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THE DEVELOPMENT OF THE REGIONAL STRUCTURE OF EASTERN KANSAS AND ADJOINING AREAS

by

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Abstract

The rocks of eastern Kansas and adjoining regions have been gently folded during five principal periods of deformation. During each of these periods the pattern of the folding was distinctly different. Criteria for analyzing these structural movements have been developed. These are based on the concept that, if a sequence of rocks deposited above a horizontal surface is deformed before the development of a younger horizontal surface, an isopach map of the sequence of rocks between the surfaces will be interpretable as a structure map. This concept and its limitations are discussed in the first part of this paper.

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In the region studied, nearly plane surfaces were eroded at the base of the Upper Cambrian rocks, at the base of the St. Peter sandstone (middle Ordovician), at the base of the Devonian rocks, at the base of the Chattanooga shale (upper Devonian or Mississippian), and at the top of the Mississippian rocks. These surfaces and also depositional surfaces that were originally nearly horizontal, have been utilized in drawing isopach maps and in analyzing the structural history of the region.

The first of the five periods of deformation studied in this way occurred after the basal part of the Upper Cambrian rocks was deposited and before the St. Peter sandstone (middle Ordovician) was laid down. The principal structural features that were formed were a deep syncline trending north from the central Ozark region into eastern Iowa, and a south-plunging arch (the Southeast Nebraska arch) on the crest of which the St. Peter sandstone now overlies pre-Cambrian granite.

During the second period of deformation, which took place between the deposition of the St. Peter sandstone and the Mississippian limestones, the Ozark uplift rose from the deepest part of the syncline in which the Cambrian and Ordovician rocks had been deposited and the Southeast Nebraska arch became a subsiding structural basin, known as the North Kansas basin. These movements were accompanied by the development of the Chautuauqua arch and the initial arching of the Central Kansas uplift.

The third period of deformation, which began during Mississippian time and continued into the Permian, is most clearly revealed by the beveling of the Mississippian limestones. During this period of deformation the Nemaha anticline was formed and also the Salina and Forest City basin synclines. The Cherokee basin syncline, which crosses the axis of the older Chautauqua arch at right angles, was warped downward in early Pennsylvanian time. The Ozark and Central Kansas uplifts continued to rise during this period.

During the fourth period of deformation, which occurred between Permian and early Cretaceous time, the upper Permian and underlying rocks of eastern Kansas were tilted southwest toward the south-pluging Hugoton embayment syncline in western Kansas, already well developed after Mississippian deposition.

The fifth period of deformation began after the deposition of the Dakota formation and probably took place mainly after the close of Cretaceous time. During this deformation the rocks of this region were tilted north toward a great basin in central Nebraska, as shown by the present attitude of the Dakota.

As a result of the repeated changes in the pattern of regional folding the surface rocks in many areas do not reflect the attitude of the older rocks. The movement of nascent oil and connate water must have been greatly modified from time to time by the changing patterns of deformation.

INTRODUCTION

Subsurface study of the geology of the rocks of Kansas in recent years has revealed that their present attitude is the result of at least five distinguishable periods of structural movement. In some areas, the later movements reversed or otherwise changed the direction and amount of earlier regional dip, with the result that the regional structure of the deeper rocks differs, in many places, from the structure of the surface rocks.

The several periods of structural movements have been analyzed mainly by cross sections and thickness maps prepared from well logs. Inasmuch as the extent to which thickness maps can be used in the interpretation of structural movements may not be fully realized, by many geologists, it is desirable first to discuss the criteria used to analyze the diverse structural movements of eastern Kansas and adjoining areas.

Criteria for Determination of Structural Movement

If an originally flat surface such as X-X' of cross section A (fig.1) is covered by younger rocks to a uniform thickness and the rocks are then folded and beveled by erosion to the surface Y-Y' of cross section B, the variations in the thickness of the rocks between the two surfaces as shown in cross section B will reveal the place and the amount of folding. The thin areas represent anticlines and the thick areas represent synclines.

Thickness maps will ~~this~~ thus simulate structural maps if, as in cross section A, the limiting surfaces were originally horizontal planes.

The flat surfaces that limit the sequence may be sedimentary surfaces like X-X' of Figure 1, or the result of beveling by peneplanation or marine planation like Y-Y' of the same figure. It is obvious that thickness maps will not reveal structural movement with mathematical accuracy unless both upper and lower surfaces were originally geometrically plane and horizontal. Such surfaces are of course rare, although they were at times approached by sedimentation. When both the limiting surfaces are depositional like X-X', the variations in thickness reveal the structure with a high degree of accuracy. When one or both of the surfaces are erosional, the accuracy with which the structure is revealed by differences in thickness will depend upon how closely the surfaces originally approached horizontal planes.

The following discussion refers especially to regional structure. In order to dissociate the concepts from ideas of local structure, the horizontal distances represented in the diagrams in Figures 1 to 7 should be assumed to be about 100 miles.

In Figure 2, the line O-O' of cross section A represents a deeply eroded surface. A thickness map of the unit between surfaces O-O' and RR' will represent the approximate topography of the surface O-O' if this surface were covered without deformation. After deformation, the surface O-O' shown in cross section B will be modified by renewed erosion but in any case the structural movements can not be determined

from a thickness map of the unit because one of the limitng surfaces did not even approach a horizontal plane.

Under the conditions represented in Figure 3, where the erosional relief of the surface S-S' is small when compared with the regional deformation, the regional structure will be approximately shown by a thickness map of the unit between SS' and TT'. A, b, c, etc. represent wells that have penetrated the sequence at high and low points of the eroded surface. The use of data from these wells in drawing a thickness map will give a distorted impression of the local structure but the regional deformation will be approximately represented.

Although thickness maps may reveal the place and amount of folding, they do not reveal the sequence of events or the time of folding. In cross section A of Figure 4, the deformation of the assumed originally horizontal lower surface X-X' is represented as having taken place before the deposition of the overlying sediments. Undoubtedly some erosion of the anticlinal areas that were raised above the level of deposition would have occurred before their burial. The structure indicated by thickness maps under these conditions would thus be somewhat less than the actual deformation. Cross section B of Figure 4 represents the folding and beveling of the rocks as having occurred at the end of the sequence of deposition. Cross section C represents the deposition of a sequence of rocks that was being deformed more or less contemporaneously with deposition. In

C, both the upper and lower surfaces are depositional.

The thickness maps of units ~~deposited~~ deposited under these different conditions will be identical and will reveal only the amount of deformation. In order to discover the sequence of events it is necessary to construct such cross sections as A, B, and C, to determine the relation of the sequence to the overlying and underlying rocks.

The conditions illustrated in Figure 4 are represented in the rocks of the region studied. Cross section A is exemplified by the sequence between the top of the Mississippian and the base of the Hertha limestone at the base of the Kansas City group of the Pennsylvanian in Kansas. The beveled surface at the top of the Mississippian was deformed before the region was submerged in the Pennsylvanian sea (cross section B, fig. 21). Cross section B of Figure 4 is exemplified by the sequence between the base of the St. Peter sandstone and the top of the Chattanooga and Boice shale sequence (fig. 18). Both upper and lower surfaces of this sequence of rocks were beveled by erosion. Cross section C of Figure 4 illustrates conditions that prevailed during the Pennsylvanian when differential warping was more or less contemporaneous with deposition.

