THE ORIGIN OF THE FAULTS, ANTICLINES, AND BURIED "GRANITE RIDGE" OF THE NORTHERN PART OF THE MID-CONTINENT OIL AND GAS FIELD.

By A. E. Fath.

INTRODUCTION.

The structural geologist is ever confronted by the problem of the origin of the geologic features with which he deals. An understanding of their fundamental causes permits a better interpretation of their significance, which in studies of natural resources, such as oil and gas, has a direct economic bearing. In regions where the rock folds and faults are of large magnitude the structural mechanics are generally apparent, at least in part, but in the Mid-Continent field, where but few of the anticlines and faults represent elevations of more than 200 feet, the origin of these features is more obscure. These small rock folds and fractures have commonly been considered the distant effects of forces originating in the Ozark Mountains, the dominating structural feature of the region, but the difficulty of applying this explanation to the features that have come under the writer's observation has led to other considerations, which are presented in this paper.

The need of understanding the origin and mechanics of the structural features in the Mid-Continent oil and gas field may be inferred from the fact that much of the oil and gas in this region occurs in localities where the structure of the containing rocks is favorable for its accumulation—that is, where there are anticlinal or domal flexures. In searching for new oil and gas pools it is therefore of paramount importance not only to know the structure of the surface rocks in the regions to be prospected but also to understand how the structural features exposed at the surface may differ from those which govern the accumulation of oil and gas in the deep-lying strata.

In addition to the anticlines and domes there are, in places, many faults of the en échelon or offset type, grouped into remarkable parallel belts or series, the study of which suggested the fundamental principles on which the present discussion is based. Still another geologic feature of considerable significance in this region is a buried "granite ridge" trending northeastward from Butler County, Kans., to Pawnee County, Nebr.

The alinements of these three features—the major anticlines, the fault belts, and the buried "granite ridge"—are remarkably parallel, and to the writer this parallelism indicates a genetic relationship. It is the purpose of this paper to point out this relationship and to present an interpretation of its meaning.

REGIONAL GEOLOGY.

Before the structural features are described in detail, a brief summary of the regional geology will be presented as a background for the discussion. Rocks of undoubted pre-Cambrian age, such as granites and quartzites, crop out at numerous places around the northern part of the Mid-Continent field, in the St. Francis Mountains of southeastern Missouri, the Arbuckle and Wichita mountains of southern Oklahoma, the Rocky Mountains of New Mexico, Colorado, and Wyoming, the Black Hills in southwestern South Dakota, and the Sioux quartzite area of southeastern South Dakota, southwestern Minnesota, and northwestern Iowa. These outcrops probably do not represent rocks of precisely the same age, but they represent the ancient basement complex upon which all the Paleozoic stratified rocks of the Mid-Continent region were deposited. Within the oil-field region of eastern Kansas similar crystalline rocks have been found at comparatively shallow depths in holes drilled for oil.[1] (See Pl. XIV.) Such drill holes are

[1] Taylor, C. H., The granites of Kansas: Southwestern Assoc. Petroleum Geologists Bull., vol. 1, pp. 111–126, February, 1917. Powers, Sidney, Granite in Kansas: Am. Jour. Sci., 4th ser., vol. 44, pp. 146–150, August, 1917. Wright, Park, Granite in Kansas wells: Am. Inst. Min. Eng. Bull. 128, pp. 1113–1120, August, 1917. Moore, R. C., and Haynes, W. P., The crystalline rocks of Kansas, in Oil and gas resources of Kansas: Kansas Geol. Survey Bull. 3, pp. 140–173, 1917. Moore, R. C., Geologic history of the crystalline rocks of Kansas: Am. Assoc. Petroleum Geologists Bull. 2, pp. 98–113, 1918.

Generalized section of formations in eastern Kansas.

Geologic age.	Group.	Formation.	Principal character.	Thickness (feet).
Permian	Sumner group	Wellington shale	Shale	500–800
		Marion formation	Shale, limestone and conglomerate.	150
	Chase group	Winfield formation	Limestone and shale	8–25
		Doyle shale	Shale	60–90
		Fort Riley limestone	Limestone	40–50
		Florence flint	Cherty limestone	20–35
		Matfield shale	Shale	57–70
		Wreford limestone	Limestone	28–50
	Council Grove group	Garrison formation	Shale and thin limestones	135–150
		Cottonwood limestone	Limestone	5–12
Pennsylvanian	Wabaunsee group	Eskridge shale	Shale	30–40
		Neva limestone	Limestone	10
		Elmdale formation	Shale and thin limestones	130
		Americus limestone	Limestone	8
		Admire shale	Shale	300
		Emporia limestone	Limestone	9
		Willard shale	Shale	45–55
		Burlingame limestone	Limestone	7–12
	Shawnee group	Scranton shale	Shale	160–200
		Howard limestone	Limestone	3–7
		Severy shale	Shale	40–60
		Topeka limestone	Limestone	20–25
		Calhoun shale	Shale	25–50
		Deer Creek limestone	Limestone	20–30
		Tecumseh shale	Shale	40–70
		Lecompton limestone	Limestone	15–30
		Kanwaka shale	Shale	50–100
	Douglas group	Oread limestone	Limestone	50–70
		Lawrence shale	Shale	150–300
		Iatan limestone	Limestone	3–15
		Weston shale	Shale	60–100
	Lansing group	Stanton limestone	Limestone	20–40
		Vilas shale	Shale	0–125
		Plattsburg limestone	Limestone	4–80
		Lane shale	Shale	50–150
	Kansas City group	Iola limestone	Limestone	0–40
		Chanute shale	Shale	25–100
		Drum limestone	Limestone	0–80
		Cherryvale shale	Shale	25–125
		Winterset limestone	Limestone	5–30
		Galesburg shale	Shale	5–60
		Bethany Falls limestone	Limestone	4–23
		Ladore shale	Shale	3–40
		Hertha limestone	Limestone	0–22
	Pleasanton group	Dudley shale	Shale	160
		Parsons formation	Shale and limestone	80
		Bandera shale	Shale	60–140
	Henrietta group	Pawnee limestone	Limestone	45–52
		Labette shale	Shale	20–120
		Fort Scott limestone	Limestone	30
		Cherokee shale	Shale	350–700
Unconformity				
Mississippian		Boone limestone	Limestone	300–500
Unconformity				
Ordovician and Cambrian.			Dolomite and sandstone	1,000–2,200
Unconformity				
Pre-Cambrian			Granite	

