12.) Although this condition would probably be considered unusual by most geologists, there is some evidence indicating that it is not unique to the Pershing field. In the early development of the region a hole drilled near the crest of the Saucy Calf anticline proved to be dry, and this had the effect of restricting prospecting there until development of the Cochahee domes had aroused renewed interest in the area.

Mason[31] in 1919 gave data which seem to show that similar conditions exist in many of the other oil fields in Osage County. He stated that of the wells on the 33 domes or anticlines about which he

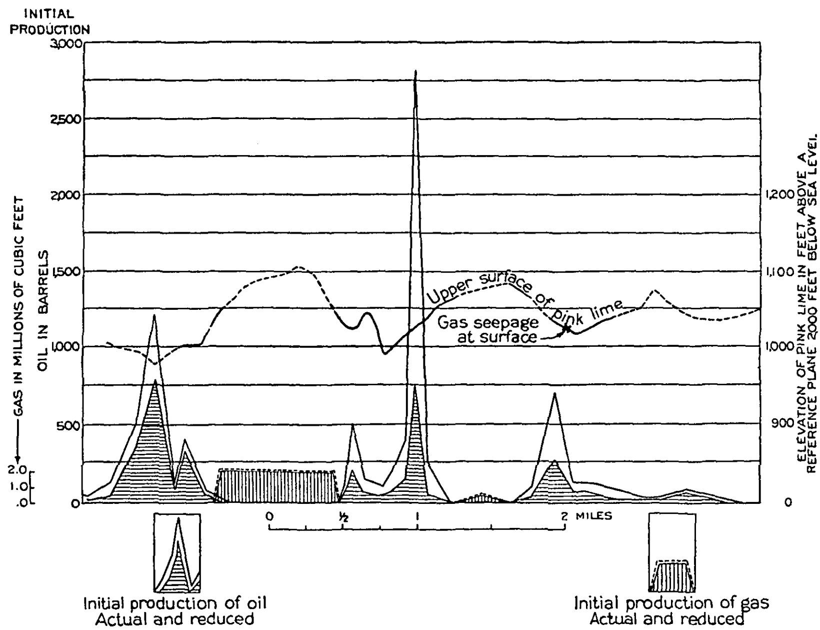


FIGURE 12.—Diagram showing the relation of the initial production of the wells in the Pershing oil and gas field, Okla., to the structure of the pink lime along a line extending from northwest to southeast across the field. Vertical exaggeration of attitude of pink lime about 26 times. The upper of the two lower curves represents the actual initial production; the shaded areas the theoretical initial production reduced to date of January 1, 1921.

had some information, 75 per cent of those drilled in the lower half of the area of closure, as shown by the surface structure, yielded oil and 7 per cent were barren of oil or gas, but that only 60 per cent of the wells in the upper half of the area of closure were oil-bearing and 11 per cent were dry. Analyzing the domes further by studying wells located the same distance above the highest parts of the bounding synclines, he found a gradual decrease in the percentage of gas wells upward to the crests, and a decrease of oil wells which he states "is partially compensated for by an increase in gas production, but, taking them together, the increased value of higher zones that might

[31] Mason, S. L., A statistical investigation of the effects of structure upon oil and gas production in the Osage: Am. Assoc. Petroleum Geologists Bull., vol. 3, pp. 409–410, 1919.

be expected is not found." Mason considered merely the barrenness or the productivity of the wells and took no account of their relative yields; moreover, his study dealt only with the folds as shown by outcropping beds. In the Pershing field an analysis of this sort would hardly show similar results, as only one totally barren well was located high on either of the domes and several dry holes were drilled around the outskirts of the field, but an examination of the yield of the wells unmistakably shows the same relative barrenness of the crests. Similar barrenness or light production in the higher parts of the folds have been observed in several fields in Oklahoma that have been studied in detail.[32] If this condition is as widespread as the observations indicate it is of intense practical importance to the oil operator to recognize its existence as soon as possible in the development of a new field.

Cause of barrenness.—Several possible explanations of this barrenness of the crests in the Pershing field that seem to be in accord with the conditions existing there might be offered, but none of them are capable of proof. Speculation as to the processes involved is profitable, however, if it succeeds in establishing some of the fundamental criteria to be sought for in subsequent investigations in areas where similar conditions exist. For this purpose some of these explanations are here briefly set forth.

