A STUDY OF THE FRACTURE PATTERNS
OF RILEY COUNTY, KANSAS

by

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INTRODUCTION

Purpose and Location

The purpose of this paper is to describe a survey of fracture patterns, both joint and fault, in Riley County, Kansas. The type, direction and other important features of these fracture patterns were determined for the purpose of establishing the geologic cause of their origin.

Stratigraphic Units in Riley County

With the exception of the very southeast and northwest corners, most of the outcropping rocks in Riley County are of Permian age. The greatest part of this survey was conducted on these rocks. The average thickness, age and stratigraphic sequence are shown in Table 1 (16, 160-170).

Table 1. Table of stratigraphic units in Riley County.

Series	Group	Formation	Member	Average thickness in feet
Wolf-camp	Council Grove	Nolan Ls.	Herington Ls.	20
			Paddock Sh.	11
			Krider Ls.	3
		Odell Sh.		30
		Winfield Ls.	Cresswell Ls.	17
			Grant Sh.	10
			Stovall Ls.	1
		Doyle Sh.	Gage Sh.	48
			Towanda Ls.	7
			Holmesville Sh.	25
		Barneston Ls.	Fort Riley Ls.	40
			Oketo Sh.	5
			Florence Ls.	40
		Matfield Sh.	Blue Springs Sh.	40
			Kinney Ls.	8
			Wymore Sh.	30
		Wreford Ls.	Schroyer Ls.	18
			Havensville Sh.	7
			Threemile Ls.	10
		Speiser Sh.		25
		Funston Ls.		8
		Blue Rapids Sh.		20
		Crouse Ls.		12
		Easly Creek Sh.		15
		Bador Ls.	Middleburg Ls.	6
			Hooser Sh.	10
			Eiss Ls.	7
		Stearns		14
		Beattie Ls.	Morrill Ls.	5
			Florena Sh.	7
			Cottonwood Ls.	6
		Eskridge Sh.		37
		Grenola Ls.	Neva Ls.	20
			Salem Point Sh.	8
			Burr Ls.	10
		Roca Sh.		20
		Red Eagle Ls.	Howe Ls.	3
			Bennett Sh.	7
			Glenrock Ls.	9
		Johnson Sh.		20
		Foraker Ls.	Long Creek Ls.	7
			Hughes Creek Sh.	40
			Americus Ls.	3
	Admire	Hamlin Sh.	Oaks Sh.	12
			Houchen Creek Ls.	2
			Stine Sh.	36
		Five Point Ls.		3
		West Branch Sh.		20
		Falls City Ls.		7
		Hawxby Sh.		30
		Aspinwell Ls.		5
		Towle Sh.	Unnamed Sh.	30
			Indian Cave Ss.	120

MAPPING PROCEDURE

Joints

The strikes of joints were determined by the use of a Brunton compass. At each location the numerical strength and consistency in direction of each set were established by observation. The most numerous and consistent set was given a value of 15. The second most numerous and consistent set was given a value of 10. All other sets were given a value of 5. The strike of the joints, their weighted values and other information, such as "through-set" joints, "off-set" joints and dip of joints, if present, were recorded.

Each location was numerically recorded in a field notebook and also recorded on a large field map of Riley County. On rough terrain, aerial photographs were used to find satisfactory points at which to take measurements.

Each township was divided into four equal parts (Plate I). The large numbers in each quarter township indicate the number of measurements made within that area. The average for the entire county was approximately 6.1 measurements per quarter township.

In several parts of the county it was impossible to make as many measurements as desired because of the lack of rock outcrops. As Plate I indicates, some of the townships, especially along the western boundary of Riley County, are not full size. In these cases it was necessary to take a few measurements in the adjoining county.

Before plotting information on the map, the strikes of all joints within 10° of one another for each quarter township were averaged together. In order to find the relative magnitude or strength for each of the sets so computed, it was necessary to average all of the individual magnitudes within each 10-degree unit. The results were then drawn on a semi-transparent paper in a polar co-ordinate fashion. Finally, the ends of all resulting lines within 15° of one another were tied together. Any remaining unattached lines were tied to the nearest leg of the joint-strike diagram. The small number at the end of each line in a joint-strike diagram indicates the number of measurements which were averaged together within that 10-degree unit.

Faults

The field procedure for mapping faults was much the same as that used in mapping the joint patterns. A Brunton compass was used to find the direction of the fault plane and the amount of dip wherever possible. A hand level and stadia rod were used to determine the amount of throw of each fault. The same instruments were used to measure the amount and direction of dip of the rock strata surrounding the faulted zone in the southeast corner of Riley County.

FRACTURE PATTERNS

General Description of the Joint System

<u>Major Sets</u>. In general, Riley County has two dominant sets of joints. Plate I shows that the variation in strike of either set in most of the joint-strike diagrams is through a range of 10° to 15°. This variation is regional and not local in character. At many locations the joints have an irregular or jagged appearance.

A study of Plate I will show that there is a pronounced variation in strike of the major joints from one locality to another. A generally north-south and east-west strike dominates the joint-strike diagrams in the second row from the left side of the map. The same pattern is shown by the top four diagrams of the third and fourth rows and the bottom two diagrams of the third row.

Joint-strike diagrams on all other parts of the map range from north-south and east-west strikes to approximately northwest and southeast for Set I and southwest and northeast for Set II. The greatest variation in strike occurs throughout the entire southeastern corner of the map and along the Blue River which bounds Riley County's eastern side.

Lithologic characteristics of the limestones in Riley County vary considerably. In order to determine whether lithologic differences may have been responsible for variations of the average strikes as represented by the diagrams, a record was kept of the kind of limestone upon which measurements were made. In several instances measurements were completed on different limestones in the same area. All tests indicated no important variation due to lithologic causes.

In small areas the joints of one major set were usually more closely spaced and more persistent in strike than those of the other set. However, a major set of joints cannot be traced continuously over a large area.

At several places, especially in the southern third of Riley County, it was noticed that the joints of one set were closely spaced and continuous and that the joints at right angles were more widely spaced and discontinuous. The continuous joints were called "through-set" joints and the discontinuous joints were called "off-set" joints. This condition was noticed only on the most brittle limestones.

Some of the joints in the county are not vertical. This is especially true for the area around Winkler and for the area east of Winkler along North Otter Creek.[1] In almost every case an angle of hade appeared on the north-south set of joints. At some places the dip was westward, other places eastward and at a few localities, dip in both directions was present. No conclusions have been drawn other than that the direction of dip for the joints just described may possibly be the same direction as the dip of the rock strata.