generally termed "granite wells." The crystalline basement thus encountered is much shallower than had previously been thought possible. In places it lies less than 1,000 feet below the surface, and in these localities it is directly overlain by upper Pennsylvanian rocks, and these in turn by Permian rocks. In the light of available evidence it now seems probable that the granite thus discovered indicates the presence of a buried "ridge" (named the Nemaha Mountains by Moore and Haynes), which probably formed a low island in the early Pennsylvanian sea and was entirely covered by later sediments.

The Paleozoic sediments overlying the pre-Cambrian basement consist in general of shales, sandstones, and limestones of Cambrian, Ordovician, Mississippian, Pennsylvanian, and Permian age, whose subdivisions are given in more detail in the accompanying table. A feature of this stratigraphic section which deserves special attention is the contrasting character of its lower and upper parts. The pre-Cambrian crystalline rocks are strong and are regarded as competent to transmit deformational stresses through long distances. The Cambrian, Ordovician, and Mississippian rocks are less strong but still somewhat competent, especially in contrast to the weak Pennsylvanian and Permian rocks, which consist predominantly of soft plastic clay shales and are therefore relatively incompetent to transmit stresses.

Located principally in Missouri but extending also into adjacent States is the Ozark uplift, which is the dominating structural feature in the northern part of the Mid-Continent field. The formation of this uplift had two distinct phases, the first in late Mississippian or early Pennsylvanian time and the second in post-Paleozoic time. Erosion has removed much of the Paleozoic sediments involved in this uplift, and in places the pre-Cambrian rock is exposed. The outcropping rocks of eastern Kansas and northeastern Oklahoma, on the flanks of the uplift, dip gently westward at a rate normally between 15 and 80 feet to the mile. Their present attitude is due directly to the disturbance that produced this uplift, but because they are not at the heart of the disturbance their westward dip is generally spoken of not as a part of the Ozark uplift itself but as the Prairie Plains monocline.

Cambrian, Ordovician, and Mississippian strata were involved in both phases of this widespread Ozark deformation, but the overlying Pennsylvanian and Permian formations were affected only by the post-Paleozoic disturbance. The time occupied by the first deformational period is represented in an extensive erosional unconformity, with no marked angular divergence between the Mississippian and Pennsylvanian series. Although the first phase of the Ozark deformation took place before the deposition of the Pennsylvanian strata, slight deformational movements, probably of the nature of readjustments, continued intermittently—that is, concurrent with deposition—until post-Paleozoic time, when the second and more widespread stage of the disturbance occurred. These slight movements of readjustment are significant and will be referred to later.

ORIGIN OF THE FAULTS.

The writer's interest in the origin of the structural features in the Mid-Continent oil field was first aroused in trying to determine the cause of the belts of en échelon faults in the Bristow quadrangle, Creek County, Okla. The preliminary report [1] on this area attempted no explanation; in fact, at that time the writer had none. However, during the preparation of this report the origin of the faults had been discussed with R. H. Wood, a colleague interested in the Hominy quadrangle, immediately to the north, who advanced the idea of torsional forces operating along lines of weakness. Because no adequate source of these forces was at that time apparent, no logical conclusions were reached. The writer is most familiar with the faults in the Bristow quadrangle, and therefore in this discussion the detailed descriptions apply more directly to those occurring in that area. Nevertheless, it is believed that the descriptions are equally applicable to all similar faults in the region.

The faults in the northern part of the Mid-Continent oil and gas field, as described by

[1] Fath, A. E., Structure of the northern part of the Bristow quadrangle, Creek County, Okla.: U. S. Geol. Survey Bull. 661, pp. 69–99, 1918.

several authors,[1] are shown on Plate XII. They lie in a broad northward-trending zone, which crosses Okfuskee, Creek, Pawnee, and Osage counties, Okla., and probably extends into Hughes and Seminole counties on the south and into the State of Kansas on the north. These faults, which locally modify the westward dip of the strata, are of the normal type and are noteworthy not only because of their approximate parallelism but also because of their grouping into belts or series which also have a parallel trend, although in a different direction. Most of the individual faults trend about N. 20°–45° W. and lie en échelon to one another in such a manner that the linear belts or series into which they are grouped trend from north to N. 25° E., or roughly at an angle of 45° with the trend of the faults. The faults are of minor magnitude both in vertical displacement and areal extent, the largest stratigraphic throw observed in the Bristow quadrangle amounting to about 130 feet and the greatest length to about 3¼ miles. As a general rule they are straight, but some have slightly curved traces. Where they cut sandstone beds slickensided surfaces are developed, and these indicate that some of the fault planes dip southwest and some northeast, at angles which range between 50° and 65° from the horizontal. A variation in the amount of dip of a fault plane may account for its curved trace.

As mentioned above the faults are normal—that is, the downthrow is in the direction of the hade—and hence the forces that caused the individual fractures were probably tensional in nature and operated in a direction normal to their trend, or N. 45°–70° E. On the other hand, the linear grouping of these fractures into belts and their general uniform development suggest that the faults of any one series were caused by forces that operated in a direction parallel to the series—that is, north to N. 25° E. The question arises: How can horizontal forces operating in weak strata like those forming the Pennsylvanian series of this region produce belts 50 miles or more in length of diagonal tensional faults? To suppose that the controlling forces were transmitted by the weak Pennsylvanian strata is unreasonable, for the stresses would have been relieved by adjustment within the mass.