Examination of the lithology of the oil-bearing beds might yield a clue. Specimens of the oil sand thrown from the holes in shooting the wells are being investigated by A. F. Melcher, of the United States Geological Survey, to determine the porosity, permeability, coarseness of the sand grains, nature of the cementing material, and other important characteristics. A regrettably small number of samples were collected, and a number of those that were taken seem to be not truly representative of the oil sand proper, but the results that have been obtained by Mr. Melcher indicate strongly that the porosity of the oil sand on and near the top of the South dome at least is less than that of the sand on the flanks and in the synclines. Such a relation points to the presence on the tops of the domes of a greater amount of finely divided material to fill the spaces between the grains of the sand. If this is the case it is of extreme importance to determine the nature of the cementing or filling material. Qualitative chemical analyses and rough microscopic examinations by Mr. Melcher and the writer apparently indicate that the presence of minute, probably secondary calcite crystals is associated with the lower porosity. Fragments of these sand samples are being quantitatively analyzed for their calcite content in the chemical laboratory

[32] Swigart, T. E., and Schwarzenbek, F. X., Petroleum engineering in the Hewitt oil field, Okla., p. 113, U. S. Bur. Mines, in cooperation with the State of Oklahoma and the Ardmore Chamber of Commerce, 1921.

of the United States Geological Survey to determine the part that calcite plays in the reduction of pore space in the oil sand in the Pershing field.

Should the assumption that secondarily deposited calcite is the principal pore-filling material (a condition which is commonly thought to exist in many oil fields) prove to be correct, its greater abundance in the upper parts of the domes still remains to be accounted for. It might be due to the precipitation of calcium carbonate in the sands on the crests of the domes, to its solution from the sands on the flanks, or to a combination of both processes. Washburne[33] has discussed evidence indicating that calcium carbonate has been dissolved from the oil sands of many fields and mentioned possible causes of this process, with distinguishing characteristics that would be expected. No data are obtainable on the degree of cementation of the sands in the lower parts of the synclines surrounding the Pershing field, but the writer thinks that precipitation of calcium carbonate in the sands on the domes is equally probable, and the possibility of this process being effective should be considered. Such precipitation might be caused by reactions between different ground waters or by concentration of one water through the lowering of pressure upon it or through its evaporation.

Decrease of pressure upon a water, the lowered temperature following expansion, and the consequent reduction of its solvent power might result from the natural or artificial escape of imprisoned gases or liquids or a general lowering of the hydrostatic head.

The gas might escape from the sand into the underlying or the overlying beds along fault planes or at points where the adjacent strata are least impervious. It is possible that minor faults have been produced on and near the crests of the domes during the deformation of the strata, and gas could have leaked out of its reservoir along these faults. While the field work for this study was being done a very small seepage of gas from a joint plane was noted in the bed of the stream in the NW. ¼ sec. 8, T. 24 N., R. 10 E. (See Pl. VII.) Although this gas might have been coming from one of the wells several hundred feet distant, it nevertheless proves conclusively to the writer that vertical migration of gas through alternating beds of sandstone and shale is possible. Where gas escapes along fault planes, however, the zones of cementation and consequently of low porosity and small production would be expected to be relatively straight, narrow, and probably in large part on the flanks and not the crests of the domes. As the barren areas in the Pershing field correspond approximately to the upper parts of the domes—the lines bounding the areas of small wells essentially

[33] Washburne, C. W., Oil-field brines: Am. Inst. Min. and Met. Eng. Trans., vol. 65, pp. 276–279, 1921.

paralleling the structure contour lines—it would seem that some other explanation must be sought.

The lenticularity of the Bartlesville sand, suggested by evidence of several kinds, would furnish conditions favorable to the escape of gas from the tops of the domes through less impervious parts of the adjacent strata. Less intercalated shale would be expected in sandstone formed in the shallow water over the hills than in sandstone formed in the surrounding valleys, because of the probably greater wave action in the shallow water. A more precise knowledge of the distribution and character of the individual sandstone lenses is necessary before the effectiveness of this explanation can be properly evaluated.

Lateral expansion of the gas reservoir from the highest parts of the domes followed by sealing of the upper margin of the oil might have been caused by lowering of the hydrostatic head following general uplift of the region or by the extraction of oil and gas from the sand by wells drilled to it, but the possibility of the occurrence of such an expansion and its effect upon cementation can not well be determined at this stage of the investigation.

