Geologic Structure in the Cushing Oil and Gas Field, Oklahoma*

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Introduction

DURING the latter part of 1915 and the first half of 1916, the writer held the position of geologist in connection with the conservation work instituted by the U. S. Bureau of Mines, on oil and gas land belonging to the Indians of the Five Civilized Tribes in Oklahoma. The duty of the geologist was to correlate formations containing oil, gas, and water, and to determine the relations of these substances in the different formations so that the conservation agents might carry on their work most intelligently. On account of the rapid development of the Cushing field, which lies in the western part of the Creek Nation, much work was done there by the inspection force.

In the course of the geologic studies a large amount of information was collected, which, on analysis, has disclosed some interesting facts worthy of publication. The report, of which the following remarks are an abstract, has been prepared and submitted to the U. S. Geological Survey for publication. This report is now (June, 1917) in the press and will doubtless be issued in a few weeks.

Methods Used

In addition to the structure maps showing the folding of the Pawhuska limestone, which crops out in several places in the Cushing field, separate structure maps of the three most important productive sands—the Layton (Fig. 2), Wheeler, and Bartlesville—have been prepared. These structure maps were prepared by obtaining the logs of nearly all the wells

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Published to afford opportunity for discussion at the St. Louis meeting in October. In this brief abstract only the more important data and conclusions are given. Published by permission of the Director of the U. S. Bureau of Mines and the Director of the U. S. Geological Survey.

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drilled in the Cushing field, by subtracting the surface elevations from the depth of each sand given in the log of that well, to obtain the elevation above or the depth below sea level of that sand." Inasmuch as the accuracy of structure maps depends upon the accuracy of the elevations and of the logs, the maps prepared cannot, of course, be considered absolutely accurate, but in general they were sufficiently accurate to serve as an excellent working basis in the analysis of the information collected.

In an attempt to prepare a convergence map showing the increase in the thickness between the Layton and Bartlesville sands, the intervals between these two formations, as indicated by the available logs, were plotted on a map, but as the local irregularities were so great that it was impossible to construct a convergence map, the map which accompanies the more detailed report shows only certain groups of the same or similar intervals. For instance, all wells showing an interval of less than 1050 ft. (320 m.) were separated from those in which the interval was between 1050 and 1100 ft., which in turn were separated from the areas where the interval was between 1100 and 1150 ft., and so on.

In studying the oil, gas, and water bodies in each sand, maps showing their relations were prepared by plotting the content of each sand as recorded in the logs collected. In studying the water conditions, the depths below sea level at which water was encountered in certain wells were plotted on a map. This map showed that the depths were very diverse, a fact that led to a detailed study, by the use of contours on the surface of the edge water, of the actual position of the water backing up the oil and gas.

Summary

The work done in the Cushing field has consisted in the study and analysis of the information collected in the course of the inspection of the oil and gas land and the following principal facts have been disclosed as a result:

1. The folding of the formations in the Cushing field usually becomes greater with increase of depth, and there are many marked differences in structure among the Layton, Wheeler, and Bartlesville sands, and the surface beds.
2. The interval between the Layton and the Bartlesville sands is generally greater around the edges of the anticlines than on their crests.
3. The distribution of the bodies of oil, gas and water, indicates that the source of the oil lay west or northwest of the Cushing field.
4. In general, the oil area in an elongated dome where folding is simple extends farther down on the long axis of the anticline or dome than it does on the steeper sides; or, in other words, the area beneath which a sand contains water only extends higher on the steep flanks of an elongated dome than at the ends where the beds are more gently tilted.

5. The water surfaces on which the oil and gas rest in the different sands are not level, but are inclined away from the center of the anticlinal folds. This inclination does not conform with but is usually less than the dip of the bed in which it occurs.

Development

The Cushing field, the most productive light-oil field in the world, embraces nearly 35 square miles (90.6 sq. km.) of productive territory, in which have been drilled about 2500 wells ranging in depth from 1200 to nearly 3000 ft. (365 to 914 m.) (Fig. 1). Oil was first discovered in March, 1912, when C. B. Shaffer and others drilled well No. 1, on the Annie Jones (F. M. Wheeler) farm in the NW. $\frac{1}{4}$ Sec. 31, T. 18 N., R. 7 E., about 1 mile north of the present site of Drumright. This well was drilled to the Wheeler sand and for more than a year and a half this sand produced the entire oil output of the field. In December, 1913, however, the Prairie Oil and Gas Co. completed the first well to the Bartlesville sand in Sec. 3, T. 17 N., R. 7 E. Development has been extremely rapid, especially since the discovery of oil and gas in the Bartlesville sand, and at one time the daily production of the field reached more than 300,000 bbl. of oil. The total marketed output of all the oil sands in the Cushing field has been more than 200,000,000 bbl.