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[1]Winkler is located in the southeastern part of T6S, R6E.

Minor Sets. Several minor sets of joints are present in Riley County. Locally there are two sets of joints of approximately equal strength at right angles to one another which bisect the right angles formed by the two major sets of joints. This observation is true for certain localities only since at many places the strengths of the minor sets of joints vary greatly and in other places there are more than one minor set of joints included in the right angles formed by the two major joint sets.

At some locations the minor sets of joints appeared to have a haphazard arrangement. In such places it was impossible to plot any strike other than that of the two major sets.

Topographic Expression of the Joint System. There is some topographic expression of the joint system in Riley County. The streams and creeks have a dendritic pattern but in some places they appear almost trellis-like, that is, they tend to parallel each other. This parallelism may be indicative of dips which are steeper than those ordinarily found in this region. Some of the small crooks and turns in creek beds tend to follow the joint pattern.

Along the middle of Riley County's eastern border the Blue River flows in the same direction as the north-south set of major joints. This parallelism seems to indicate some sort of structural control that may or may not be related to the jointing. If the dip of the strata has determined the direction of jointing and if the Blue River follows this dip, the apparent joint control over the stream is only coincidental.

The most noticeable topographic expression of joint sets is in some of the rock ledges along small streams and creeks. These ledges have broken off along one set of joints causing the formation of a very straight, sharp valley wall.

General Description of the Faults

Normal Faults. Most of the normal faults lie in one zone in the southeastern corner of the county (Plate I). This zone contains six faults in all. The longest fault is approximately 1 2/3 miles long and most of the others are approximately 1/3 mile long. One and one-half miles southwest of this zone is a single fault approximately 1 1/3 miles long. Throws vary from as much as 16 feet to as little as 1 or 2 feet. Melville R. Mudge of the U. S. Geological Survey acquainted the author with the locations of these faults.

A comparison between the strike of these fault planes and the strike of the joints of Set I (the north-south set) in the same area has been made. The largest fault in the faulted zone has a strike of N. 22°W. Joints of Set I in the same area have an average strike of N. 19° - 25° W. In the area in which the single large fault is found, the strike is N. 41° W. for the fault and N. 34° - 46° W. for the joints.

The same interesting parallelism was noticed in connection with a group of short step faults which are located in Pottawatomie County, NE¼ Sec.17, T9S, R8E. At that place the faults were found to have the same strike as joints in Set II.

__Thrust Faults__. Most of the thrust faults in the county are exposed along highway and railroad cuts. All except one are in the Stovall and Cresswell limestones and are located in the central part and the southwest corner of Riley County (Plate I). In areas where the Stovall and Cresswell are the uppermost limestones, they are usually well covered with a thick layer of mantle. Undoubtedly many more thrust faults are present but are concealed by the mantle.

Only the approximate strike of these faults has been plotted on Plate I. In one case only was there enough of the fault plane exposed to make an absolute determination of its strike. Locations of the faults are as follows: NE$\frac{1}{4}$ NE$\frac{1}{4}$ Sec.20, T7S, R6E; SW$\frac{1}{4}$ NW$\frac{1}{4}$ Sec.33, T8S, R6E; NE$\frac{1}{4}$ Sec.1, T9S, R4E; NE$\frac{1}{4}$ NE$\frac{1}{4}$ Sec.8, T9S, R5E (Flexure); SE$\frac{1}{4}$ Sec.31, T9S, R5E; SW$\frac{1}{4}$ Sec.6, T11S, R9E.

There are several small thrust faults located in the Stovall limestone on a north-south ridge in the NE$\frac{1}{4}$ NE$\frac{1}{4}$ Sec.20, T7S, R6E. These faults are parallel to the length of the ridge. The downthrow sides are on the east of the fault planes and there is a throw of 1 to 3$\frac{1}{2}$ feet.

At another location, SW$\frac{1}{4}$ NW$\frac{1}{4}$ Sec.33, T8S, R6E, the fault plane of a thrust fault in the Stovall limestone has a strike of N. 50° W. and a displacement of 3 feet with the downthrow side on the northeast and facing a valley. In many instances the Gage shale seems to have yielded by plastic flow but at this location there are some faint indications of shear lines.

The faults in the SE$\frac{1}{4}$ Sec.31, T9S, R5E are very interesting because they have ruptured both the Stovall and the Cresswell limestones and shale has been forced into the space opened by the break in the strata. At this location it was also noticed that the downthrow side was nearest the valley.

The flexure in the NE¼ NE¼ Sec.8, T9S, R5E and the fault in the NE¼ Sec.1, T9S, R4E are both in the Stovall and both have the lower side facing a valley. One fault was found in the Elmont shale, SW¼ Sec.6, T11S, R9E, and is located on the west bank of Deep Creek.

Relationship of the Basement Complex to the Fracture Pattern

The Nemaha Range. Because it is thought that the fracture pattern of this county has been influenced by the basement complex, all important facts pertaining to it have been collected. According to Moore (15) the Nemaha Range extends from Bern, Nebraska, to northern Butler County, Kansas, a distance of 175 miles.[1] It is 10 to 25 miles wide and has a very irregular surface which rises as high as 600 feet above sea level at its northern end and drops to near sea level at Zeandale, Riley County, Kansas. From this point southward the dip of the axis is much greater. Deep Creek flows on an anticlinal structure in southeastern Riley County. The anticline in turn is in a posi-

[1]Since the time of this written account by Moore, it has been discovered that the Nemaha Range extends into Oklahoma at least as far as Oklahoma City.

tion almost directly above the Granite Ridge.

Areal geologic maps show that the town of Winkler is located on an anticline (9, 100). Undoubtedly the structure is also present further south but flat topography and an abundance of mantle cloak its presence. The Winkler anticline is part of the Abilene Arch which extends from Kingman County northward into Nebraska.

REVIEW OF PREVIOUS WORK ON FRACTURES IN THE MID-CONTINENT REGION

The Mid-Continent region has been and still is very interesting to geologists because of its vast reserves of oil. Such interest has caused a great many geologists to study this area and they have advanced various theories concerning the origin of its structural features. An attempt has been made to classify these ideas, to emphasize their strong points and their weaknesses and to establish a connection between the one or ones which most nearly fit the field data assembled for Riley County. No theories were found which were concerned with Riley County alone; however, there is little doubt that the general geologic conditions for Riley County are the same as those for the entire Mid-Continent as a whole.