Decrease in quantity of the solvent liquid might have been caused by evaporation of water vapor to moving gas, a process which has been experimentally studied by Mills and Wells.[34] As the gas underground must be nearly saturated with water vapor at all times, Washburne[35] has called attention to a possible supplementary process—the migration of water vapor by diffusion through entrapped gas from larger to smaller pored sediments. Another possible explanation might be the evaporation of water vapor into unsaturated gas where the carbonate-bearing liquid lies in actual contact with the main gas reservoir. The shape of the areas in the Pershing field that are inferred to be more highly cemented apparently lends some weight to such an explanation, but two of the conditions essential to it—the presence of sufficiently unsaturated gas and the contact of the water with the gas reservoir (the separating oil being absent or so disseminated as to be noneffective as a barrier)—are thought to be so improbable as to render the explanation invalid.

Reeves[36] has offered the theory that the greater amount of carbonates in the pore spaces of the Whitehorse sandstone on the axis of the Cement anticline is due to the decrease of pressure and the lowering of temperature of ground waters forced upward toward

[34] Mills, R. V. A., and Wells, R. C., The evaporation and concentration of waters associated with petroleum and natural gas: U. S. Geol. Survey Bull. 693, 1919.

[35] Washburne, C. W., Oil-field brines: Am. Inst. Min. and Met. Eng. Trans., vol. 65, pp. 269–270, 1921.

[36] Reeves, Frank, Geology of the Cement oil field, Caddo County, Okla.: U. S. Geol. Survey Bull. 726, pp. 55–56, 1921.

the surface from the materials that were undergoing greatest deformation; and another explanation for the upward movement of water in the Cement field, given by Heald,[37] is that water would be squeezed through shear zones from the consolidating beds around the buried hills to the surface. No evidence has been found in the Pershing field that the strata above and below the oil sand are likewise cemented to an unusual degree, although owing to the nature of the records available such conditions could exist without being detected.

Chemical reaction resulting in the deposition of calcite on the domes in the Pershing field may have been produced by any of several possible causes. Foreign waters may have gained access to the oil sand along fault planes, but the location and shape of the barren areas are somewhat unfavorable to such an explanation, as has been stated. Waters from other beds may also have obtained entrance to the sand from improperly cased oil wells or may have been squeezed out of adjacent shale beds. Reactions between the oil and the water[38] may have directly or indirectly caused precipitation, and there are doubtless many other possible causes which might be mentioned.[39]

The writer favors no particular one of these suggested explanations, as it has not been definitely proved that secondary calcite and not shale is the controlling factor in the lower porosity of the oil sand over the domes. It is indeed possible that the cause of the barrenness is to be ascribed to conditions quite unrelated to cementation. The coarseness of the sand grains, a natural gumming of the oil, or the thickness of the "pay sand" are examples of causes which may be eventually called upon to provide an explanation. Further work upon the information available regarding the Pershing field must be done, and even then success in solving this problem is by no means assured. The facts, however, urgently call for a satisfactory explanation, because of their obvious economic bearing.

PHYSICAL AND CHEMICAL PROPERTIES OF THE OIL, GAS, AND WATER.

Water was collected from producing wells at different places on the edges and near the center of the field and at places where it was mixed with different amounts of oil and gas. Oil samples were taken from wells in the center and near the edges of the field, associated and unassociated with water and gas, and from open tanks where it had weathered for several days. Gas was collected from wells where oil was and was not present. These samples were submitted to the chemical laboratories of the United States Bureau of Mines and the United States Geological Survey, but although the analyses

[37] Reeves, Frank, op. cit., p. 56.

[38] Rogers, G. S., The Sunset-Midway oil field, Calif.—Geochemical relation of the oil, gas, and water: U. S. Geol. Survey Prof. Paper 117, 1919.

[39] Johnson, R. H., The cementation process in sandstone: Am. Assoc. Petroleum Geologists Bull., vol. 4, No. 1, pp. 33–35, 1920.

have been completed, interpretations of their possible significance have not yet been made.