If the upper few thousand feet of strata in this region are too weak and incompetent to transmit such horizontal forces some other agent must be sought. Lying at some unknown depth beneath the surface of this region are the massive granites and quartzites and their associated rocks which constitute the basement complex, and above them are massive limestones and sandstones such as are known in the St. Francis, Arbuckle, Wichita, and other mountain ranges surrounding this region. A granite ridge is known to underlie the Permian and Pennsylvanian strata in a part of northeastern Kansas. The crystalline rocks of the basement complex are fully competent to transmit earth forces, and they are more closely related than the overlying rocks to deep-seated deformational movements of the earth's crust. These competent rocks could transmit horizontal forces, such as movements along fault planes or shear zones, through considerable distances especially if they were overlain by a heavy load of sediments. An attempt will be made to explain the faults of the northern Mid-Continent region by postulating that the controlling or master forces that produced the fault belts at the surface through the long distance over which they occur operated in a direction parallel to those belts and were transmitted in a horizontal direction by the massive competent rocks that lie at considerable depth beneath the surface. It is believed to be a reasonable speculation that the faults of the Mid-Continent region are the natural surface expression in overlying weak rocks of such deep-seated horizontal movements.

As the strata overlying the deep-seated beds are relatively weak and incompetent their deformation would differ from that of the com-

[1] Fath, A. E., and Heald, K. C., Faulted structure in the vicinity of the recent oil and gas development near Paden, Okla.: Oklahoma Geol. Survey Bull. 19, pt. 2, pp. 353–360, 1917.

Fath, A. E., and Emery, W. B., Structural reconnaissance in the Okemah-Tiger Flats region, Okfuskee and Okmulgee counties, Okla.: U. S. Geol. Survey Bull. — (in preparation).

Fath, A. E., Structure of the northern part of the Bristow quadrangle, Creek County, Okla.: U. S. Geol. Survey Bull. 661, pp. 69–99, 1918.

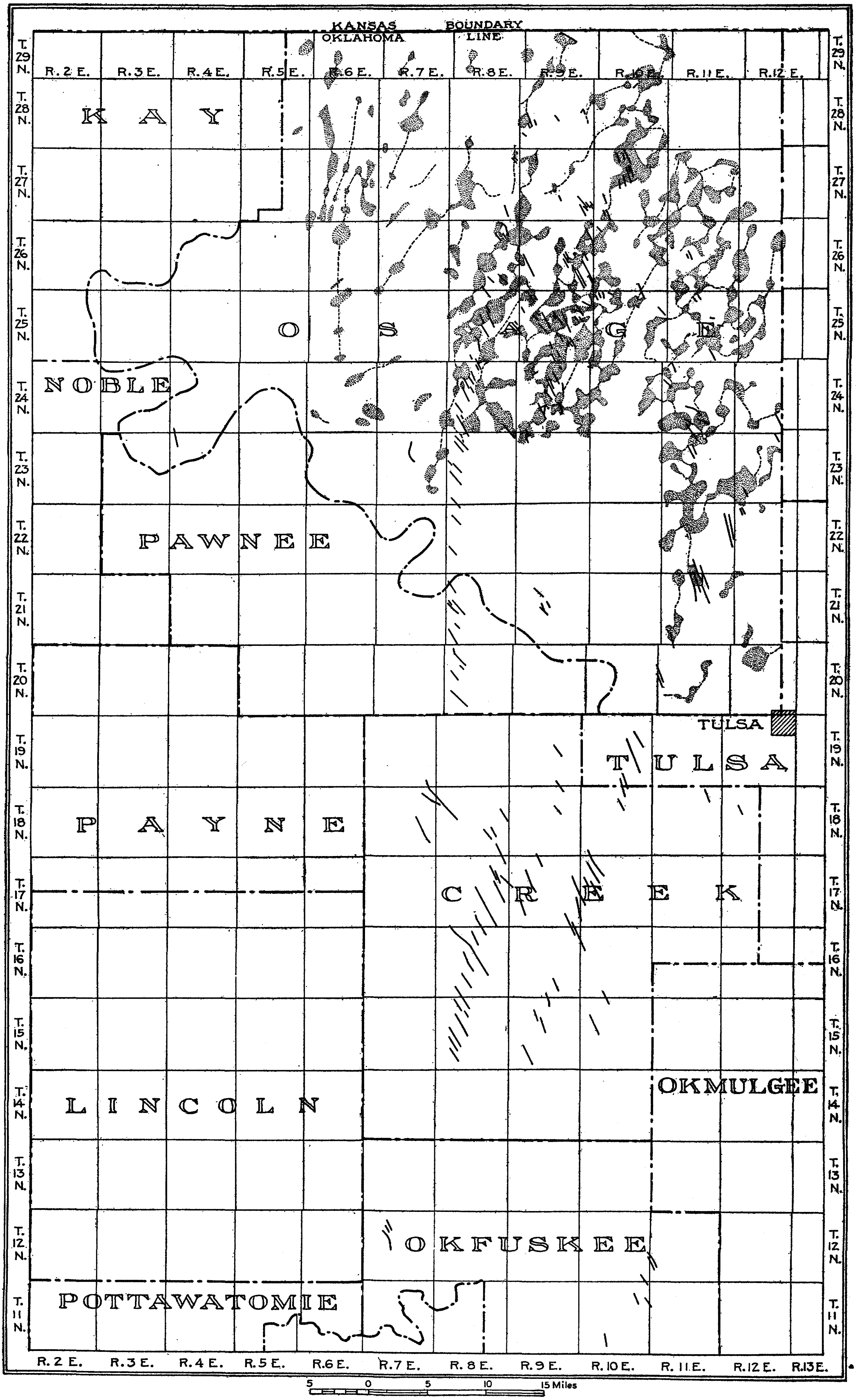
Fath, A. E., Geology of the Bristow quadrangle, Creek County, Okla.: U. S. Geol. Survey Bull. — (in preparation).

Wood, R. H., unpublished report on the Hominy quadrangle, Creek, Pawnee, Tulsa, and Osage counties, Okla.

Buttram, Frank, The Cushing oil and gas field, Okla.: Oklahoma Geol. Survey Bull. 18, 1914.