Structural Features of the Mid-Continent Region

According to Blackwelder (2) domes in the Mid-Continent region are of relatively small dimensions and have little or no system of alignment. He warns that:

> Owing to the fact that these domes are usually so flat that they cannot be discovered without rather precise altitude measurements of suitable rock ledges, it sometimes happens that a series of domes has been mapped along the outcrop of a certain well-defined limestone, whereas in the intervening broad shale outcrops the structure has not yet been worked out. This produces a spacious alignment which is well exemplified by the series of prominent domes recently mapped along the outcrop of the Herington and Winfield limestones from Central Kansas, south to Kay County, Oklahoma.

As Blackwelder has said, structure is often worked out along an escarpment which gives a false appearance of alignment. Thus, any conclusions drawn from such results are erroneous. Other structural characteristics mentioned by Blackwelder are as follows: Domes average about 1 to 3 miles in length with some less than 1 mile and a few, like the Eldorado anticline, 10 to 15 miles long. The dips range from 1 to 90 feet per mile and average less than 50 feet per mile. Some of the domes have subsidiary lobes. There are occasional saucer-like basins of about the same magnitude. Normal faults are common in some parts of the region. These faults trend in a general west or north direction. The upthrow side is usually to the northeast. Blackwelder did not believe that there is any relationship between the origin of faults and domes. He states that on drilled structures, such as those at Augusta, Cushing and Eldorado, the deeper formations are more steeply inclined. Well logs proved that this thinning is largely confined to shales.

A good general description of the normal faults in Okfuskee, Creek, Pawnee and Osage Counties, Oklahoma, has been given by

Fath (5). Their trend is N. 20° - 45° W. and they lie en echelon to one another in belts which trend north to N. 25° E. A more specific description has been given us by Sherrill (22) who states:

> Most of the individual faults in any zone are approximately parallel and strike in a northwesterly direction. Few of them exceed 3 miles in length and most of them are nearer 1 mile. The throw, which is rarely more than 100 feet and generally nearer 50 feet, is commonly greatest near the center of the faults and diminishes toward the ends. The number of faults with the downthrow toward the southwest seems to be about the same as the number with the downthrow in the opposite direction. In most of the faults some rotational movement between the opposing walls is present, and in a considerable number this has been carried to such an extent that a pivotal fault has resulted.
>
> It is not definitely known whether the amount of throw increases or decreases downward, but most of the evidence indicates that the faults die out with depth - probably not extending below the Pennsylvanian formations.
>
> Especially significant would seem to be the fact that, where developed, the fault zones are closely parallel with strike of the outcropping Pennsylvanian strata, and the changes in the general direction of strike in different parts of the region are accompanied by corresponding changes in the direction of trend of the fault zones.

Theory of Lateral Compression

In 1918 Moore (15) suggested:

> At the close of the Paleozoic the region suffered slight but extensive organic movements, reaching outward from the Ozark highlands, where the upheaval was greatest. This gave the strata of Eastern Kansas a general inclination toward the northwest and developed various minor folds in the rocks. Undoubtedly the presence of a resistant mass of crystalline rock projecting far into the strata in Central Kansas caused opposing pressures here and developed folds over the ridge, and

thrusting and sliding of the strata. Wright[1] has suggested such thrusting in his explanation of the structures. The movements in the overlying strata probably also affected the crystalline rocks and resulted in some of the slickensided and chloritized rocks found in portions of the basement complex.

Powers (21) stated that he favored lateral compressive forces which had been transmitted through the basement complex. He thought of the buried mountain ridges as buttresses. Because the Nemaha is steepest on the east side, the direction from which the forces came, he felt his theory was well established.

Brown (3) also advocated the theory of lateral compression and believes that the folds of Osage County are primarily the result of compressive forces acting from all directions.

The above ideas contain two different mechanisms by which lateral compression could cause folding and faulting: thrust through the basement complex and thrust through the sedimentary strata itself.

Analysis of the Lateral Compression Theory. Objections to the idea of thrust through the post-Cambrian rocks are many. Rock strata are not able to transmit horizontal thrust stresses over a great distance. The greatest deformation would be nearest to the source of the stress and would diminish very rapidly in intensity as the distance from the center of origin increases. Such is not the case in the Mid-Continent region.

There is very little chance that compressive forces in the Paleozoic sediments could cause extensive normal faulting. How-

[1] Wright, Park, Granite in Kansas: Bul. Amer. Inst. Min. Eng., p. 1118, 1917.

ever, if the thrust was through the pre-Cambrian crystalline rocks and if ranges such as the Nemaha Mountains were pushed up by the action, normal faulting would be possible over the raised areas. Under these conditions one would expect that from the point of origin outward there should be extensive thrust faulting because the Paleozoic rocks would be carried forward with the movement of the crystalline mass.

Another serious objection to the theory is the fact that the structural domes and anticlines are not found to have a definite alignment nor a common direction, nor do they tend to be very elongate. Had their cause been one of thrusting, directions of all would be about the same and they would be very long and narrow.

Theory of Horizontal Slip in Basement Complex

As early as 1921 Fath (5) had postulated that:

> The faults (of North-central Oklahoma) 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 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.

> 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, Oklahoma.

In another article Fath (4, 164-165) suggests that although the initial movement along the Granite Ridge took place in pre-Pennsylvanian times it has been followed by many minor movements since. Other exponents of Fath's theory are Merritt and McDonald (14), Levorsen (10) and Foley (6). Merritt and McDonald disagree with Fath in that they think the throw of the faults in the sediments should decrease rather than increase with depth. They also suggested the Ouachita movement as the origin of the thrust which caused horizontal slip along the Granite Ridge. Levorsen suggests that the first movement along the ridge was one of gravitational faulting and that later tilting of the area caused horizontal slip.

Analysis of the Horizontal Slip Theory. If the Ouachita thrust was the source of stress, it would be logical to assume that the horizontal movement would be greatest near the point of origin and that it would lessen with distance from this point. As recorded by Nevin (18, 116) experiments conducted by Cadell convinced him that, "Horizontal pressure applied at one point is not propagated far forward into a mass of strata." Thus, the faults should be most numerous and have the most throw near the Ouachita Mountains. This does not seem to be true. Sherrill (22) states that:

> Other sources of stress may be assumed, but the lack of continuity of the surface fault zones and the manner in which their trend swings with the strike of the Pennsylvanian formations make it difficult to believe that all of them follow pre-Pennsylvanian buried faults.