Baumé readings of the gravity of the oil were made by the oil companies in several leases in the field, and although the conditions under which they were made probably varied greatly, the major differences are so consistent as to be worthy of notice. Several wells in the northern part of the field found oil that ranged in gravity from 31° to 38° Baumé (chiefly 32° and 33°). A few wells in the central and west central part of the field reported readings of 35° to 39° (usually 37° and 38°), and many wells in the southeastern part yield oil ranging from 38° to 41° (chiefly 41°).

This increase in the Baumé reading of the oil from the Bartlesville sand downward from the higher parts of the domes and southward is striking. Attempts to discover its association with the presence of a cap rock or a shale parting between the oil sand and the gas sand[40] or with the elevation or position relative to the general structure of the containing beds were entirely unsuccessful. The only discernible persistent characters associated with differences in the gravity of the oil were the recorded color and thickness of the oil sand and the yield of the wells. In the wells about which the necessary information was available heavy oil (low Baumé reading) was found in brownish sand that was relatively thin, light oil occurred in comparatively thick gray or white sand, and wells of larger yield in general produced the lightest oil (highest Baumé reading).

It seems possible that the sandstones which were deposited in the shallowest water (as indicated by their lesser thickness) may have been exposed to some sort of aeration that caused the brownish color. Oil later accumulating in such sandstones would probably have been subject to some oxidation, which would increase the actual gravity and lower the Baumé reading. Unoxidized oil might have retained enough of its lighter constituents to serve as an expulsive force and to remain less viscous and so to respond more readily to the gas pressure, thus causing larger production. However, the brown color of the sand may be merely the effect of discoloration by the heavy oil, and greater amounts of gas from any cause whatever would probably make the oil lighter and the recovery from a well greater. A possible explanation lies in differences in the chemical composition of edge waters in different parts of the field.

UNDRILLED LOCATIONS.

Study of the initial production of oil and gas from the Bartlesville sand in conjuction with the structure of the pink lime reveals

[40] Rich, J. L., Oil and gas in the Birds quadrangle: Illinois Geol. Survey Bull. 33, p. 139, 1916.

the fact that at a number of places in the Pershing field the chances of obtaining other oil wells of small and medium yield are excellent. These places are all in the hands of oil companies, and it is quite probable that their worth is fully recognized.

Development of a proved field is of two sorts—the drilling of "inside" locations and the search for possible extensions of the pool. In a field such as the Pershing it is natural to expect that the number of good undrilled locations is much greater in areas protected by line wells than around the margins of the field. It appears, however, that some chances of minor extensions remain.

An example of such a possible extension is found in the northern part of the SW. ¼ sec. 8, T. 24 N., R. 10 E. Wells that may later be drilled there will probably not have an initial production of more than 30 barrels a day, but the area of the extension may be somewhat larger than is here indicated. Less definite evidence indicates that extensions may perhaps be expected in the western and southern parts of the NW. ¼ and eastward along the south line of sec. 4, T. 24 N., R. 10 E., in the western part of the NE. ¼ and the northeastern part of the NW. ¼ sec. 31, T. 25 N., R. 10 E., and in the southern part of the NW. ¼ and the eastern part of the SE. ¼ sec. 7, T. 24 N., R. 10 E.

Possibly productive areas of more than 15 acres inside the Pershing field that have not been drilled include most of the NW. ¼ sec. 8, T. 24 N., R. 10 E., where initial yields ranging from 40 to 75 barrels a day are probable; and the NE. ¼ sec. 8, T. 24 N., R. 10 E., the western part of the NE. ¼ and the northeastern part of the SW. ¼ sec. 5, T. 24 N., R. 10 E.; the southwestern part of the SW. ¼ sec. 32 and the northwestern, central, and the southeastern parts of the SE. ¼ sec. 31, T. 25 N., R. 10 E.; and the southern and eastern parts of the SE. ¼ and the eastern part of the NE. ¼ sec. 36, T. 25 N., R. 9 E., in all of which initial yields of 5 to 40 barrels a day may be expected. (See Pl. VII.)

Sufficient information has not been assembled to demonstrate the advisability of spacing the wells more closely in the Pershing field, although closer drilling would probably have been profitable in 1919 and 1920. The present spacing in the field usually allows for one well to every 6 or 7 acres. The economy of drilling wells to drain every 3 or 4 acres would depend upon the interest rate on capital and the rather difficultly determinable extent and speed of drainage of the oil from the area about each well. It seems very likely that closer drilling in the areas where the sand is least porous would still be profitable.