Heald, K. C., Geologic structure of the northwestern part of the Pawhuska quadrangle, Okla.: U. S. Geol. Survey Bull. 691, pp. 57–100, 1918.

Heald, K. C., and others, Structure and oil and gas resources of the Osage Reservation, Okla.: U. S. Geol. Survey Bull. 686, separate chapters issued in 1918 and 1919.



SKETCH MAP OF A PART OF NORTHEASTERN OKLAHOMA SHOWING THE DISTRIBUTION OF EN ÉCHELON FAULTS AND, IN OSAGE COUNTY, A PREDOMINANT NORTHERLY ALINEMENT OF THE ANTICLINES AND DOMES.

The heavy short lines are the faults, the stippling represents the approximate areas of anticlinal and domal closure (closed contours), and the dashes either indicate lines of folding connecting the anticlines and domes or suggest an alinement of the anticlines and domes connected. Much of the blank area on this map represents lack of information.

petent beds. Instead of breaking or shearing along a nearly vertical plane or zone parallel to a fracture or shear zone in the underlying

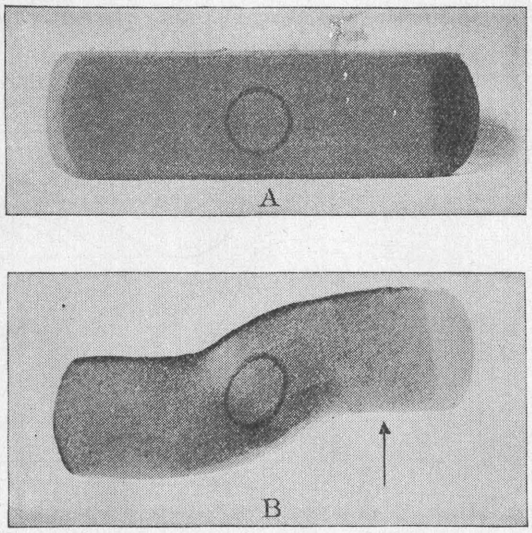


FIGURE 4.—A circle on a rubber eraser (A), elongated by distorting the eraser (B). The direction of elongation is the direction of tension.

granites along which a horizontal movement has taken place, they would bend or be dragged over the displaced competent beds, and tension would be produced in these layers at an angle of about 45° to the direction of movement. This result may be illustrated by drawing a circle on one side of a rubber eraser or other flexible substance and distorting the eraser by a force acting in the direction shown in figure 4. The circle on the eraser will also be distorted, being elongated in a diagonal direction at an angle of about 45° with that of the distorting force and contracted in a direction at right angles thereto. In other words, the distorting force may be resolved into two forces at right angles to each other, one producing elongation in the mass and the other producing contraction. The same effect accompanied by the production of fractures normal to the tension is pictured in Plate XIII, which shows an undeformed flat piece of modeling clay partly pierced by several conical holes along a medial belt and the same piece of clay after being deformed by a force operating in the direction indicated by the arrow. The rounded holes have been elongated in the direction of tension and contracted in the direction of compression. Fractures, which have been centralized by the weakening of the mass at the holes, have been produced parallel to the direction of compression and are pulled apart in the direction of tension.

The fractures produced in the rocks immediately overlying the harder competent rocks in which the horizontal displacement occurred would be irregular breaks which would remain open fissures if it were not for the adjustment to these open spaces that would immediately take place in the thick series of soft formations. In this adjustment the fractures would be closed up by one side or the other slumping or giving way, producing a vertical displacement of the beds on opposite sides of the fissure somewhat similar to the relation of adjacent members of a tumbled row of toy blocks, as shown in figure 5—that is, there would be a normal fault. The fissuring itself would cause no displacement of the strata, but the adjustment would. Although the deep-lying fractures may be irregular breaks, their upward extensions into the overlying less-loaded material would probably be straighter and at the surface would be represented by regular normal faults.

The application of this explanation to the faults in the Mid-Continent field shows that the direction of the movement in the deep-lying competent rocks must have been along the belts of faults, the territory on the east side of each fault belt moving northward relative to the west side. If the faulted region is considered as a whole, in which each unfaulted strip on the east of a fault belt moved northward relative to its respective strip on the west, the general movement may be likened to a regional shearing, the slip planes in the granite

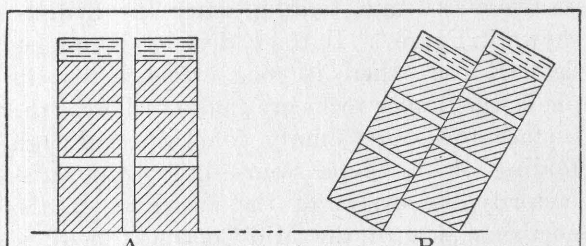


FIGURE 5.—Diagrammatic sketch to illustrate normal faulting. A, Two blocks slightly separated; B, the same blocks tumbled.

basement being marked by the belts of faults in the weak and incompetent surface beds.

It is patent that if the incompetent beds were sufficiently thick faulting of this type would be gradually dissipated and would fail to reach the surface. It is therefore probable that the Pennsylvanian rocks beneath the surface contain many such fault zones, which failed to reach the surface because the movements that initiated them were not as great as those which produced the faults that now show at the surface. If this is so the displacements of the faults observed at the surface increase with increasing depth until they reach the competent rocks in which the controlling force operated.

ORIGIN OF THE ANTICLINAL FOLDS.