In Riley County many of the normal faults appear to die out upward and some of them appear to die out with depth. The throw of the largest fault is greatest in the Cottonwood and begins to lessen in the Neva limestone. No faulting was found below the Howe limestone. None of the normal faults in the southeast part of the county can be traced upward beyond the Funston limestone. This would indicate a peculiar stratigraphic zonal selectivity that would be difficult to explain on the basis of horizontal slip.

Theory of Vertical Readjustment Due to Deep-Seated Rock-Flowage

One of the chief exponents of this theory is Gardner (8) who in 1917 wrote:

> In the uplife of mountains, a deep-seated flowage of rocks takes place so that the basic magmas move laterally to the area of least resistance. In do doing, pressures are set up on the fluid rocks permitting hydraulic forces to act equally in all directions. At places where the total strength of overlying rocks is not competent to withstand this pressure, there is a local buckling of the whole mass. Such a structure may be very local in nature. There is every conceivable graduation of local uplifts from the round saline dome to the elongated bulged anticline.

Later in 1922 Gardner (&) stated:

> It is believed that the local folds of the Mid-Continent oil fields are not the result of tangential pressure moving outward from an area of maximum lift, such as the Ozark and Arbuckle areas, but that these smaller folds are the result of the same pressure that produced the larger lift; that they are smaller expressions of the same thing and not secondary results; that they were probably coincident and represent areas of failure to withstand deforming forces, the components of which were essentially vertical.

Other supporters are Nevin and Sherrill (20) who have defended the theory, Sherrill (22) who has given it a working mechanism and McCoy (13) who has suggested a different type of mechanism.

<u>Analysis of the Vertical Adjustment Theory</u>. Blackwelder (2) states that while there is no doubt that vertical forces are necessary for isostatic adjustment they apply only to large regions and cannot explain folding of a minor character. A different view is presented by Nevin and Sherrill (20).

> ...the pre-Cambrian basement in this area has two dissimilar characteristics: (a) north-northeast zones of weakness which may be due to structural or lithologic causes and (b) resistant masses containing local weaker areas which show little definite alignment...
>
> ...folding should take place throughout the entire width of a zone of weakness, and vary in intensity as the weakness of the zone itself varied. Where the uplift is relatively intense, breaking would be probable and should express itself as upthrust normal faults; where there are pre-existing lines of weakness, faulting would be expected.

There can be no doubt that vertical forces were responsible for raising the vast Mid-Continent region above sea level. There also can be little doubt that the same forces have caused its tilted and slightly warped surface. Therefore, it seems very possible that this hydraulic action in the deeper rocks should also find the minor weakness in the basement complex and exert its action upon them. Minor folds would be formed and many of them would be reflected at the surface.

Ley (11) suggests that during late Mississippian and early Pennsylvanian times there was erosion on a land mass of never more than 100 feet maximum relief and that, "The direction and pattern of the drainage was, however, largely controlled by local warpings." His study was based on stratigraphic conditions and is quoted as further proof of minor folding by vertical forces.

The mechanism which Sherrill (22) has suggested for the formation of the fracture pattern is best described in his own words:

> If relatively brittle sedimentary beds are subjected to sufficient torsion, breaks will be formed. If the stresses are in a direction tending to move the northeast and southwest areas down, relative to the southeast and northwest parts, then a torsion or twisting is produced and the resulting breaks trend in a general northwesterly direction.
>
> Moreover, if sedimentary beds are uplifted into north and south folds, there is a tendency to develop north and south tension cracks within this steepened area...
>
> Suppose that the twist itself is not carried to such an extent that the northwest breaks are developed, but that while the beds are in this state of torsion an uplift along a general north and south axis increases the stress. Only a component of this increase would be effective in the direction of stress due to twist. Such an increase might appear slight in itself, yet be sufficient to cause breaks in the general area where it is effective. These breaks should trend northwest due to the dominant guidance of the twist; and, as they would occur in the north and south steepened area, they should appear as north and south trends of an echelon breaks.

McCoy has made an extensive paleographic and historical study in the Mid-Continent area (13). At some places he found the limestones much thicker than at others which suggested sinking basins and so he wrote:

> Considering the two conditions just mentioned, the area of Osage, Tulsa, Creek and Pawnee Counties acted as a fulcrum for tension in the lower sediments since they were sinking both to the northeast and southwest to accommodate the particular sedimentation of that time. The relief of these tensile stresses would be the opening of faults and cracks in a northwest-southeast direction about in line with the average faults now shown on the surface in this district. The fulcrum would not remain at one definite place but would oscillate with the changes in the seas. Consequently, relief faults should be expected from the north part of Okfuskee, Lincoln and Payne counties, throughout the area northeast across the Kansas state line. The pronounced faulting would be most prominent in the sediments below the Fort Scott, (Oswego) limestone and would probably be associated with the irregular "highs" of the hard formations below the top of the Mississippian. Pennsylvanian sediments, being soft, would rapidly adjust themselves to this structural arrangement and the majority of the faults would materially effect the sediments up to and including the Pawhuska limestone. In many cases the faults would not extend entirely to the surface in the Pennsylvanian rocks, but would be reflected by strong dips, and many local structures would result throughout the area.
>
> By the time a large portion of the sediments were eroded from the Arbuckle mountains to the north, Permian limestone seas extended farther to the south than had the seas of the Pennsylvanian time. The accumulation of sediment north of the Arbuckle mountains was not so rapid and the limestone forming seas had probably moved farther west in Kansas. Consequently, the tensile stresses heretofore described are obliterated and faults should not be expected in the sediments of the upper Ralston and Permian formations. The upper formations would settle over faulted areas thus forming structures throughout the western Osage, Kay, Noble, Garfield, and Grant counties, Oklahoma. Some faulting might accompany this settling, but such movement would be entirely subsequent to the regional adjustment.
>
> By the same principle of tensile stresses developed by settling basins, faults would be opened up on the flanks of granite cores of central Kansas. The Kansas City and Stanton seas were the first Pennsylvanian basins to settle both to the northeast and west of the "granite ridge". During these times tension faults for

> adjustment would be started in almost a north-south direction off the granite "highs". At later times as the basin migrated to the west, sediments of the upper formations would settle down over the faulted areas with marked dips. The settling would adjust itself largely to the granite topography, but faulting would probably be developed primarily in the direction mentioned. It should be understood that faults developing by the process just described would not continue for great distances. The maximum extent would probably be only a few miles, and the tendency to "scissor" might be expected. Groups of faulted zones might extend for quite a distance in the direction of faulting, but the faults themselves would be individual and largely disconnected.