Figure 5 shows the progressive deformation of a syncline interrupted by a low angular unconformity with topographic relief represented by V-V'. The variation in the thickness of rocks between U-U' and W-W' represents the total of many differential movements during the deposition of the sequence plus the movement that occurred during the hiatus at V-V'. Such a sequence occurs between the Cotton-

wood limestone member of pre-Beattie limestone of the early Permian of Wolfcamp age of Kansas, which is comparable to U-U', and the top of the Topeka limestone of late Pennsylvanian age, which is comparable to W-W'. The irregular line V-V' represents an unconformable contact such as that between the Pennsylvanian and the Permian strata.

A more complex situation results when the sequence studied includes formations warped by successive structural movements having different effects. In Figure 6, cross section A represents the situation after the beveling of folded rocks by the surface M-M'. The surface was buried by horizontal sediments that were later warped in a new and different fold as in cross section B. The new pattern of folding greatly altered the former structure of the rocks below M-M'.

It is obvious that the regional structure of the beds above M-M' will not reveal the structure of the underlying beds. Cross section C shows the thickness of the unit between surfaces DD' and MM' plus the unit between MM' and NN': A thickness map of these units combined would be affected by opposing structural movements and would reveal neither.

In Figure 6, the anticline at the right of cross section A has been shifted to the left and greatly reduced as a result of the later synclinal folding shown in cross section B. Something like this when the west-trending Chautauqua arch, which developed in southeastern Kansas between St. Peter and Mississippian time, was crossed

in early Pennsylvanian time by the north-trending Cherokee basin syncline. Such reduction or elimination of regional structural features by later movements is not uncommon and a number of other examples of the kind in the Kansas-Missouri area will be mentioned later.

In the use of thickness maps as guides to reveal structural movements, the relations of the sequence to the underlying and overlying rocks must be considered in order to be sure that the limiting surfaces used were originally flat. In Figure 7, cross section A shows the thickness of the rocks between surfaces X-X' and Y-Y'. Y-Y' is known to have been originally a plane horizontal surface. X-X' in other areas has proved to be a beveled surface with almost no erosional relief. The variations in the thickness of rocks between X-X' and Y-Y' thus suggest the occurrence of a beveled syncline such as is shown in cross section B. However, if the thickening of the sequence between X-X' and Y-Y' is accompanied by a compensating thinning of the underlying rocks, it becomes evident that the original beveled surface at the base of the sequence was trenched by a broad valley before resubmergence and that the thickening of the sequence Y-Y' to X-X', which would appear on a thickness map, is due to its deposition in a pronounced erosional basin and not to deformation. Figure 8 shows a diagrammatic cross section of such a valley eroded in the pre-Chattanooga surface in central

Kansas (Lee, 1940, pl. 4). The valley, which is about 40 miles wide and about 150 feet deep, was later filled by Chattanooga shale.

The selection of units for which to make thickness maps that will be significant in interpreting structural movements requires consideration of the character of the limiting surfaces of the units. Some suitable surfaces are illustrated as Y-Y' in the diagrammatic cross sections of Figure 9. Cross section A represents a cyclical sequence of rocks that was being differentially tilted toward the right during its deposition. The surfaces of most of the formations may be assumed to have been originally plane and horizontal, but some surfaces such as X-X' that were eroded during emergent phases between the cycles of deposition are less desirable than others for drawing thickness maps significant of structural movements.

Cross section B represents an eroded sequence of rocks overlain unconformably by younger formations laid evenly across the beveled outcrops of the older formations. Residual hills of low relief on such a surface as Y-Y' may confuse the expression of local structure on thickness maps without seriously impairing their usefulness in interpreting regional structure.

In the midcontinent region where the seas were seldom if ever deep, the base or top of any formation of uniform thickness or the base or top of any formation that thickens with regularity, as in cross section C, may be assumed to have been at one time flat and

essentially horizontal. Some modification of this assumption must be made in offshore areas of deep and rapidly subsiding basins of other regions where, in some cases, beds were deposited with initial dips.

Cross section D represents a beveled surface that was tilted before the deposition of the sequence X-Y'. The relation is indicated by the regular overlap of the various formations toward the left and an increase of the hiatus in the same direction. A thickness map of the sequence X-Y' will represent the deformation that preceded the sequence, but will understate the structural movement, because the area on the left may have suffered some erosion before submergence. Such erosion occurred in early Pennsylvanian time on the crest of the rejuvenated Nemaha anticline, (fig. 22).

In cross section E, the tilting of the beveled surface was progressive and occurred during the deposition of the sequence X-Y' (compare fig. 12). Overlap as shown on the left may occur, but the test of the value of the surface in interpreting regional structure lies in the regularity of the thickening of the lower units of the sequence X-Y'.

APPLICATION OF CRITERIA

These criteria of structural movement were first used in Kansas in the study of that part of the Forest City basin that is in Kansas (Lee, 1943). Later they were applied to a study of the whole Forest City basin. In this project, Reed of the Nebraska

Geological Survey, Hershey of the Iowa Geological Survey, and McQueen, Greene, and Grohskopf of the Missouri Geological Survey, collaborated with the writer, who represented the State Geological Survey of Kansas and the United States Geological Survey (Lee, Grohskopf, Hershey, and Reed, 1946). Thickness studies by the writer, in collaboration with Constance Leatherock and Theodore Botinelly of the United States Geological Survey, have since been extended across the Nemaha anticline into the Salina basin, (Lee, Leatherock and Botinelly, 1948). Thickness maps compiled from these reports reveal the structural development of eastern and central Kansas, southeastern Nebraska, southern Iowa, and northern Missouri. Data exist for the compilation of similar thickness maps in Illinois and adjacent states and in Oklahoma. It is probable that when thickness maps for larger areas have been added to the Kansas and Missouri nucleus, the low deformational swells that characterize most of the structural features of the midcontinent region will be found to be linked to distant and more pronounced orogenies.

The original maps of the reports mentioned were drawn with lines of equal thickness at 50 to 100-foot intervals. In order to avoid confusion, in presenting the data on small maps, the thickness intervals of the original maps have been increased and most of the local details of thickness have been suppressed.

The skeletonized columnar section (fig. 10) shows the relative position of the stratigraphic units discussed in this paper. Because of the many unconformities, the full sequence of formations is not represented at any point in Kansas, and each of the formations

is absent in parts of the areas.

Of the many unconformities recognized in the pre-Cretaceous rocks, five produced essentially flat surfaces beveling rocks that had previously been extensively deformed. These surfaces occur at the base of the Upper Cambrian rocks, at the base of the St. Peter sandstone or Simpson group, at the base of the Devonian rocks of the area, at the base of the Chattanooga shale of late Devonian or Mississippian age, and at the top of the Mississippian rocks. These surfaces and also depositional surfaces that were originally nearly horizontal have been used in the preparation of the thickness maps.

It is probable that these major angular unconformities will be ~~reconginzed~~ recognized in broad areas adjacent to Kansas and even in some distant regions. During some periods of exposure, the warped strata were evenly beveled, in Kansas, but it is possible that these may be traced elsewhere to areas of considerable topographic relief.