Stratigraphy

This investigation has been only in the nature of a study of underground conditions with a view to determining the relation of the contents of the more important oil- and gas-producing sands, and very little stratigraphic work was done. The rocks of the area, according to Buttram,¹ are exclusively sedimentary and, except the "terrace" sands and the alluvial deposits, are all of late Pennsylvanian age.

In this part of Oklahoma the rocks dip in general to the west, the base of the Pennsylvanian series cropping out in northeastern Oklahoma in the western foothills of the Ozark Mountains. The Pennsylvanian formations at the surface become successively younger as the Cushing field is approached and are hidden from view about 12 miles west of the field by the overlying Permian series. The exact line between the Pennsylvanian and the Permian series is uncertain, but in accordance with the provisional current usage of the Geological Survey it has been drawn at the base of the Cottonwood limestone, which is about 50 ft. above the Neva limestone. It should perhaps be drawn as low as the Neva limestone, or possibly, as some writers think, at the base of the Elmdale,

¹ Frank Buttram: The Cushing Oil and Gas Field, Oklahoma. *Oklahoma Geological Survey, Bulletin* No. 18 (1914).

FIG. 1.

FIG. 1.—SKETCH MAP OF CUSHING FIELD SHOWING GENERALIZED STRUCTURE OF LAYTON SAND AND LOCATION OF PRINCIPAL STRUCTURAL FEATURES. CONTOUR INTERVAL IS 100 FT.

FIG. 2.—COMPOSITE COLUMNAR SECTION SHOWING RELATIVE VERTICAL POSITIONS OF PRODUCTIVE OIL SANDS IN THE CUSHING FIELD AND SOME OF THE BETTER KNOWN FORMATIONS IN KANSAS AND OKLAHOMA.

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FIG. 2.

which embraces 130 ft. of sediments below the Neva limestone of the Kansas section (Fig. 2). This limestone forms an escarpment just west of the town of Cushing, Oklahoma, 12 miles west of the oil field.

The most important outcropping formation in the Cushing field is a prominent limestone, which according to Buttram is probably equivalent to the Pawhuska limestone of northern Oklahoma. Later investigations made by the U. S. Geological Survey in regions northeast of the Cushing field indicate a necessity for some nomenclatural revisions, which, however, are not yet completed. It is even somewhat probable that the limestone called by Buttram the Pawhuska, and used in this report as a key horizon, may not be the same as that conspicuously exposed near Pawhuska.

In the Cushing field the drill penetrates a series of alternating sandstones, shales, and limestones. The limestones apparently become less prominent and the sandstones more prominent toward the south end of the field near Shamrock. According to Buttram,² the Pawhuska limestone near the center of the field in the vicinity of Drumright lies about 2340 ft. (713 m.) above the Wheeler sand. The Bartlesville sand in the Cushing field is supposed to be equivalent to the Bartlesville sand of the fields of northeastern Oklahoma, and lies near the base of the Pennsylvanian series.

Description of the Productive Sands

In the Cushing field, oil is being produced from six different sands—the Layton, Jones, Wheeler, Skinner, Bartlesville, and Tucker.

The Layton sand is found at depths ranging from about 1200 to more than 1500 ft. (365 to 457 m.), the depth depending on the locality. It is productive of oil principally in the northern part of the Cushing field, in the district south and east of Drumright, and in an area a few miles south of Shamrock. Generally it underlies a hard limestone, 10 to 20 ft. thick, called by the drillers the Layton lime, in contrast to the Layton sand, which is a soft sandstone not fully saturated with oil. The top of the sand is at many places barren and the "pay" sometimes lies in streaks, a condition probably due to differences in porosity and to intraformational barriers caused by cross-bedding. The maximum thickness of the sand reported is about 100 ft., and the average of many reports is about 50 ft. At a few isolated points no Layton sand has been found. The sand is coarse-grained, porous, and comparatively soft, and is fairly uniform in texture and porosity. In the Cushing field about 14 square miles of this sand produced oil, and 12 square miles when first drilled into carried much gas.

The Jones sand lies about 200 ft. below the Layton sand and pro-

² Frank Buttram: The Cushing Oil and Gas Field, Oklahoma. *Oklahoma Geological Survey, Bulletin No. 18* (1914), 43.

duces oil in commercial quantities only in a small area on the south side of the dome in the north part of the field, although it contains a little oil and gas at many other localities. The sand at a few places is as much as 50 ft. thick, although the average thickness lies between 15 and 35 ft.