The processes suggested by Sherrill (22) and McCoy (13) by which the fracture pattern of the Mid-Continent region could have been formed seem quite logical. All plains and plateau areas have been subjected to warping many times in the history of their development. It seems probable, therefore, that stresses resulting from warping have acted intermittently at many times in the past.

Theory of Differential Compaction

Differential compaction can take place over buried irregularities in the pre-Cambrian rocks or over buried sand lenses. Berger (1) writes of a surface structure in the Sallyards Field, Kansas, which is the reflection of a buried sand lens. Many of the major structures in the Mid-Continent region seem to be due to differential compaction over irregularities of the basement complex, while the minor structures appear to be due to differential compaction of lagoonal areas and around relatively non-compactable lenses.

Blackwelder (2) wrote that:

> ...sediments are more or less compressed vertically by and proportionately to, the weight of the overlying beds, and that this condensation is different in amount among clays, sands, and other types of sediments.

From typical well logs in the Eldorado field he determined that the amount of compaction for sand was 2 percent, for limestone 5 percent and for shales 15 to 35 percent. The average was 23 percent. From these figures he concluded that a pre-Cambrian hill 700 feet in height was necessary to produce the Eldorado anticline which has a relief of 160 feet. He also pointed out the fact that the buried Nemaha Mountains have a relief several times greater than the anticlinal structures lying above.

Link (12), another exponent of the compaction theory, found by experiments that he could produce tension cracks which were inclined a few degrees from the azimuth of the axis of a buried ridge. He stated that upon contraction, minute en echelon tension fissures were first noticeable.

> With continued contraction the minute off-set fissures ordinarily join one another and ultimately develop into one continuous, jagged, open tension fissure. The en echelon alignment must consequently, be regarded as the incipient manifestation of what may later on become a much larger development of a tensional phenomenon. If tension stresses are arrested at this early stage, obviously the en echelon system remains as such and concomitant or later movements along the planes may give rise to normal or reverse faulting.

In 1920, Moore (17) wrote favoring folding by unequal condensation of sediments rather than by lateral compression as had once been his opinion.

<u>Analysis of the Theory of Differential Compaction</u>. There can be little doubt that condensation of sediments has taken place throughout the Mid-Continent area. Dips observed on the surface strata are gentle and increase somewhat with depth. Beds of shale are somewhat thinner at the crest of a structure than at areas some distance from that crest. There is very little change of this kind in limestones or sandstones. There are hills of pre-Cambrian rock beneath the surface structures which have more relief than those surface structures.

However, there are some phenomena which the theory of differential compaction does not explain. A regional fracture pattern could not be produced by compaction alone. Only very local areas such as the crest of an anticline could be expected to have joint sets which continue in the same direction for some distance.

Link's idea cannot explain the direction of joints for Riley County. The anticlinal plane of the Nemaha Range has a strike of N. 15° - 20° E. His experiment showed that tension fissures were formed in a direction which varied only a few degrees from the axis of the buried ridge. This variation is not enough to account for joints which have general strikes of N. 20° - 40° W. and 60° - 80° E.

As has been stated before, the Mid-Continent region has passed through many fluctuations of land level. It has been raised high above sea level and has been tilted. There are many historical evidences which indicate that it has been warped. All these facts seem to indicate that differential compaction is not the only force which has been active in the area.

The experiments of Nevin and Sherrill (19) have clearly demonstrated that compaction has played an important part in the formation of regions such as that in the Mid-Continent. However, they also present their reasons for believing that compaction alone cannot explain the structures found here.

INTERPRETATION OF FIELD DATA

Joints

The joints of Riley County are not clean cut, straight breaks but are often jagged and irregular in direction. Locally, when concretions are present, the fracture is around and not through the concretions. In homogeneous limestones the joints are not so irregular but their surfaces appear to be curved. Such conditions are indicative of tension as the cause of stress.

Major Joints. There is little disagreement that the entire Mid-Continent area has been formed by the same causal stresses. Joints in Sets I and II (Plate I) appear to be regional in character and so must be related to the same stresses.

Minor Joints. The apparent lack of regional pattern for minor joint sets is probably due to purely local causes. Differential weathering, unequal compaction in lagoonal basins and local subsidence or uplift are some of the reasons for the great variety of numbers and magnitude among the minor sets of joints.

The three volcanic intrusions in the county may have caused some minor jointing in their immediate areas. Their ascent seems to have been primarily by the process of stoping so the surrounding country rock has been disturbed little, if any.

Faults

Normal Faults. Link (12) has suggested that in the Mid-Continent area the belts of en echelon faults are the result of later movement along the planes of established joints. Nevin, in a discussion of the article by Link, criticized the theory. Later Nevin (18, 131) wrote in his own book that:

> Unfortunately, little, if any, distinction has been made and many minor faults, as well as some fracture cleavage, have been called joints. For example, in a recent description of some experimental work the terms "faults" and "joints" were used interchangeably, just as though the mechanics of their formation were similar. This all helps to conceal the basic fact that the major movement in jointing is perpendicular to the fracture surface. This distinction is truly characteristic and is not merely a matter of definition.

Nevin's criticism undoubtedly has much merit but the parallelism between joints and normal faults in the county can hardly be regarded as coincidental. Therefore, it is maintained that the joints, with displacement perpendicular to the joint planes, were formed first. Later conditions allowed a certain amount of vertical displacement and normal faulting took place along the established lines of weakness.

Thrust Faults. Exposed thrust faults in the Winfield formation tend to be aligned in position above the Abilene Arch. Fault planes are in a northern direction and those on the western leg of the structure have their downthrow side to the west. The amount of throw is about the same in each case and is never very large.

The Stovall limestone is usually found to be about a foot thick and although the Cresswell limestone varies somewhat, it is rarely more than 12 to 15 feet thick. The Gage shale below the Stovall is somewhat clayey and although varying in thickness, is less than 50 feet thick. Above the Cresswell limestone is the Odell shale which is also very thick.

The uniformity and small throw of the displacements in the Stovall suggest that they are the result of compaction rather than of a more active stress such as lateral compression. Their thrusts are all away from the crest of the anticline and are always toward a valley. Easy lateral relief due to the erosion of valleys has probably caused some lateral movement in the Gage shale. Such a movement would be augmented by the seepate of water into the clayey zones in the Gage shale.