FIRST PERIOD OF DEFORMATION

The first period of deformation is revealed in Figure 11 by the variations in the thickness of the rocks between the base of the Upper Cambrian and the base of the St. Peter sandstone. The St. Peter sandstone is correlated with the sandstone member of the Simpson group of central Kansas. South of the Chautauqua arch in Kansas, the Simpson group becomes thicker by additions at the base (Lee, 1949). Throughout most of eastern and central Kansas, the St. Peter overlies a beveled surface on which rocks ranging in age from the pre-Cambrian (Lee, 1943, fig. 9) to the Smithville formation (McQueen, 1931,

pl. 12) were exposed.

Although the surface of the pre-Cambrian rocks upon which the Upper Cambrian rocks were deposited was an erosional surface, it seems to have been essentially flat in Missouri and in broad areas in Kansas. All but one of the wells drilled to the pre-Cambrian in Missouri encountered Lamotte sandstone overlain by Bonneterre dolomite, but the variations in the thickness of the Lamotte sandstone beneath the regular and persistent Bonneterre dolomite imply some topographic relief. In central Kansas, quartzite hills rose 200 feet or more above the regional plain (Walters and Price, 1948), but the erosional relief of the pre-Cambrian surface, thus revealed, was low compared to the structural relief that had developed before the deposition of the St. Peter. In northeastern Oklahoma, hills of pre-Cambrian rock are believed to have survived until late Arbuckle time. In Vernon County, Mo., opposite Fort Scott, Kan., McQueen (1931) reports that a hill of pre-Cambrian rocks is capped by the Gunter sandstone member of the Van Buren formation at the base of the Ordivician. The Lamotte and Bonneterre formations are absent in considerable areas in eastern Kansas and elsewhere, but except in areas of local relief they

seem to have been deposited and later eroded.

The upper surface of the pre-Simpson sedimentary sequence was extraordinarily flat. This is indicated by the regular thickness of the St. Peter sandstone in central and eastern Kansas and northern Missouri, where it is rarely less than 50 feet or more than 100 feet thick in an area several hundred miles in diameter. However, much greater thickness of the St. Peter have been drilled in three or four wells of the hundreds of wells drilled. In one well the thickness was more than 400 feet. These unusual thicknesses of St. Peter sandstone were probably deposited in sink holes or in local channels incised on the otherwise level surface. They have been ignored in drawing the thickness maps.

Figure 11 shows by lines of equal thickness, drawn at 200-foot intervals, the thickness of the sequence between the base of the Lamotte sandstone and the base of the St. Peter sandstone in northern Missouri and parts of Kansas, based on studies of wells in Missouri by McQueen (1931) and in Kansas by Keroher and Kirby (1948). The Map shows an area in northeastern Kansas, called the Southeast Nebraska arch, where the St. Peter rests on pre-Cambrian granite. Before the deposition of the St. Peter, rocks ranging in age from Lamotte sandstone to Jefferson City dolomite were beveled. They cropped out in more or less concentric bands around the exposed pre-Cambrian core of the Southeast Nebraska arch. They appear east of the arch and increase in thickness eastward to more than 2,000 feet in northeastern Missouri, revealing a beveled syncline

trending from north to south in eastern Missouri and Iowa formed prior to the deposition of the St. Peter. The Southeast Nebraska arch was probably never raised very high above sea level but was beveled, step by step, as fast as the surface was exposed to erosion.

Unfortunately, the map showing the thickness of the rock sequence between the St. Peter sandstone and the base of the Lamotte sandstone cannot be extended into the Ozarks, or into the areas of of the Chautauqua arch and the Central Kansas uplift, because the St. Peter, which forms the upper limit of this sequence, was later eroded from these anticlinal areas. The Roubidoux formation, however, has survived. Its upper surface was a depositional surface suitable for use in drawing a thickness map of structural significance. In the Ozark area of southern Missouri, the thickness of the sedimentary rocks from the top of the Roubidoux down to the top of the Lamotte sandstone (fig. 11), shows that the south-plunging syncline was already well developed there also by the end of Roubidoux time.

The deformation shown by the thickness lines in Missouri was not the result of movements that occurred just before the deposition of the St. Peter sandstone, but was the result of a long series of small movements. This is illustrated by cross section A-A' of Figure 12 which extends from central Kansas to southeastern Missouri. The wells are correlated on the top of the Roubidoux formation, The wells of Missouri reveal beveled surfaces at the base of the Potosi

dolomite, at the base of the Van Buren formation, and at the base of the Roubidoux formation. Each of these surfaces is overlain by deposits that overlapped toward the west upon beveled outcrops of older formations.

In Missouri, the Van Buren and Gasconade sequence overlaps from Proctor to Eminence and in Kansas wedges out on the beveled surface of the Bonneterre dolomite. The Roubidoux formation, in Missouri, everywhere overlies the Gasconade dolomite. In Kansas, however, it overlaps in succession toward the west, the beveled margin of the Van Buren and Gasconade sequence and the Bonneterre, and overlies the pre-Cambrian in some anticlinal areas.

These relations imply that the Ozark basin began its subsidence at least as early as Potosi time and that subsidence was intermittently active during the remainder of Arbuckle time. The deformation that immediately preceded St. Peter time was only the final increment of a long series of similar movements.

It has been assumed by some geologists that the thinning or absence of the lower part of the Arbuckle group in places in central Kansas, as in Barton and Greenwood Counties, indicates the occurrence of pre-Cambrian hills that remained unsubmerged until Roubidoux time. In the light of relations shown in this and other cross sections (Keroher and Kirby, 1948), it is difficult to explain the presence of Bonneterre dolomite and Lamotte sandstones below the Roubidoux formation on the flank of pre-Cambrian rocks in Barton and Greenwood Counties (fig. 12) without assuming that the Bonneterre and

some other persistent formations were originally deposited throughout the area and that they were eroded from the crests and beveled on the flanks of pre-Roubidoux anticlines. If these areas represent pre-Cambrian hills, the Bonneterre and Lamotte must have been deposited in Kansas some 2,000 feet higher than in Missouri without commensurate thinning of either formation.

The arch in Greenwood County (well No. 5), which is beveled by the Roubidoux formation (fig. 12), is the southern extension of the Southeast Nebraska arch, which reaches into Oklahoma. The minor syncline in McPherson County (well No. 4) trends northward. It is probable that the pre-Roubidoux arch in Barton County (well No. 2) is parallel to the other structural features of the time, although there is as yet no direct evidence.

SECOND PERIOD OF DEFORMATION

The second period of deformation began after St. Peter time and continued intermittently until the deposition of early Mississippian limestones. During this period successive structural movements followed a pattern of folding different from that of the first period of deformation.

Figure 13 shows by lines of equal thickness drawn at 200-foot intervals, the thickness of the sequence of rocks from the base of the St. Peter sandstone to the base of the Devonian rocks. The beveled surface at the top of the sequence increases locally at the expense of the overlying Devonian rocks. These relations reveal

that in some places, hills stood as much as 70 feet above the pre-Devonian plain. (Lee, Grohskopf, Hershey and Reed, 1946, sheet 3). These irregularities confuse the details of local structure but the relief on the pre-Devonian surface is too low to interfere materially with the interpretation of the regional structure.

During the deposition of this sequence there was in some areas a complete reversal of the structural movement that took place during the first period of deformation. The Ozark arch rose from what had been a subsiding basin during Arbuckle time and the Southeast Nebraska arch became an area of subsidence known as the North Kansas basin. During the deposition of this sequence the North Kansas basin was part of a broad, gradually subsiding syncline that extended into eastern Iowa and flanked the contemporaneously rising Ozark region.