About 100 ft. below the Jones sand is the Cleveland sand, from which, so far as the writer knows, oil has never been produced in commercial quantities, although, like the Jones sand, it contains some oil and gas at many localities. The Cleveland sand is thinner than the Jones sand and is not reported in some logs. Its thickness ranges from a few feet to 30 ft.

From 600 to 900 ft. (183 to 274 m.) below the Layton sand is the next commercially productive formation, known as the Wheeler sand, named from the Wheeler farm a short distance northeast of Drumright, where it was penetrated by the first well drilled in the Cushing field. This sand is one of the most uniform in the field in thickness. It includes the overlying "Wheeler lime," from which it is separated by a shale "break," and ranges in thickness from 50 to about 100 ft. The lower sandy member is correlated by the drillers with the "Oswego lime" of northeastern Oklahoma and southeastern Kansas. It is a coarse-grained, brownish limestone that includes porous or sandy layers which contain the oil. The part below the shale "break" is more porous than the part above it and comprises about half the formation. At some places the limestone above the shale "break" carries gas in commercial quantities and at others, on the sides of the folds, it carries water. The shale "break" between the two members ranges in thickness from 5 to 25 ft. In the Cushing field about 11 square miles of the Wheeler sand produced oil and about 21 square miles produced gas, exclusively. The Wheeler sand, like the Layton and Bartlesville sands, is spotted.

The Skinner sand lies 250 to 400 ft. below the Wheeler sand and locally produces oil in the northern part of the Cushing field and at a few places near the center of T. 17 N., R. 7 E., southeast of Drumright.

From 350 to 550 ft. (106 to 167 m.) below the Wheeler sand lies the Bartlesville sand, the most productive oil sand in the Cushing field. This sand ranges in thickness from a few inches to about 200 ft. and in porosity from compact brown shale to lenses of porous brown coarse-grained sandstone. In different wells it varies greatly in thickness, texture, and porosity and in its content of oil, gas, or water. In some wells in the north part of the field it attains a thickness of over 200 ft., and one part of the sand may be "dry," another part may carry great volumes of gas under tremendous pressure, still another part may furnish great quantities of oil and others may be filled with salt water. These so-called "streaks" are probably due to differences in porosity and apparently occur in no regular order, salt water under great pressure being found in some wells above excellent oil "pay," below which more water may be

found and below that more "pay." Notwithstanding these facts the sand has been immensely productive, though its yield has not been [so great as might be expected from a body of sand so thick, for the real "pay" may form only a small percentage of the total thickness of the sand. The total oil and gas area in the Bartlesville sand is about 20 square miles, of which but 2 square miles carry gas only.

The Tucker sand lies from a few feet to about 200 ft. below the Bartlesville sand, and is thought by some to be a part of that sand. The principal area in which oil is produced from the Tucker sand lies near Drumright and is not large. This sand is uniform in porosity, medium-grained, and blue or bluish-green, and although its average thickness is perhaps less than that of the Bartlesville, not enough wells have been drilled through it to determine this question. Many of the logs show that the Tucker sand is separated from the Bartlesville sand by a thin bed of green shale, which is recognized by the drillers as a "marker."

Structure of the Cushing Field

The dominant structural feature in the Cushing field is a broad north-south anticlinal fold along whose axis there are domes and along whose sides there are many subsidiary folds and irregularities. The structure contours of the three oil sands are very irregular and differ locally from the contours of the Pawhuska limestone, although the general structure axes are practically coincident. Each sand in the field exhibits small irregularities that apparently bear no definite vertical relation to each other. A detailed description of the folding of the various sands contoured and of the surface beds may be found in the forthcoming bulletin on this subject.³

Through the construction of the contour maps showing the folding of the three oil sands, it has been possible to determine in detail the differences in folding among these beds and the surface beds. The amount of folding in different directions from the crests of various domes and anticlines is given in Table 1.

In practically every case where the dip has been measured, folding becomes greater with depth. The greatest difference in folding usually occurs between the surface beds and the Layton sand.

The possible causes for the irregularities observed may be any one, or a combination of two or more, of the following:

1. The difference in resistance to compression of the hard and soft beds of which the formations in the Cushing field are composed.
2. The lenticular form of the Bartlesville sand.

³ Carl H. Beal: Geologic Structure in the Cushing Oil and Gas Field, Oklahoma, and Its Relation to the Oil, Gas, and Water. *U. S. Geological Survey, Bulletin No. 658* (1917).

3. One or more unconformities between the surface beds and the Bartlesville sand.
4. Folding during deposition.
5. Cross-folding.