Because the movement in the Gage shale is from the crest of the Abilene anticline toward the flanks there would be a slight flattening of the area. Such action would cause the Stovall to be bent and warped and at places where the lateral forces became too great, small thrust faults would develop.

Irregularities on the surface of the Stovall would not be reflected in the thicker Cresswell limestone except where the causal stress was exceptionally great. Field observations seem to fit these conclusions. At two of the places where the Stovall limestone is faulted there are faults in the Cresswell. At other places only the Stovall is faulted.

DISCUSSION

Relationship of the Theories of Compaction and Vertical Uplift to Structural Features of Riley County

Several theories have been analyzed for those characteristics which best explain the origin of the structures of the Mid-Continent region. Many of its structural features are undoubtedly due to differential compaction but differential vertical uplift best explains the over-all present attitude. All geologic evidences indicate that the structures of Riley County, a part of the Mid-Continent region, were subjected to the same general stresses that prevailed over the Mid-Continent region as a whole.

The fracture pattern of Riley County indicates that a northwest - southeast direction of active tension was the over-all controlling factor in establishing the regional strike of the north-east - southwest set of joints (Set II). The northwest-southeast set together with its normal faults appears to have been formed as a result of a combination of differential uplift abetted by differential compaction and rotation by the active tensile stress.

Just what geologic conditions were responsible for the development of active tension is difficult to determine and will probably not be established as a certainty until more study of the subject has been made. It is hoped, however, that this paper may help somewhat to determine the cause of this development.

The Theory Which Best Fits Fracture Patterns of Riley County

McCoy's (13) theory of warping involves a system of migrating, sinking basins with the Granite Ridge acting as a horizontal-line fulcrum. Sherrill's (22) is somewhat the same but favors a downwarping in certain areas in a region which formerly had been elevated. Sherrill believes this action to have been augmented by an upward movement of the Nemaha Mountains. He also believes that an upward movement of the buried range was necessary for the formation of a fault pattern such as that found in north-central Oklahoma.

<u>Stresses Necessary for the Formation of Joints</u>. The theory which best fits the fracture pattern of Riley County is diagramed on Plate II. Active tension in a direction approximately N. 30° W. - S. 30° E. would cause joints whose strike would be approximately N. 60° E. - S. 60° W., but the direction of the joints where they cross the buried ridges would be influenced by an additional factor. Near the crest of the buried ridges the active tension would be resolved into a tangential couple which would have the effect of rotating the joints in a clockwise manner to a position at right angles to the ridges. This clockwise rotation would be most pronounced in the zone closest to the ridges (Plate II). The buried ridges may be thought of as a series of fulcrum points around which the joints of Set II are rotated clockwise.

Variations of the joint-strike diagrams of Plate I from the theoretical explanation given on Plate II are due to (1) local deviations in the general strike and shape of the buried ridges, (2) the depth to the ridge and (3) major irregularities of the basement complex. It should be noted that the rotation factor varies inversely with both the horizontal and vertical distance from the fulcrum points of a ridge. The deviation of the joints of Set II in the southeast part of Plate I is probably due to the change in shape of the Nemaha Ridge. Here the ridge bulges out dome-fashion so that its western front produces a line of northwest - southeast fulcrum points.

Joints of Set I were formed by a combination of differential compaction and uplift between the two ridges and were aided somewhat by uplift of the ridges. It must be understood that, although compaction and uplift caused the formation of joints in Set I, active tension had some control of their strike.

"Through-set" joints appear in Set I in some localities and in Set II in other localities. Evidently both sets were formed at about the same time but seldom simultaneously.

Stresses Necessary for the Formation of Normal Faults. The normal faults of Riley County are all on the west flank of the Nemaha Range. Their nearness to the anticlinal crest explains their formation as well as why they are grouped in an en echelon fashion. Tensile stresses caused by differential compaction and acting in opposite directions from the ridge crests would be greatest near the top of a buried ridge. The great amount of tension would cause formation of normal faults and also cause them to choose zones following the anticlinal crest. Here again it is necessary to point out that differential compaction was aided by differential vertical uplift of the buried ranges. Tectonic structures are, in general, best developed closest to the source of the causal stress.

Age of Warping

The vertical adjustments, to which the present attitude of the Ozark Plateau is due, occurred at the end of Mississippian times. Undoubtedly there must have been many minor adjustments until the end of the Paleozoic era. The post-Paleozoic uplift was the greatest of all and the fracture pattern in Riley County is probably due to it. Compaction, differential uplift and active tension produced the two major sets of joints at about the same time.

Later faulting was produced by the combined efforts of differential compaction and uplift. It is probable that faulting occurred at the time the uppermost strata were unconsolidated and those below were becoming more consolidated. If the Cottonwood and Eiss limestones and the strata below were fairly brittle with the strata above less consolidated, an upward dying out of the fault planes could be expected.

CONCLUSIONS

The fracture patterns studied reveal that their existence is due mainly to tensile stresses. The active tension probably occurred during the time of regional uplift at the end of the Paleozoic era. Such a condition of tension explains only the first set of major joints. The other set must have been formed about the same time by the combined forces of differential compaction and differential uplift. A great amount of local vertical adjustment probably took place at about the same time of regional upwarping.

A remarkable parallelism between the strikes of the joint planes of major Set I and the fault planes of the normal faults in Riley County suggest that they are very closely related. It is thought that the joints were formed first and that at a somewhat later date vertical displacement took place along the joint planes. The stresses which initiated the displacements probably were caused mainly by compaction over irregularities because the fault planes are never very long and are concentrated into zones.

The normal faults may have occurred at a time when the uppermost strata were still relatively unconsolidated with the deeper ones more brittle because of a greater degree of induration. Such a condition would explain why the fault planes die out with height.

The Nemaha Ridge is probably a weak zone in the basement complex and may have been raised faster than its surrounding areas. Such a "punching up" would produce and localize the fault zones to areas close to the ridge.

Some of the minor sets of joints were formed at the same time as the major sets and some were formed at a much later date.

All of the minor sets are due to local causes.

All of the thrust faults in the Stovall limestone of Riley County have short fault planes and a small amount of throw. They probably are due to relief by erosion of stresses resulting from differential compaction and downdip plastic flow of the enclosing thick shales. Their position on the Abilene anticline is responsible for their high topographic position. Relief of the stored stresses in the direction of erosional valleys orients the direction of the strike of the thrust. Hence, the strike of the thrusts bears no relation to the strike of the joints.