The Ozark uplift, the Chautauqua arch, and possibly the Central Kansas uplift began to develop shortly after the deposition of the St. Peter sandstone. The center of the North Kansas basin subsided more than 900 feet below the beveled margin of the pre-Devonian sequence of Kansas on the flank of the Ozark uplift and probably more than 1,000 feet below its beveled crest.

Cross section A-A' of Figure 13, which is shown in Figure 14, extends northeast from the flank of the Chautauqua arch in Central Kansas to the margin of the North Kansas basin near the Nebraska line. The wells are correlated on the top of the St. Peter sand-

stone. The cross section shows the thickening of individual formations toward the North Kansas basin. Wells Nos. 3 and 4 show a pre-Chattanooga valley. The irregularities in the basinward thickening of individual formations are due, at least in part, to erosional relief on some of the contacts, especially at the top of the Sylvan or Maquoketa shale, in part to the deviation of the cross section from a straight line, and perhaps in part to local structural movements.

Figure 15 shows the pre-Devonian areal geology. Rocks in central Kansas that were later removed by erosion have been restored. The Silurian rocks are present in the synclinal area of the thickness map (fig. 13) and the older formations are beveled in bands flanking the areas of uplift. The erosion that preceded the deposition of the Silurian rocks removed the Maquoketa or Sylvan shale from an area in central Kansas near the Nebraska line and as a result the Silurian was deposited on the Viola limestone in that area. The distribution of the Sylvan shale in central Kansas suggests that the saddle separating the Chautauqua arch from the central Kansas uplift was already established.

The next phase of the second period of deformation is shown in Figure 16 by the thickness of the Devonian dolomite and limestone sequence, which was deposited upon a beveled surface and was similarly beveled by erosion prior to the deposition of the Chattanooga. The thickness lines are drawn at 100-foot intervals.

Throughout most of the region the pre-Chattanooga surface was exceptionally flat and very perfectly bevels the Devonian limestones and older rocks. A great many wells have been drilled through the Chattanooga shale in ~~shotheastern~~ southeastern and northeastern Kansas. In most areas its thickness increased gradually northward with great regularity. This regularity could not have occurred if there had been marked erosional relief on either its upper or lower surface.

However, in central Kansas the determination of regional movements based on the thickness of the Devonian limestones is complicated by a pre-Chattanooga valley, already mentioned, which drained from east to west and was joined by a tributary from the south (fig. 17). These valleys were eroded through the Devonian limestones and into the underlying formations, leaving an outlier of Devonian limestone. The main valley, as shown diagrammatically in Figure 8, was 40 miles wide and more than 150 feet deep (Lee, 1940, pl. 4). In these valleys the shale increases in thickness at the expense of the underlying rocks, so that the lines showing the thickness of the Devonian limestones are without structural significance in these areas.

The contact of the upper surface of the Devonian limestones with the overlying Chattanooga shale was destroyed in much of southeastern Nebraska, by pre-Pennsylvanian erosion, so that the pre-Chattanooga thickness of the Devonian cannot be contoured in that

area. However, enough of the upper suface of the sequence remains in marginal areas to reveal that the North Kansas basin continued to subside during and after deposition of the Devonian limestones.

The syncline that earlier flanked the Ozark uplift on the north has been broken into two basins elongated toward the south and separated by a well-developed anticlinal divide. The trend of these structural features suggests that they were the result of stresses that later produced the Nemaha anticline. The belt of thinning shown extending south from the southeastern corner of Nebraska in Figure 16 reveals a pre-Chattanooga anticline more than 250 miles long. The Falls City oil pool of Nebraska lies on its northern extension. Inasmuch as this fold closely parallels the Nemaha anticline, which had its major development much later, initial movements of the Nemaha anticline may have accompanied this pre-Chattanooga folding, although direct evidence is not available because of post-Mississippian erosion. Thickness maps of sequences younger than the Devonian limestone do not reveal any later activity of this pre-Chattanooga anticline.

The Ozark area, the Chautauqua arch, and the Central Kansas uplift were re-elevated and beveled before deposition of the Chattanooga shale. The separation of the last two structural features was definitely brought about at this time, as is shown by the preservation of the Devonian outlier in the saddle between them. Devonian limestone (which was probably originally deposited across the Ozark uplift and possibly upon the Central Kansas uplift) and most of the rocks of Simpson age were eroded from these positive and rising

areas. Rocks ranging in age from Simpson to Devonian now flanked the rocks of the Arbuckle group exposed on these rising areas in the pattern made familiar in Kansas by McClellan's map of the distribution of the pre-Chattanooga formations (McClellan, 1930), except that the Nemaha anticline shown on that map was not yet in existence. Rocks of Devonian and Silurian age are not now present on the southwestern flank of the Central Kansas uplift.

The subsidence of the North Kansas basin during this interval was at least 600 feet below the beveled margin of the Devonian carbonate rocks on the flank of the Chautauqua arch and probably as much as 1,000 feet below the beveled structural crest.

Figure 17 shows by 100-foot thickness lines the present thickness of the shales between the pre-Chattanooga surface and the base of the Mississippian limestones.

The Boice and Chattanooga shale sequence was removed by post-Mississippian erosion from much of southeastern Nebraska and northeastern Kansas on and west of the Nemaha anticline. The original distribution of the shales is thus not known. The dashed lines in the eroded area, which are based on data from areas where the Mississippian limestone remains, suggest the original thickness of the sequence. There is no reason to doubt that shales were deposited across the area subsequently raised by the Nemaha anticline, but the location of the western margin of the basin is speculative. It seems probable that the Chattanooga shale did not cover the rising areas of the Ozark and Central Kansas uplifts but that it was deposited upon their flanks in areas from which it was later eroded.

The variations in the thickness of the shale sequence east of of the Nemaha anticline where it is still overlain by Mississippian limestones reveal that the southerly elongation of the North Kansas basin, which is shown by the thickness map of the Devonian limestones (fig. 16), continued at least to the beginning of Mississippian limestone deposition.

Movement of the Chautauqua arch is shown by the interpolated 50-foot thickness line, which reveals a low structural arch plunging westward. A similar but more pronounced structural arch extended northward from the Ozarks to southwestern Iowa. This arch continued to separate the North Kansas basin from a basin in southeastern Iowa.

The surface of the Devonian limestone in the North Kansas basin subsided more than 250 feet below the flank of the Ozark uplift. Most of these shales, which are commonly referred to as "the Kinderhook," are of doubtful age. They are for most part correlatives of the Chattanooga and Grassy Creek shales of Missouri, which some geologists believe to be of Devonian age. The hematite oolite ~~and~~ and the overlying shale sequence in (?) southeastern Nebraska and northeastern Kansas, described by Reed (1946) as the Boice shale, are probably of Kinderhook age. The Boice shale lies in apparent conformity below the 100 feet of Kinderhook limestones at the base of the Mississippian in that area, but it rests unconformably on the underlying Chattanooga. Both the upper and lower surfaces of the Chattanooga and Boice shale sequence were exceptionally flat except

the lower surface in the valley areas in central Kansas. Surviving parts of these valleys that seem to have had a trend toward the northwest are shown by the 200-foot thickness line, which in this area has no structural significance.