Anticlines are generally regarded as due to the buckling of strata accompanying compression at right angles to the axes of the folds. In view of the weakness of the rocks in which the folding has taken place in the Mid-Continent region this explanation does not seem adequate, and another line of reasoning may be followed. An extensive series of faults or shear zones in the pre-Cambrian basement rocks has been postulated in explaining the belts of faults, but the readjustment along these ancient lines of weakness probably was not everywhere horizontal. Vertical movement along these breaks would probably be even more common, and the effect in the overlying incompetent beds would be quite different from the belts of faults described above. It is a commonly recognized fact that faulting resolves itself in distance into folding, and so in this region although the lowermost incompetent beds would be faulted similarly to the competent rocks the faulting would diminish in intensity away from the competent rocks, and at a sufficient distance would resolve itself into folding, after the manner shown in figure 6. In the Eldorado oil and gas field, Kansas, there is good evidence that in places the deeper rocks are faulted whereas the surface rocks are simply folded.[1] Although folding of this type seems to explain satisfactorily the origin of the anticlines in the northern part of the Mid-Continent field, it does not fully explain many of their attendant phenomena.

Nevertheless, to carry this line of reasoning further, the question arises: Do the anticlinal folds in this region indicate displacements along extensive master faults or shear zones in the basement complex comparable to those which are believed to have produced the belts of en échelon faults as indicated above? In Plate XIV and the Osage County part of Plate XII are shown numerous well-known axes of extensive anticlinal folding. It is to be noted

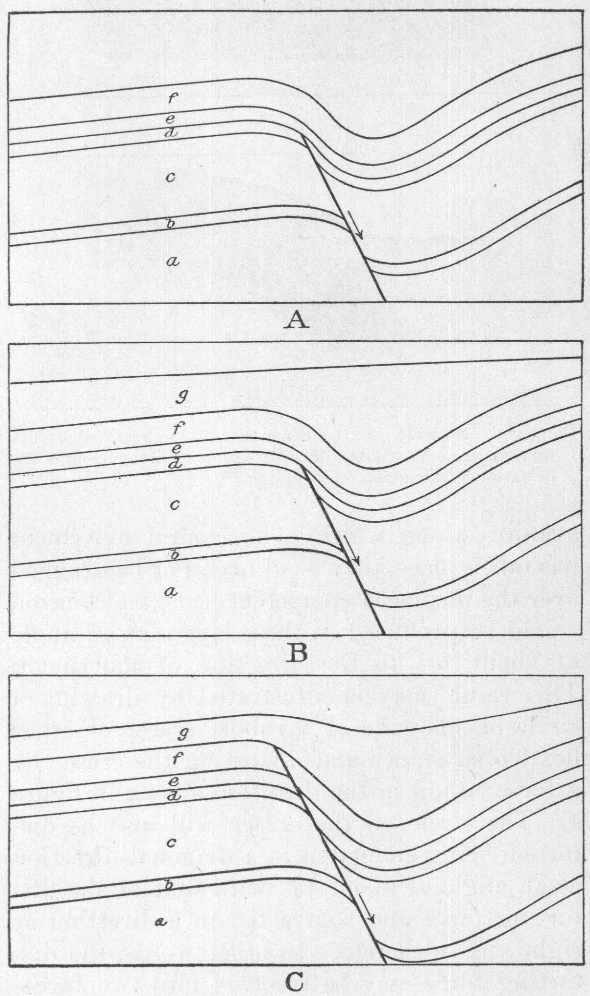
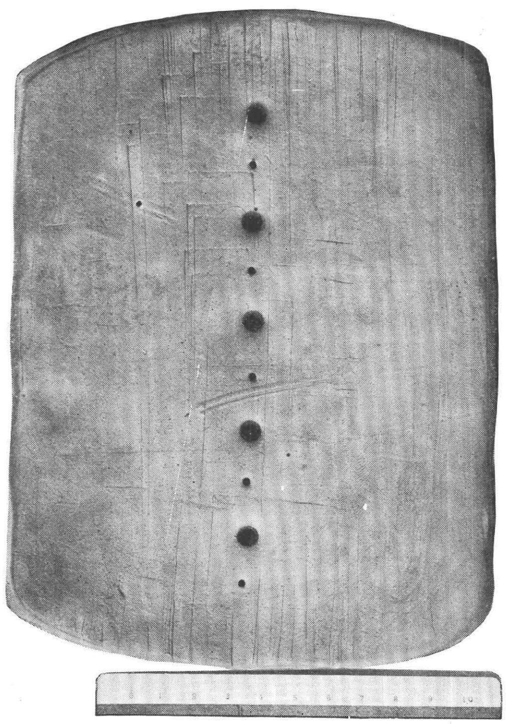


FIGURE 6.—Diagrammatic sketches illustrating progressive stages in the upward dissipation of a fault and its resolution into anticline folding. A, The fault affects all the strata; B, bed *g* has been deposited upon the faulted and flexed beds *a* to *f*; C, after a later additional movement along the same fault bed *f* is considerably more flexed than bed *g*.

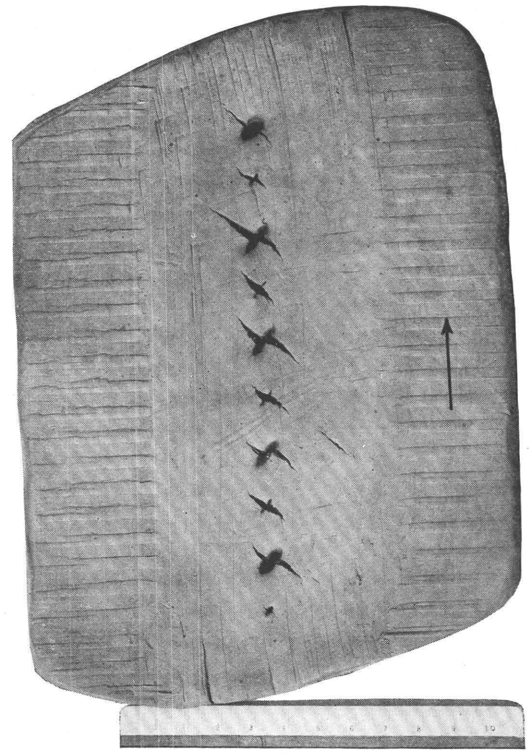
that they are segregated into distinct belts extending across the region and that they are not only parallel to but also comparable in length to the belts of en échelon faulting. Moore[2] states that the "granite wells" extending from Pawnee County, Nebr., southwestward to But-

[1] A report on the Eldorado field is now being prepared by the writer.