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LITERATURE CITED

(1) Berger, W. R.
The relation between the structure and production in the Sallyards Field, Kansas. Amer. Assoc. Petro. Geol., Bul. 5:276-281. 1921.

(2) Blackwelder, E.
The origin of the central Kansas oil domes. Amer. Assoc. Petro. Geol., Bul. 4:89-94. 1920.

(3) Brown, R. W.
Origin of folds of Osage County, Oklahoma. Amer. Assoc. Petro. Geol., Bul. 12:501-513. 1928.

(4) Fath, A. E.
Geology of the Eldorado Oil and Gas Field, Butler County, Kansas. State Geol. Surv. of Kans., Bul. 7. 187 p. 1921.

(5) 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. Surv., Professional Paper. 128: 75-84. 1921.

(6) Foley, L. L.
Origin of the faults in Creek and Osage Counties, Oklahoma. Amer. Assoc. Petro. Geol., Bul. 10:293-303. 1926.

(7) Gardner, J. H.
Rock distortion of local structures in the oil fields of Oklahoma. Amer. Assoc. Petro. Geol., Bul. 6:228-243. 1922.

(8) Gardner, J. H.
The vertical component in local folding. Amer. Assoc. Petro. Geol., Bul. 1:107-110. 1917.

(9) Jewett, John M.
The geology of Riley and Geary Counties, Kansas. State Geol. Surv. of Kans., Bul. 39. 164 p. 1941.

(10) Levorsen, A. I.
Geology of Seminole County, Oklahoma Geol. Surv., Bul. 40-BB:28-39. 1928.

(11) Ley, H. A.
Subsurface observations in southeast Kansas. Amer. Assoc. Petro. Geol., Bul. 8:445-453. 1924.

(12) Link, T. A.
En echelon tension fissures and faults. Amer. Assoc. Petro. Geol., Bul. 13:627-643. 1929.

(13) McCoy, A. W.
A short sketch of the paleogeography and historical geology of the Mid-Continent Oil District and its importance to petroleum geology. Amer. Assoc. Petro. Geol., Bul. 5:541-584. 1921.

(14) Merritt, J. W. and O. G. McDonald.
Oil and gas in Creek County, Oklahoma. Okla. Geol. Surv., Bul. 40-C:12-35. 1926.

(15) Moore, R. C.
Geologic history of the crystalline rocks of Kansas. Amer. Assoc. Petro. Geol., Bul. 2:98-113. 1918.

(16) Moore, R. C., J. C. Frye and J. M. Jewett.
Tabular description of outcropping rocks in Kansas. State Geol. Surv. of Kans., Bul. 52. 201 p. 1944.

(17) Moore, R. C.
The relation of the buried granite in Kansas to oil production. Amer. Assoc. Petro. Geol., Bul. 4:255-261. 1920.

(18) Nevin, C. M.
Principles of structural geology. New York: John Wiley & Sons, 1942.

(19) Nevin, C. M. and R. E. Sherrill.
Studies in differential compaction. Amer. Assoc. Petro. Geol., Bul. 13:1-22. 1929.

(20) Nevin, C. M. and R. E. Sherrill.
The nature of uplifts in north-central Oklahoma and their local expression. Amer. Assoc. Petro. Geol., Bul. 13:23-30. 1929.

(21) Powers, S.
Reflected buried hills and their importance in petroleum geology. Econ. Geol., Bul. 17:233-259. 1922.

(22) Sherrill, R. E.
Origin of the en echelon faults in north-central Oklahoma. Amer. Assoc. Petro. Geol., Bul. 13:31-37. 1929.