Figure 18 shows by 100-foot isopachous lines the overall thickness in Kansas of the rocks between the base of the St. Peter and the base of the Mississippian limestones in the area in which both these datum beds survive. It is also interpretable as a structure map and sums up the results of the several similar movements shown by the three preceding thickness maps. It records the total deformational movements that modified the originally flat St. Peter sandstone during the second period of deformation. The regularity of the lines is due to the exceptional smoothness of the limiting surfaces, which eliminates errors that were introduced into the other maps by the use of intermediate imperfectly beveled surfaces. The lines are broken in areas from which the Mississippian limestones have been eroded.

This map shows a subsidence of the North Kansas basin of 1,100 feet in the areas where both the upper and lower surfaces of the sequence survive. In the center of the North Kansas basin, where both the shales and the upper part of the Devonian have been eroded, the subsidence was several hundred feet greater. The St. Peter sandstone and lower rocks of the sequence were eroded from the crests of anticlinal areas. The base of the St. Peter in the North Kansas basin probably subsided not less than 2,500 feet below the eroded crest of the St. Peter on the Chautauqua arch.

The cross section shown by Figure 19 (A-A', fig. 18) extends from the saddle between the Central Kansas uplift and the Chautauqua arch in Rice County in central Kansas, toward the deepest part of the North Kansas basin in Nemaha County in northeastern Kansas, but does not reach the bottom of the basin, which lies farther north in Nebraska. In Figure 19 the wells of the cross section are correlated on the base of the Mississippian limestones. The cross section shows the thickening into the basin of all the units except the Sylvan or Maquoketa shale, which was irregularly dissected by pre-Silurian erosion.

THIRD PERIOD OF DEFORMATION

A third period, during which the deformation differed from that of both the earlier periods of folding, began in Mississippian time and continued to the middle of Permian time. The first phase of this period is shown in Figure 20 by the thickness of the Mississippian limestones. Their upper surface was so perfectly beveled in most areas that the Mississippian limestones are thinned on the crest of even small anticlines. In some areas, however, broad shallow valleys have been identified; but these valleys do not interfere with the determination of regional structure. The thickness lines as shown are drawn at 100-foot intervals and are generalized. Only the most prominent regional structural features are represented. Folds were developed during this period of folding in two directions almost at right angles. The Nemaha anticline trends northeast and the Forest City

basin syncline, although modified by local movements, trends roughly in the same direction between the 300-foot contours. The Central Kansas uplift and the Salina basin trend northwest. The Ozark area and the Central Kansas uplift of the second period of folding were re-elevated, but the Chautauqua arch was not conspicuously revived. In the area of the Chautauqua arch the base of the Mississippian formed a broad irregular structural platform, which for a time remained slightly higher than in the Forest City basin and probably higher than in areas in Oklahoma.

The most important structural feature that originated during the third period of deformation was the Nemaha anticline, a beveled arch that extended from a point south of Oklahoma City slightly east of north to Omaha. Its development was accompanied by secondary parallel folds, which are especially numerous and well-developed in the constricted area between the Central Kansas uplift and the Nemaha anticline. These folds are not fully revealed by the generalized thickness map, but the axes of some of the most prominent of these folds have been plotted to show their relation to the regional structure.

The Forest City basin was a broad beveled syncline between the Ozark uplift and the northern end of the Nemaha anticline with which it was roughly parallel. Four hundred fifty feet of Mississippian limestones were preserved at its lowest point near Kansas City. The Nemaha anticline west of the basin, however, was raised so high that beveling exposed the pre-Cambrian granite. The configuration

of the thickness lines shows that the Cherokee syncline had not yet begun to form.

The most prominent northwest-trending structural feature is the Central Kansas uplift. It is shown in outline by the zero line of the Mississippian limestones. The upper Mississippian rocks had been deposited across the Central Kansas uplift, but they were removed by the beveling which in that area re-exposed the Arbuckle group and, in some places, the pre-Cambrian rocks.

The Salina basin was a broadly beveled northwest-trending syncline parallel to and northeast of the Central Kansas uplift. Three hundred fifty feet of Mississippian rocks were preserved in its deepest part near Salina. Toward the south between the Nemaha anticline and the Central Kansas uplift, this basin was closed by a low structural divide (Lee, Leatherock, and Botinelly, 1948, pl. 8). The approximate position of the broad crest of this divide is shown on Figure 20 as an anticlinal axis. Toward the southeast the Salina basin syncline dies out a short distance beyond its intersection with the Nemaha anticline. The Salina basin was confined on the northeast by beveled Devonian rocks, which had risen contemporaneously from the deepest part of the old North Kansas basin.

Figure 21 shows the thickness of Pennsylvanian rocks below the Hertha limestone at the base of the Kansas City group and represents the second phase of the third period of deformation. The thickness contours are drawn at 100-foot intervals. As in the previous map, the lines have been generalized and do not show local details. All

the regional structures that were active at the end of Mississippian time were revived during the early Pennsylvanian. Some new structural features were added and the character of the Nemaha anticline was changed.

The innovations include the abrupt downward displacement of the region east of the Nemaha anticline which in some places toward the north, was accompanied by faulting. The Cherokee basin was warped downward in southeastern Kansas at right angles across the area of the Chautauqua arch. Deformation in the Forest City basin in northeastern Kansas was revived. The Forest City basin and the Cherokee basin together formed a broad syncline between the Ozark uplift and the Nemaha anticline. The basins were at first separated by a broad low anticline known as the Bourbon arch, which for a time formed a topographic divide. After middle Cherokee time, the Bourbon arch was intermittently submerged, but it continued to be active at least to middle Pennsylvanian time.

By Hertha time, the Forest City basin extended north from the Bourbon arch into northwestern Iowa. It may be regarded as a revival of the post-Mississippian structural basin but it was longer, and the lowest point had shifted from near Kansas City to the vicinity of Falls City, Nebr., where it was only 20 miles east of the crest of the Nemaha anticline. The Cherokee basin extended southward from the Bourbon arch into the Ouachita basin of south-central Arkansas, of which it is an arm. Eighteen to twenty thousand feet of Pennsylvanian rocks all older than the Marmaton formation were deposited in the

Ouachita basin, but only a little more than 800 feet of pre-Marmaton rocks were deposited in the deepest part of the Forest City basin. The total displacement of the Forest City basin below the beveled crest of the Nemaha anticline in northeastern Kansas was more than 1,050 feet during this interval.

The northwest-trending Central Kansas uplift was re-elevated. Part of the area as shown by the zero line remained above the level of Hertha deposition. Parts of the Ozark region also were probably too high to be covered by the Hertha limestone. The Salina basin was extended toward the northwest and the point of maximum subsidence shifted northwest to Jewell County, in north central Kansas near the ~~Iowa~~ border, where 400 feet of Pennsylvanian sediments older than the Hertha were deposited.

The continued activity of the structural arch shutting in the Salina basin on the south is revealed by the thinning of the sequence in McPherson County in central Kansas, where its position is shown by the symbol for an anticlinal axis trending northwest. This arch was low and had probably become inactive before the deposition of the Hertha. As in the preceding thickness map, the Salina basin cuts across and interrupts the Nemaha anticline, forming a structural saddle at the point of intersection. The fact that the Salina basin syncline again broke the crest of the Nemaha anticline, as it did during the preceding phase, indicates that folds nearly at right angles were being developed contemporaneously or in alternation.

The secondary anticlines were less active than formerly. Not even 50-foot isopachous lines (Lee, Leatherock, and Botinelly, pl.9) reveal deformation of these anticlines clearly.