TABLE 1.—*Elevation in Feet of Highest Contour on the Surface Beds, the Layton Sand, the Wheeler Sand, and the Bartlesville Sand, on the Crests of Four Folds in the Cushing Field; also the Dip of These Beds in Different Directions from the Crests of the Folds*

(+, above sea level; —, below sea level)

	Dropright Dome				Shamrock Dome		
	Crest	2½ miles N. E. of crest along anti- cline	1½ miles west of crest	¾ mile east of crest	Crest	1½ miles west of crest	¾ mile east of crest
Surface beds (Pawhuska limestone)	+1,050	100	150	125	+1,125	135	60
Layton sand.....	—400	225	175	*250	—325	325	250
Wheeler sand.....	—1,075	225	200	*350	—1,150	175	200
Bartlesville sand.....	—1,525	175	200	200	—1,550	325	250

	Mount Pleasant Dome					Anticline in Northern Part of T. 16 N., R. 7 E	
	Crest	2½ miles west of crest	4 miles west of crest	¾ mile south- west of crest	¾ mile northeast of crest	Crest	½ mile east of crest
Surface beds (Pawhuska limestone)	+1,100	150	225	75	75	+1,050	50
Layton sand.....	—275	300	425	325	325	—400	75
Wheeler sand.....	—1,100	350	475	325	400	—1,325	50
Bartlesville sand.....	—1,450	350	†475	325	400	—1,700	100

* Part of vertical distance estimated.

† Part of horizontal and vertical distances estimated.

The Interval Between the Layton and Bartlesville Sands

The well in which is found the smallest interval between the Layton and Bartlesville sands lies on the west side of the Dropright dome in the northern part of the field; the interval here is 945 ft. (288 m.). The largest interval observed is 1366 ft. (416 m.) and lies in the southern part of the field. The gradations between these limits is irregular locally, but the increase from north to south is very noticeable in general. The map prepared showing the locations of areas where wells had certain intervals shows plainly that a definite relation exists between the folds and the thickness of the beds between these two sands, the interval being generally less on the crests of the folds. This relation would naturally be

expected if the Bartlesville sand were more steeply folded than the Layton sand, and to arrive at a conclusion as to the cause of the differences in interval, it has been necessary to study the causes for the difference in folding of the various oil sands. The possible causes for the differences in folding have been enumerated above. It must not be thought, however, that the general increase in the Layton-Bartlesville interval from north to south can also be attributed to differences in folding. This increase is undoubtedly due to the conditions under which the formations between the Layton and Bartlesville sands were deposited.

The Direction of Migration of Oil and Gas

As a result of the study of the relation of the oil, gas, and water, it was observed that the more important oil areas in each sand lay on the west side of the Cushing field, and gas in many cases had been forced to the east side of the structure, sometimes as far as the water line.

The hydraulic theory of the accumulation of oil and gas is based on the assumption that the hydrocarbons were concentrated by bodies of water that moved through the sand, and although the determination of the direction from which the Cushing field derived its oil and gas was not the primary object of the investigation, it was evident from the distribution of the oil and gas bodies that the hydrocarbons in this region probably migrated from the west or northwest.

The Relation of Oil and Gas to Structure

The maps prepared show that the areas containing only gas conform closely to the higher parts of the anticlines and domes, and the oil areas lie farther down on the sides of the same structures. The areas overlap in each sand and have narrow irregular strips in common, where both oil and gas were originally found.

In connection with this phase of the subject, a study was made of the initial productions of the oil wells. The initial productions of a large number of wells drilled to the three sands studied were plotted on the map showing the distribution of oil and gas, and lines drawn to outline the areas where wells had certain initial productions. Representative areas of each sand show that most of the places of greater initial productions were on domes or anticlines, or that they correspond, in part at least, to areas on the sides of the folds, where both oil and gas are found in the same sand. For instance, some of the more important oil areas in the Layton and Wheeler sands lie down on the west side of the anticlines whose higher parts are completely filled with gas, and, in one noteworthy instance, the most prolific area of oil in the Layton sand conforms closely to the area wherein both oil and gas occur in this sand. On one side of

the area of high oil production, wells with small initial productions were found without any marked amount of gas, whereas on the other side gas occurs without oil.