[2] Moore, R. C., Geologic history of the crystalline rocks of Kansas: Am. Assoc. Petroleum Geologists Bull. 2, p. 102, 1918.



A.



B.

A FLAT MASS OF MODELING CLAY PIERCED BY SEVERAL CONICAL HOLES, BEFORE AND AFTER BEING DEFORMED.

A shows the mass undeformed; *B* shows the mass after being deformed by forces operating in the direction of the arrow. The corrugations along the edges of the clay in *B* are impressions of the gripping mechanism by which the mass was deformed.

ler County, Kans., were drilled on anticlines belonging to a single belt of folding. This belt continues southward and includes the anticlines of the Eldorado[1] and Augusta[2] oil fields, thus extending nearly across the State of Kansas. "Granite wells" have been reported in the Eldorado field, but the details of location and depth could not be obtained for inclusion in this paper.

Paralleling this extensive belt to the south and east are the extensive anticlines and series of shorter anticlines of Cowley County, Kans.,[3] and the Oklahoma counties of Kay,[4] Garfield,[5] Noble,[6] and Creek[7] shown on Plate XIV, and the series of shorter anticlines which are typically developed in Osage County, Okla.,[8] as shown on Plate XII. Many of the anticlines and domes of Osage County, Okla., appear also to be related by a secondary east-west alinement which the present discussion does not attempt to explain. Notwithstanding such discrepancies, it is believed that if the structure of the entire Mid-Continent field were known in detail, many more lines of folding could be added to those shown on Plates XII and XIV, and these would more convincingly indicate the presence of extensive parallel zones of weakness, which have yielded to pressure, in the deep-seated basement rocks.

In assuming that these belts of folding are due to vertical displacements along master faults or shear zones in the basement complex, it must not be concluded that the displacement along any such fault would be of equal magnitude throughout its extent, or in other words that the result of such a displacement is a single continuous and uniform anticline in the surface rocks. The displacements are probably more or less local in extent. A 100-foot displacement at any one place might disappear within a short distance, and the resulting anticline in the overlying beds would have definite termini. The length of such an anticline is a measure not of the extent of the fault or shear zone but merely of the distance along its course through which noticeable vertical displacement has occurred. There may be recurrent vertical displacements at intervals along these lines or zones of weakness, forming a long linear series of anticlines, such as those in the beds overlying the buried "granite ridge" which extends practically, if not entirely, across the State of Kansas and in the parallel belts of short anticlines, such as those of Osage County, Okla., shown on Plate XII. It is possible that where these displacements die out rapidly in both directions the resultant fold in the overlying sediments will not be elongated into an anticline but will assume the more local form of a dome. A displacement in the reverse direction would cause a depression or syncline, and short synclines may alternate with domes along any one line of movement. Such relations have been mapped at numerous places in Osage County, Okla.

To form the extensive anticlinal and fault belts of the northern part of the Mid-Continent oil and gas field, a regional series of essentially parallel master faults or shear zones must have been present in the basement complex. Such regional series of parallel faults are not uncommon but are probably formed only during great orogenic disturbances. As no deformation of this magnitude is known to have taken place in the northern Mid-Continent region since the beginning of Paleozoic time, as indicated by the rocks of the region, the faults or zones of weakness postulated as present in the basement complex of this region must have originated in pre-Cambrian time. It is possible that these master faults or shear zones were formed either by thrust faulting or by normal faulting, but it is believed that the late displacements along these ancient lines which caused the faulting and dip reversals in the Pennsylvanian and Permian strata were merely a relatively late readjustment along the ancient fault planes, whether those were thrust or normal faults.

[1] Report in preparation by the writer; also McDowell, J. C., Geology in its relation to the oil industry: Am. Min. Congress Proc., vol. 19, map on p. 297, 1917.

[2] McDowell, J. C., op. cit., map on p. 294.

[3] Observed by the writer during a reconnaissance examination.

[4] Trout, L. E., Petroleum and natural gas in Oklahoma: Oklahoma Geol. Survey Bull. 19, pt. 2, pl. 23, 1917.

[5] Hager, Dorsey, Belt, B. C., and Haworth, Huntsman, Petroleum and natural gas in Oklahoma: Oklahoma Geol Survey Bull. 19, pt. 2, pl. 18, 1917.

[6] Fath, A. E., An anticlinal fold near Billings, Noble County, Okla.: U. S. Geol. Survey Bull. 641, pl. 9, 1916.

[7] Beal, C. H., Geologic structure in the Cushing oil and gas field, Okla., and its relation to the oil, gas, and water: U. S. Geol. Survey Bull. 658, pl. 5, 1917.

[8] Heald, K. C., The oil and gas geology of the Foraker quadrangle, Osage County, Okla.: U. S. Geol. Survey Bull. 641, pl. 2, 1916; Geologic structure of the northwestern part of the Pawhuska quadrangle, Okla.: U. S. Geol. Survey Bull. 691, pl. 13, 1918. Heald, K. C., and others, Structure and oil and gas resources of the Osage Reservation: U. S. Geol. Survey Bull. 686, plates in the chapters that have appeared to the date of writing, Apr. 15, 1919.

Slight deformational movements incident to the Ozark disturbance occurred intermittently during the Pennsylvanian and Permian epochs. If the parallel system of faulting in the basement complex existed throughout this time, these intermittent movements probably took place along the postulated zones of weakness. The lower Pennsylvanian strata were therefore involved in movements along the master faults prior to the deposition of the higher beds. If such movements occurred at repeated intervals, the lowermost beds would have been involved in numerous deformations and the successively higher beds in correspondingly fewer deformations. The lower beds would thus be more folded or faulted than the higher beds, and it is therefore possible that in the deeper Pennsylvanian strata there are folds and faults that have no corresponding structural features in the surface rocks, which were deposited after the specific movement took place. This theoretical condition is illustrated in figure 6, B and C, and examples of its existence in the Mid-Continent region are given below.