The changes that took place on the Nemaha anticline and in the adjoining basins in the latitude of Kansas City and Topeka can best be shown by the diagrammatic cross sections of Figure 22. Cross section A represents the beveling of the folded Mississippian and older rocks. The original Nemaha anticline was probably an asymmetric fold with the steeper limb on the east side. The deepest part of the ancestral Forest City basin, as measured by the thickness of the Mississippian limestones near Kansas City, was 450 feet, and that of the Salina basin near Salina was 350 feet. The actual movement that occurred before the beveling of the Mississippian rocks was much greater than is indicated by the surviving 450 feet in the Forest City basin, for the total thickness of rocks removed from the northern crest of the Nemaha anticline, where granite was exposed, was not less than 1,500 feet.

Cross section B shows the structural changes that were brought about before Hertha time. The beveled surface at the top of the Mississippian was gradually warped and raised above sea level. Erosion developed dendritic drainage on its surface, but the topographic relief was low in most areas. When the Pennsylvanian sea invaded the downwarped areas, differential movements for a long time kept the anticlinal areas above sea level. The gradually rising Nemaha anticline was not permanently covered on the Burns dome in

Central Kansas (fig. 20) until Marmaton time and in southeastern Nebraska not until early Kansas City time. Although the maximum structural movement of the Nemaha anticline occurred on its axis near the structural escarpment, the long exposure of the uplifted block resulted in the westward retreat of the topographic divide. In consequence, the thinning shown by the thickness lines in this belt does not reveal the position of the anticlinal axis very accurately.

At the northern end of the anticline the rejuvenation of movement was accompanied locally by 700 to 800 feet of faulting, but the displacement on the east limb was probably effected in most places by steep monoclinal dips. The maximum elevation of the crest above the eroded plain in the deepest part of the Forest City basin syncline was more than 1,050 feet near the Nebraska State line. Near the Oklahoma border, the displacement, immediately east of the escarpment, was less than 300 feet and was brought about mainly by dip. The maximum total displacement on the east flank of the Nemaha anticline at its northern end was not less than 2,550 feet by Hertha time.

Figure 23 shows the thickness of the rocks between the base of the Hertha limestone of the Kansas City group and the top of the Topeka limestone of the Shawnee group. The contour interval is 100 feet. Uplift had diminished along the Nemaha anticline, and the displacement during this interval on its east side was about 300 feet near the Kansas-Nebraska line and only about 100 feet in southern Kansas. Movement declined also on the Central Kansas uplift. The Salina basin continued to subside, but the structural divide that

shut in the basin on the south was inactive and during this interval the Salina basin had become a structural embayment or southeast-plunging syncline without closure. Secondary anticlines such as the Voshell anticline were still active but the structural movements were small.

Figure 24 shows by 100-foot contours the thickness of rocks between the top of the Topeka and the Florence limestone member at the base of the Barneston limestone of the Chase group. Because the Florence limestone has been eroded from northeastern Kansas, the thickness of this interval on the Nemaha anticline can be determined only toward the south. The displacement east of the Burns dome in central Kansas was only a little more than 50 feet. The Central Kansas uplift was reduced to a broad structural bulge and the Salina basin to a structural re-entrant. The syncline between the Central Kansas uplift and the Nemaha anticline was the most conspicuous structural feature. Only slight movements occurred on the Voshell anticline and other secondary folds parallel to the Nemaha anticline.

Figure 25 shows by 100-foot contour lines the thickness of rocks between the base of the Barneston limestone and the top of the Stone Corral dolomite at the top of the Sumner group of the Permian. The area in which thickness lines can be drawn is limited on the east, but the area of control is broad enough to show that there was no movement of either the Central Kansas uplift or the Salina basin that could be expressed even by 50-foot thickness lines. During this interval the surface was being gradually tilted toward the south,

whereas previously the regional subsidence had been to the southeast toward the Ouachita basin.

The sequence of rocks whose thickness is shown in Figure 25 includes the Hutchinson salt member of the Wellington formation. The broadening of the space between the 1,000-foot and 1,100-foot thickness lines occurs in the area in which the salt thickens. The salt basin thus immediately overlies the formerly rising Central Kansas uplift, which is shown in outline. It is evident that the Central Kansas uplift, which had been a positive and rising area since St. Peter time, became a part of a subsiding area during the deposition of the salt. Secondary northwest-trending anticlines upon the crest and flank of the Central Kansas uplift, however, show that some parallel movements continued into Cretaceous time, long after the uplift itself had become inactive.

FOURTH AND FIFTH PERIODS OF DEFORMATION

The fourth and fifth periods of deformation are revealed by structure maps of the Stone Corral dolomite and the Dakota formation in western Kansas. Figure 26 C shows the present structure of the Stone Corral dolomite by generalized 250-foot structure contours. Figure 26 B shows the present structure of the top of the Dakota formation by 250-foot structure contours (after Bass, 1926). It is assumed that both the top of the Stone Corral and the top of the Dakota were originally flat and horizontal surfaces. The Dakota structure is a composite of all the movements that deformed the

Dakota during Cretaceous, Tertiary, and Quaternary time. The Stone Corral was deformed by the same movements that deformed the Dakota. If the Dakota structure is subtracted from the Stone Corral structure, therefore, the result will show the attitude of the Stone Corral when the top of the Dakota was flat.

Figure 26A is the result of removing the structure of 26B from the structure of 26C. It is a composite, in general terms, of the deformation that warped the Stone Corral from the time of its deposition in late Permian time to the end of Dakota time. It includes late Permian deformation plus Triassic, Jurassic, and Cretaceous deformation to the end of Dakota time. Most of the deformation probably occurred between the Permian and the Cretaceous.

Figure 26A reveals that, by the end of Dakota time, the originally flat Stone Corral and associated beds had been warped into a south-plunging syncline in western Kansas. This structural feature, the Hugoton embayment, was already in existence at least as early as the end of Mississippian time (Maher and Collins, 1949 and Claire, 1948), but it was inactive from Kansas City to Nolans time. In eastern Kansas the contemporary regional tilting was toward the southwest.

The increments of folding that produced the present attitude of the Dakota are not now decipherable in this area. Since its deposition, the Dakota has been tilted to the northeast and north toward a great unnamed structural basin trending northward from central Nebraska. These movements reversed the plunge of the western Kansas

syncline at the horizon of the Stone Corral as shown in Figure 26C and shifted the position of its axis to the east. The post-Dakota movements also changed the southwestward regional dip of the Stone Corral during Dakota time to the present northwestward dip that now characterizes the outcrops of eastern Kansas. The regional northwestward dip of the rocks of eastern Kansas is thus not the result of a single post-Permian structural movement but of two periods of warping each of which may itself have been a composite movement. The first tilted the south and southeast-dipping Permian and Pennsylvanian rocks of central and eastern Kansas toward the southwest and the second tilted the pre-Dakota rocks to the northwest.

RESUME

There were thus five periods of deformation, each in a different and conflicting pattern. The first, which was active before St. Peter time, produced a deep syncline in the Ozark region and an arch in southeastern Nebraska. The second period extended from St. Peter time to the beginning of Mississippian time and was characterized in Kansas by the development of the North Kansas basin, the Chautauqua arch, and the first movements of the Central Kansas uplift, and, in Missouri, the Ozark uplift. The third period of folding extended from early Mississippain time to middle Permian time. It is characterized by the development of the Nemaha anticline, the Forest City, Cherokee, and Salina basins, and the continued activity of the Ozark and Central Kansas uplifts. The latter movement was definitely ended by the downwarping of the Wellington salt basin. The growth of the

Chautauqua arch was ended by the development of the Cherokee basin syncline.