APPENDIX

EXPLANATION OF PLATE I

Average strikes and average magnitudes of the joint pattern for Riley County

R Rotational fault

Township line

N Normal fault

T Thrust fault

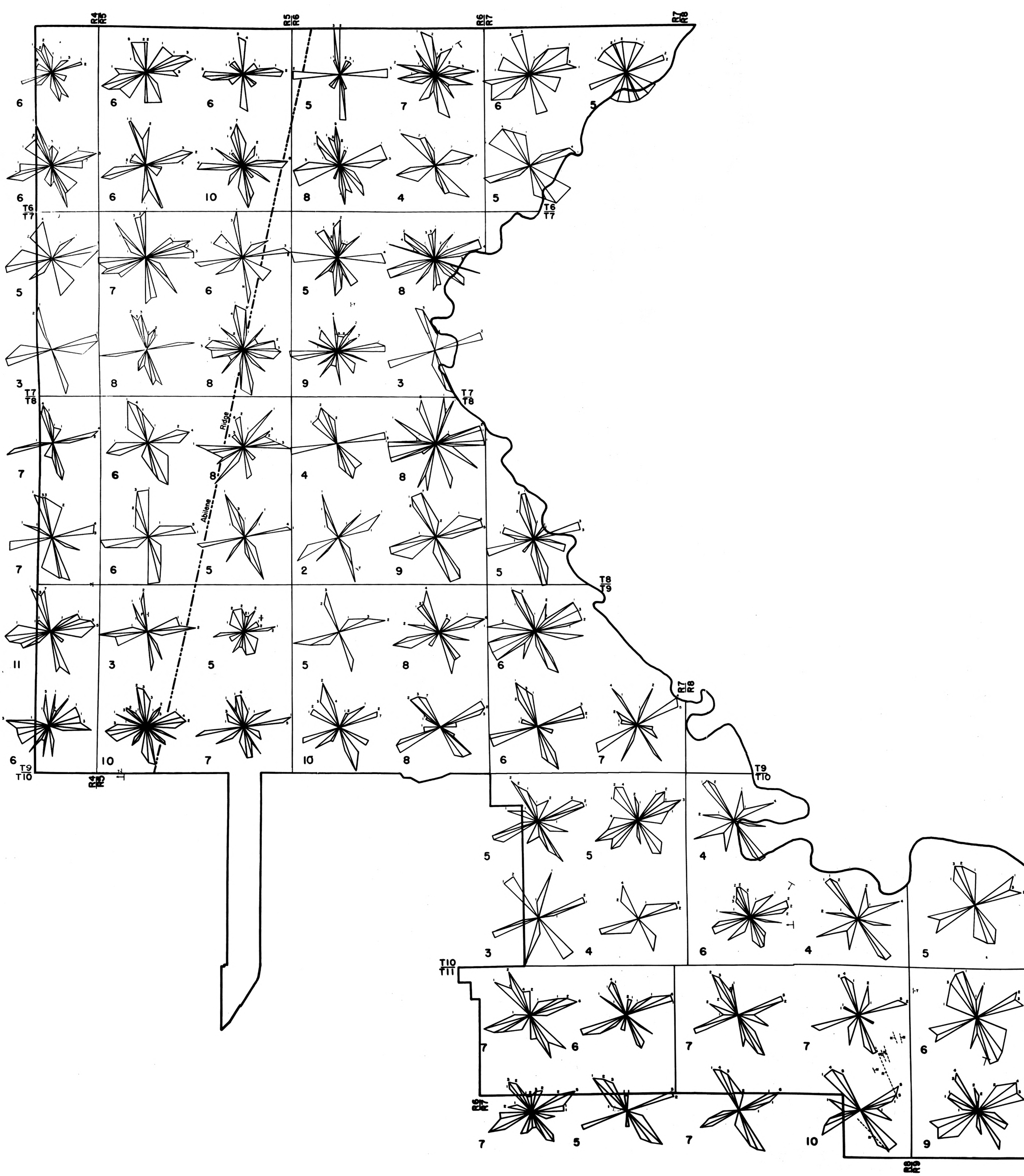
County line

F Flexure

Dome

Dip

PLATE I



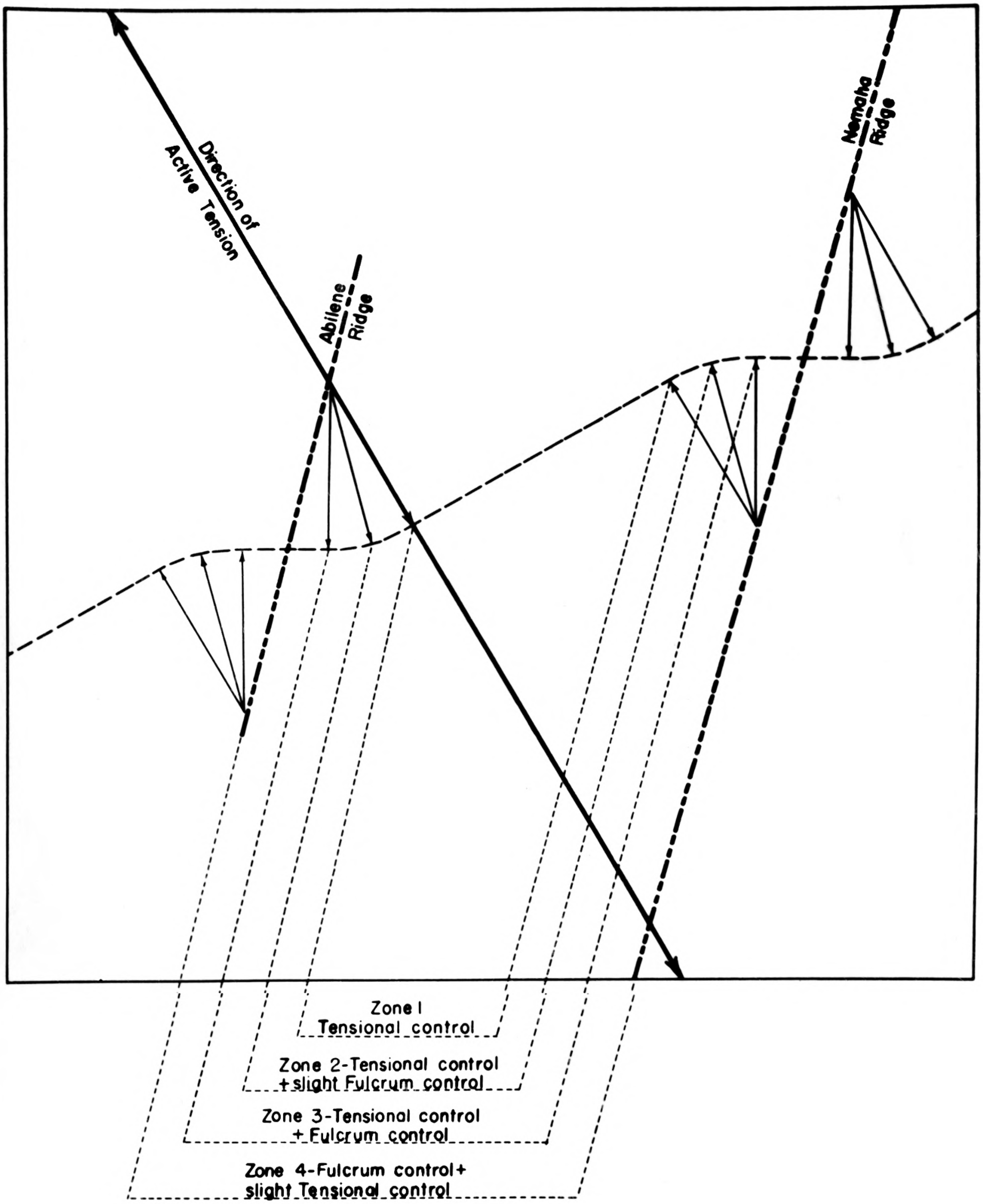
R4 R5
R5 R6
R6 R7
R7 R8
T6 T7
T7 T8
T8 T9
T9 T10
T10 T11
R8 R9
Abilene
Ridge

EXPLANATION OF PLATE II

Diagram of stresses which caused Major Joint Set II

- Direction of active tension
- Rotational components of active tension
- Direction of jointing for Joint Set II
- Crest of buried ridges

PLATE II


Direction of
Active Tension
Abilene
Ridge
Nemaha
Ridge
Zone I
Tensional control
Zone 2-Tensional control
+ slight Fulcrum control
Zone 3-Tensional control
+ Fulcrum control
Zone 4-Fulcrum control +
slight Tensional control

EXPLANATION OF PLATE III

Fig. 1. Thrust fault - SE$\frac{1}{4}$ Sec. 31, T9S, R5E.

Fig. 2. Thrust fault - NE$\frac{1}{4}$ Sec. 1, T9S, R4E.

PLATE III

Fig. 1

Fig. 2

EXPLANATION OF PLATE IV

Fig. 1. Thrust fault - SW$\frac{1}{4}$ NW$\frac{1}{4}$ Sec. 33, T8S, R6E

PLATE IV

Fig. 1