It is further to be noted that the structure in the surface rocks represents the nature of the latest movement along the master faults, which occurred since these surface rocks were deposited. En échelon faults, due to horizontal displacements in early Pennsylvanian time, may therefore exist in the deeper rocks, but a vertical movement of post-Permian time along the same faults would have produced only folding in the surface rocks. Further, a combined horizontal and vertical displacement may produce both faulting and folding. Numerous occurrences of such combined types of structure are known, such as the Catfish anticlines of the Bristow quadrangle and many others in Osage County, Okla.

It is still further to be noted that where several movements have occurred along a master fault, some of these displacements may have been in opposite directions and compensated each other, with the result that a lower bed would show less displacement or folding than a higher bed. Such reversal of movement along an otherwise normal fault is indicated in the faults near Paden, Okla.[1]

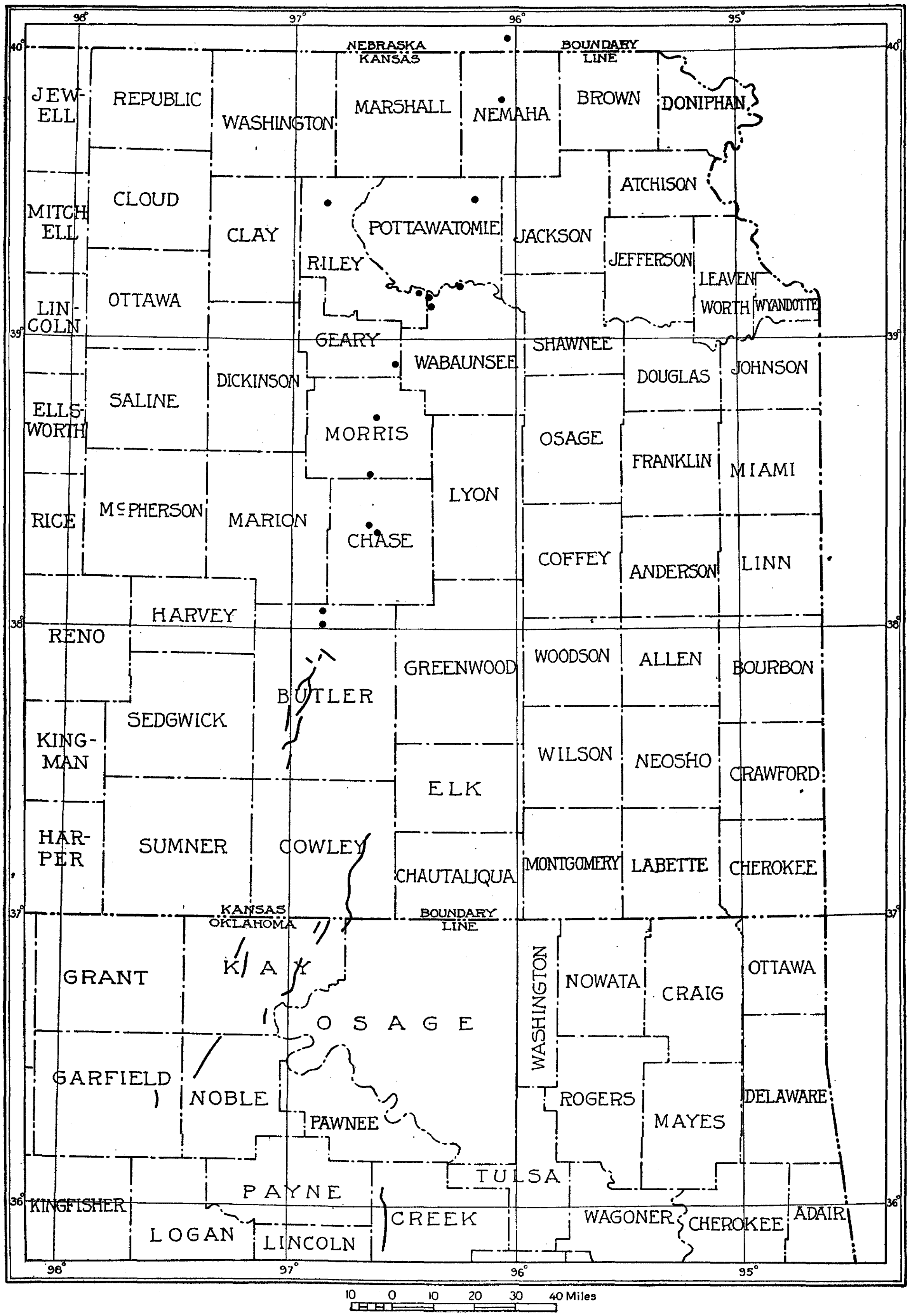
The general increase in amount of folding with increase in depth previously referred to is proved by the results of drilling in the oil and gas fields situated on the anticlinal folds. The first published demonstration of this feature of which the writer is aware referred to the Cushing oil field, in Oklahoma,[2] where three intervals of deformation are indicated through a 2,600-foot series of sediments. The following table, compiled from the structure maps of Beal's report, shows this increasing amount of folding from the surface downward to the Bartlesville sand. The greater folding with increasing depth is very well shown, with the exception of the discrepancy between the Wheeler and Layton sands on the Mount Pleasant and Shamrock domes, which may be explained by a pre-Layton local reversing movement similar to that indicated at Pedan but far more highly developed. The increase in amount of folding between the surface rocks and the Layton sand is most marked.

Increased amount of folding with increasing depth in the Cushing oil and gas field, as shown by amount of closure.

	Approximate depth (feet).	Closure (feet).			
		Dropright dome.	Drumright dome (as distinct from Mount Pleasant dome).	Mount Pleasant dome (as distinct from Shamrock dome).	Shamrock dome.
Surface rocks		75–100	15–25	50–75	75–100
Layton sand	1,350	175–200	15–25	300–325	250–275
Wheeler sand	2,100	200–225	25–50	250–275	100–125
Bartlesville sand	2,550	200–250	50–75	275–300	175–200

[1] Fath, A. E., and Heald, K. C., Faulted structure in the vicinity of the recent oil and gas development near Paden, Okla.: Oklahoma Geol. Survey Bull. 19, pt. 2, pp. 358–359, 1917.