The composite results of what were probably several movements during the fourth period revived the post-Mississippian south-plunging Hugoton embayment in western Kansas. During the fifth period, probably also a composite of several movements, the early Cretaceous strata of Kansas were tilted toward a great Tertiary basin in central Nebraska, which reversed the plunge of the Hugoton embayment syncline at the horizon of the Stone Corral.

CONCLUSIONS

It should be obvious that, in passing downward from younger to older rocks, the changes in the direction of the regional dip will modify the local structure as revealed by the surface rocks (Lee, 1943, figs. 20, 21). Fortunately, in this region, the dips involved in the regional structure rarely exceed 15 feet per mile. In strongly developed surface anticlines, reverse dips in the older rocks of 15 feet per mile will not materially affect the position of the subsurface crests. Where local surface anticlines show reverse dips of less than 15 feet per mile, a change or reversal of dip in the older rocks, in certain cases, can cause a shift in the position of the crest of the subsurface anticline (Lee and Payne, 1944, fig. 12).

It is probable that structural deformation was almost continuous and not spasmodic. The cross sections reveal that differential deformation was going on during the deposition of many of the major units

and also during the hiatuses that separate them. Cyclical deposition, especially during the Pennsylvanian, was accompanied by differential deformation.

From time to time these complex movements must have altered the direction of migration of nascent oil and gas and the associated connate water. Any speculation as to how oil and gas moved from their place of origin to structural and stratigraphic traps must take into account the structural history of the rocks involved and the fact that the strata of some areas were tilted in one direction at one time and later warped in other directions. Many of the structures in the older rocks are of relatively recent origin, but there may be older local structures such as the pre-Chattanooga arch in northeastern Kansas that were not rejuvenated by later and conflicting patterns of deformation. Such structures would thus have no expression in the surface rocks.

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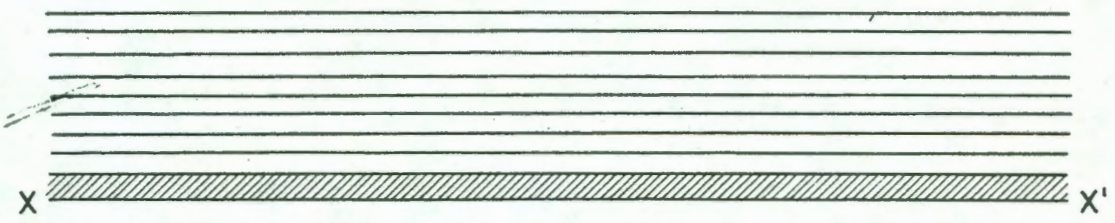
Fig. 1.—Hypothetical cross sections illustrating how deformation is shown by the difference in thickness between a folded sedimentary surface and a subsequently beveled surface.

Fig. 2.—Hypothetical cross sections illustrating the absence of any structural significance in thickness maps when one of the limiting surfaces is very irregular due to deep erosion.

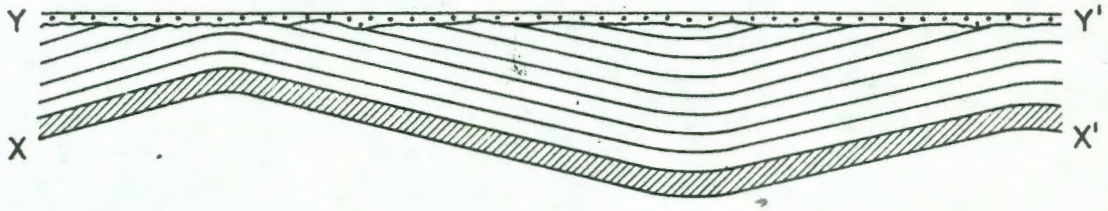
Fig. 3.—Hypothetical cross section illustrating the relation of structure to thickness of a sequence where topographic relief of one limiting surface is considerably less than the structural relief of the other. Regional deformation is approximately revealed. Letters a to h represent wells penetrating the unit.

Fig. 4.—Cross sections showing that thickness maps reveal the total deformation that took place between the limiting surfaces and not the sequence of structural events. Maps representing the thickness of the unit between surfaces X-X' and Y-Y' in sections A, B, and C will be the same, although the time of deformation in each is different.

Fig. 1.—Hypothetical cross sections illustrating how deformation is shown by the difference in thickness between a folded sedimentary surface and a subsequently beveled surface.



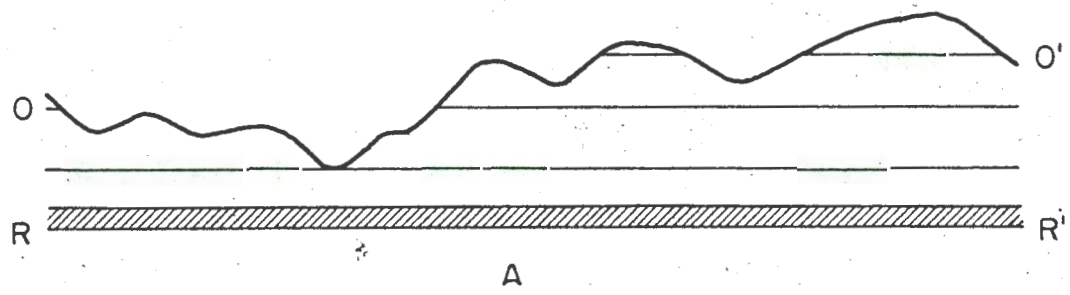
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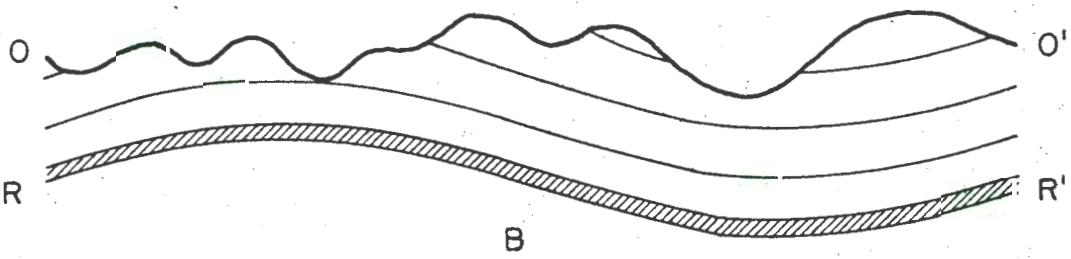
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Fig. 2.—Hypothetical cross sections illustrating the absence of any structural significance in thickness maps when one of the limiting surfaces is very irregular due to deep erosion.



A



B

Fig 2

Fig. 3.—Hypothetical cross section illustrating the relation of structure to thickness of a sequence where topographic relief of one limiting surface is considerably less than the structural relief of the other. Regional deformation is approximately revealed. Letters a to h represent wells penetrating the unit.