Peculiarities in the Distribution of Oil and Gas

A very interesting, and economically important fact, has been determined from a study of the distribution of the oil, gas, and water bodies in connection with the anticlines and domes in the Cushing field. In an elongated dome where folding is simple, the oil area in a sand apparently extends farther down on the long axis of the anticline or dome than it does on the steeper sides. Practically every important dome in the Cushing field, which has not been complicated by folding along its sides, shows this feature in each of the three oil and gas sands studied. The fact is shown particularly well in the Layton sand on the Dropright dome (Fig. 1) which lies in the north part of the Cushing field; on the steep west side water completely occupies the sand at a depth of 500 ft. (152 m.) below sea level, whereas on the gently dipping north side the oil extends down as far as 650 ft. (198 m.) below sea level and also completely occupies the Wheeler saddle on the south side of the Dropright dome, the lowest point of which is about 575 ft. below sea level. Another interesting occurrence is in the Wheeler sand on the Mount Pleasant dome, which lies east of the center of the field. This dome has a northwest-southeast axis and the lowest gas on the steep southwest and northeast sides is about 75 ft. higher structurally than the lowest gas on the southeastward plunging axis. No oil occurs in this sand on the Mount Pleasant dome.

Much detailed work might be profitably done, both experimentally and in the field, in connection with this interesting subject which obviously is of economic importance. If it can be determined that on domes and anticlines, folded to a certain degree of intensity, the oil is universally found lower on the long axis than on the steeper sides, this fact will be of great aid to geologists in the work of selecting lands for leasing, locating test wells, estimating the oil content, and in considering the mode of accumulation of petroleum and natural gas.

Inclination of Water Surfaces

The expression "water surfaces," as here used, denotes the level or inclined plane between the oil and gas in a sand and the edge water upon which the oil and gas rest. This water surface must not be confused with the surface of the ground water, which in an undulatory region is not level, and which is defined as a surface below which the rocks are saturated with water. The water surface here referred to is a surface that is confined to one porous stratum, and has been referred to previously by other writers as the "water level."

It was decided at the outset of the inspection work in the Cushing field to collect all the available information about edge water, and if possible to reach some conclusions as to its rate and method of encroachment and its original and present level in each sand on all sides of the Cushing field. Accompanying the bulletin prepared for publication by the U. S. Geological Survey, are maps showing the contours on the water surfaces in the three different sands. The contours do not show accurately the detail of the water surfaces, and the only object in drawing them was to show that the plane of separation between the oil and the water in a given sand is not level, but dips at a gentle angle away from the center of the structure.

The most complete information has been obtained on the Layton water surfaces in the northern part of the field where the maximum dip of the water surface in the Layton sand amounts to about 100 ft. in a mile. On the west side of the Wheeler saddle which lies north of the center of the Cushing field, the contours show a western dip on the water surface of about 90 ft. in a mile. In this locality similar dips were determined on the water surface in the Wheeler sand. In the southern part of the field, in the more recent development, the water surfaces show dips of about the same amount. On account of the complexity of the composition of the Bartlesville sand the information in connection with edge water in that sand is of much less value, and the detailed studies have been confined almost entirely to the Layton and Wheeler sands.

In searching for the reason for the inclination of the water surfaces, the first point necessary to settle was, whether or not the inclination existed originally, prior to the development of the field, or was wholly the result of the extraction of oil and gas, and also, if it existed originally before the field was exploited, whether it was rendered greater by the extraction of oil and gas. If the inclination existed before the field was developed it might have a significant connection with the mode of accumulation of the oil and gas; if it was acquired since development began, a study of its causes might contribute to our knowledge of the drainage of oil sands; if it existed prior to the development and was made greater by the extraction of oil and gas, its study might afford valuable conclusions both as to the accumulation of oil and gas and as to the drainage of the sands. The methods used in determining these problems will not be discussed in this report because the discussion has been given in *U. S. Geological Survey Bulletin No. 658*, referred to above. The conclusion arrived at was that the inclination of the water surfaces in the Layton and Wheeler sands existed prior to development, and was rendered greater by the rapid extraction of oil and gas. In some places the subsequent inclination was as great or greater than the dip of the oil sands, from which it was concluded that some of the wells near the centers of the more productive areas which lie on the crests of the domes and anticlines would begin to

show water before the wells on the flanks of these folds, and after the wells on the crest had gone completely to water there might still be a small commercial deposit of oil remaining on the sides of the folds.

The Necessity of Similar Work

The results obtained from this study, which was necessarily hasty and carried on without the benefit of all available information, are thought to have been well worth the effort of collecting and analyzing the information. The writer believes that much more detailed work might be done in this and in other oil fields, with very far-reaching and conclusive results, and has submitted the results of this study with the hope of stimulating similar and more detailed investigations. Undoubtedly our knowledge of the accumulation of oil and gas and the changing conditions under which they exist during development, and during the productive life of a field, is slight, and much work of this sort must be done before sufficient facts are available for the formulation of any tenable theories to account for many of the at present unexplainable phenomena encountered in oil fields.