[2] Beal, C. H., Geologic structure in the Cushing oil and gas field, Okla., and its relation to the oil, gas, and water: U. S. Geol. Survey Bull. 658, pp. 21–35, 1917.



SKETCH MAP OF EASTERN KANSAS AND NORTHEASTERN OKLAHOMA, SHOWING DISTRIBUTION OF "GRANITE WELLS" (BLACK DOTS) AND AXES OF SEVERAL EXTENSIVE ANTICLINAL FOLDS (HEAVY BLACK LINES).

The writer has found the same condition to prevail in the Eldorado field of Butler County, Kans.[1] The following advance information corroborates the increase in amount of folding with depth.

Increased amount of folding with increasing depth in the Eldorado oil and gas field as shown by the amount of closure.

	Closure (feet).		
	Wilson dome.	Chesney dome.	Oil Hill dome.
Surface rocks	40	20	30
660-foot sand	60+	40	50
Stapleton sand (2,400 feet)	100+	80+	80

This increased amount of folding with increasing depth and the consequent possibility that well-developed folds exist in oil-bearing sands without any corresponding flexure in the surface rocks are of great economic significance. Oil and gas may accumulate in such places where there is little or no folding in the surface rocks and where the conditions can not be determined by structural geologic investigations in advance of prospecting. This explanation may account for many of the smaller pools in localities where the rocks at the surface show no favorable structure. The absence of anticlinal folding in the surface rocks, therefore, does not absolutely condemn any locality for its oil and gas prospects.

As before mentioned, this explanation of the origin of the anticlines of the northern Mid-Continent oil and gas field does not account for all their attendant phenomena. It is believed, nevertheless, that it does account for a considerable part of the causes which formed them. Some of the principal features which are not accounted for in this explanation are as follows: (1) The distinct downward buckling of the surface strata on the east sides of the postulated deep-lying faults, instead of their simple dropping (and thereby the simple reversing of the dip of the strata). (2) The apparent complete absence of evidence showing that any of the vertical displacements along the postulated deep-seated faults or shear zones were sufficiently large to break entirely through the sedimentary rocks and show at the surface as faults. This is particularly striking along the "granite ridge," where the overlying sedimentary rocks are comparatively thin, less than 1,000 feet thick in places, and where the movement in the sedimentary rocks was sufficient to cause reversed dips for 200 feet or more vertically. (3) The divergence of some of the anticlinal axes from the supposed direction of the governing deep-seated fault zones in Osage County, Okla., as shown on Plate XII. (4) The secondary or east-west relation of many of the folds in Osage County, also shown on Plate XII.

[1] Report in preparation.

ORIGIN OF THE BURIED "GRANITE RIDGE" OF KANSAS.[1]

The relations of the sedimentary strata to the "granite ridge" indicate that the ridge did not come into existence until post-Boone time, for in eastern Kansas the Mississippian formations contain no clastic material such as a granite land mass near by would supply. Furthermore, the ridge is flanked and overlaid by Pennsylvanian strata; hence it is thought that the ridge was elevated during the interval of widespread erosion between the Mississippian and Pennsylvanian epochs.

With a postulated series of faults or other lines of weakness formed in the old rocks in pre-Cambrian time, the origin of the "granite ridge" of eastern Kansas can be readily explained as follows: A vertical movement occurred along one of these lines of weakness in late Mississippian or early Pennsylvanian time, and the displacement was sufficiently large to raise the up-faulted block above the Pennsylvanian seas, so that an elongated island was formed. This explanation conforms with Moore's hypothesis[2] as to the origin of this ridge and at the same time associates it with a regional series of fissures in the basement complex.

The more recently discovered granite in a well in Riley County, Kans., may indicate the presence of a second buried "granite ridge" which may parallel the one previously known.

[1] No detailed description of the "granite ridge" will be undertaken here. The available evidence has been comprehensively summarized by Moore and Haynes (op. cit.).

[2] Moore, R. C., Geologic history of the crystalline rocks of Kansas: Am. Assoc. Petroleum Geologists Bull. 2, pp. 105–106, 1918.

SUMMARY.

The parallelism of the fault belts, the anticlinal folds, and the buried "granite ridge" of the northern part of the Mid-Continent oil and gas field points to a relationship in origin. The faults, by their character and grouping, furnish the best evidence of the common cause by indicating definite lines of weakness, not in the incompetent strata in which they are found but in the strong rocks of the basement complex. Horizontal movements along these lines of weakness in the deep-lying rocks, with the consequent drag of the overlying weak sediments, would tear the lower parts of these sediments along a narrow belt parallel to the deep-seated movements, and short fractures would open which would trend at an angle of about 45° with the direction of the movements. The adjustment of the overlying weak strata to these fractures would result in the belts of short normal faults characteristic of the region.

Vertical displacements along these same lines of weakness in the basement complex would produce folds in the overlying Paleozoic sediments parallel to the lines of faulting. Although it is not clear how such disturbances would produce all the features observed in the Mid-Continent anticlines, this explanation is offered as a suggestion of the way in which the anticlines themselves were formed.

Of special economic importance is the fact that deeply buried oil and gas bearing sands are generally more intensely flexed into anticlines, domes, and synclines than the surface rocks, and it is possible that in places the oil and gas bearing strata may be folded without the surface rocks being noticeably deformed. As a consequence oil and gas pools may occur in these underground flexures where the surface rocks do not show favorable structure.

The buried "granite ridge" of Kansas may be similarly explained as the result of a large vertical displacement which occurred in late Mississippian or early Pennsylvanian time along one of the lines of weakness in the basement rocks.

In conclusion the writer wishes to acknowledge many suggestions and helpful criticisms received from his colleagues in the United States Geological Survey; in particular the assistance of A. F. Melcher in developing the models pictured in Plate XIII.