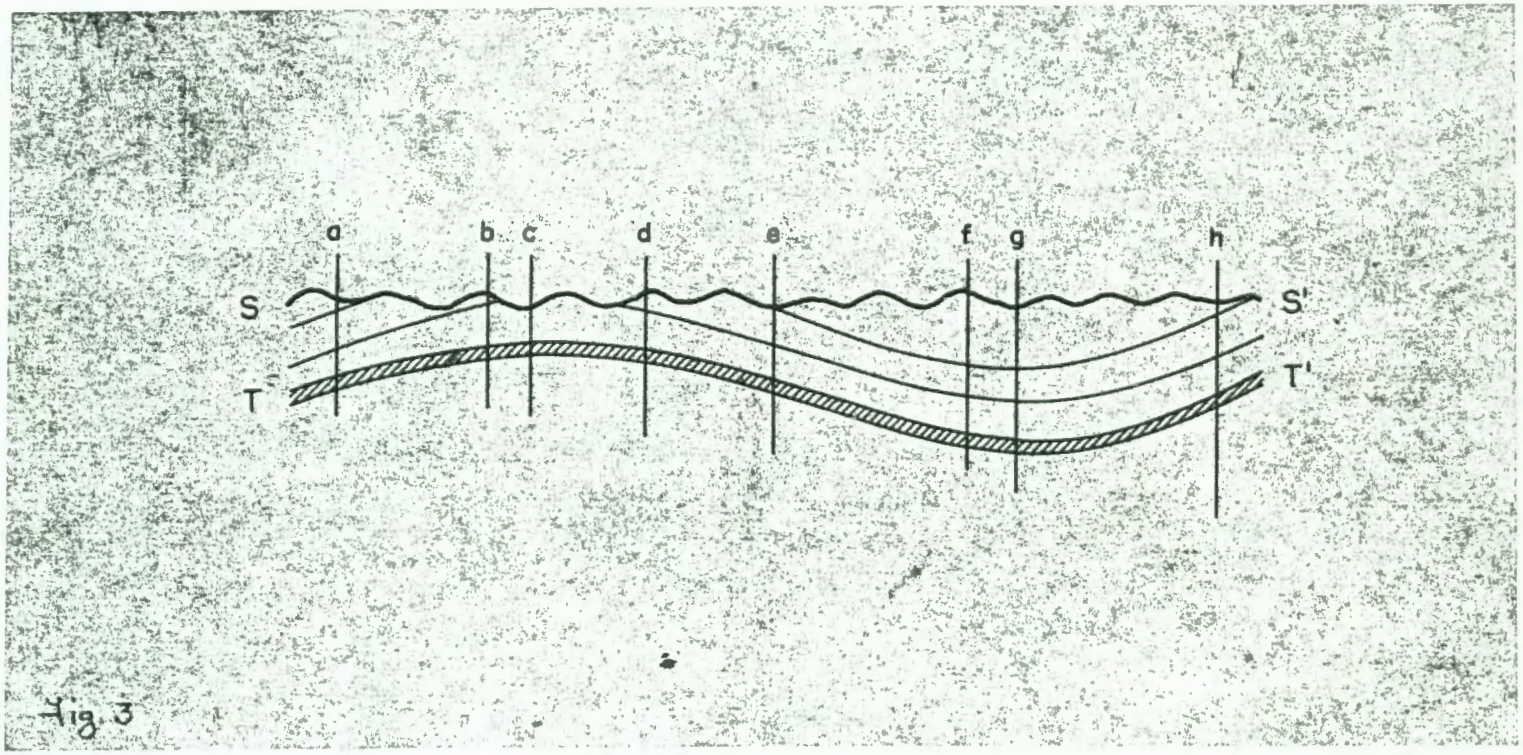


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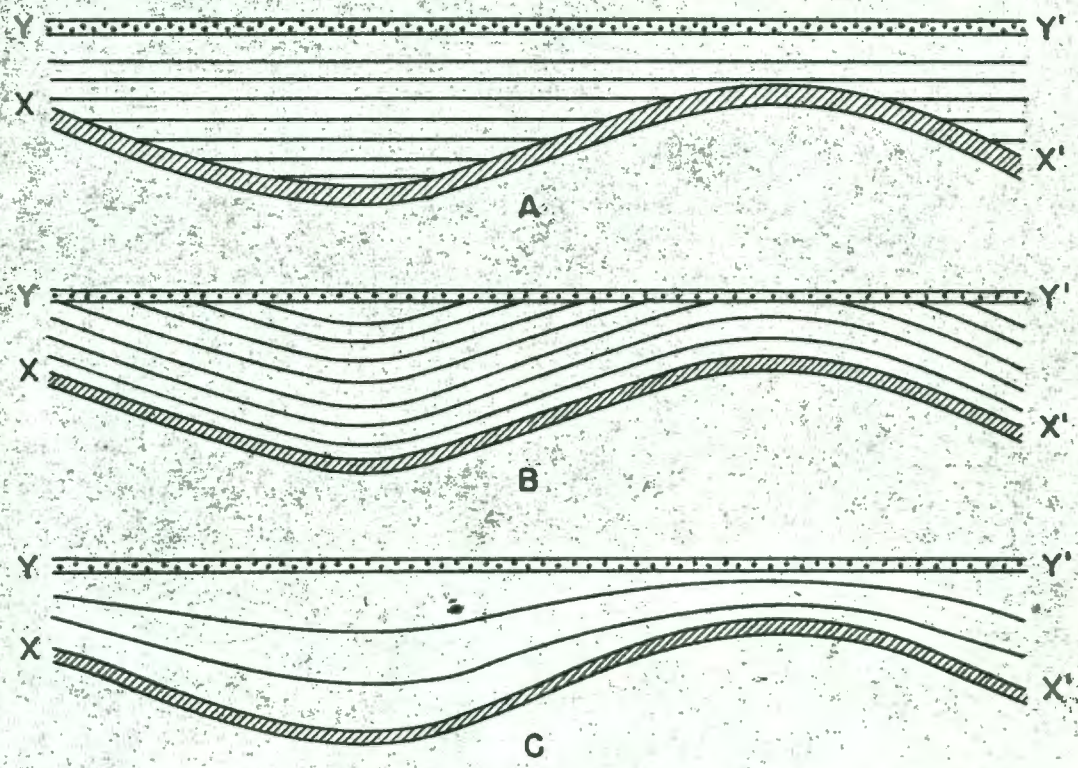


Fig. 4.

Fig. 5.—Cross section showing that the total movement inferred from the thickness of rocks between the originally flat surfaces U–U' and W–W' is not affected by an intervening unconformity V–V'.

Fig. 6.—Cross sections showing the effect on the thickness of a sequence between the originally flat surfaces N–N' and O–O' when folding represented by N–N' of cross section A was modified by later folding of another kind as shown by M–M' of cross section B. The over-all thickness between O–O' and N–N' shown in cross section C does not differentiate between the results of the two movements.

Fig. 7.—Cross sections showing the erroneous interpretation of cross section A as a beveled syncline as in cross section B, on consideration of thickness alone. The relation of the sequence between X–X' and Y–Y' to the underlying formations, however, reveals a filled valley without deformation as shown in cross section C and Fig. 8.

Fig. 8.—Diagrammatic cross section of a pre-Chattanooga valley filled by later Chattanooga shale in McPherson County, Kans. The interval between A–A' and B–B' does not reveal structural movement. The interval between A–A' and C–C' indicates deformation.

Fig. 5.—Cross section showing that the total movement inferred from the thickness of rocks between the originally flat surfaces U–U' and W–W' is not affected by an intervening unconformity V–V'.

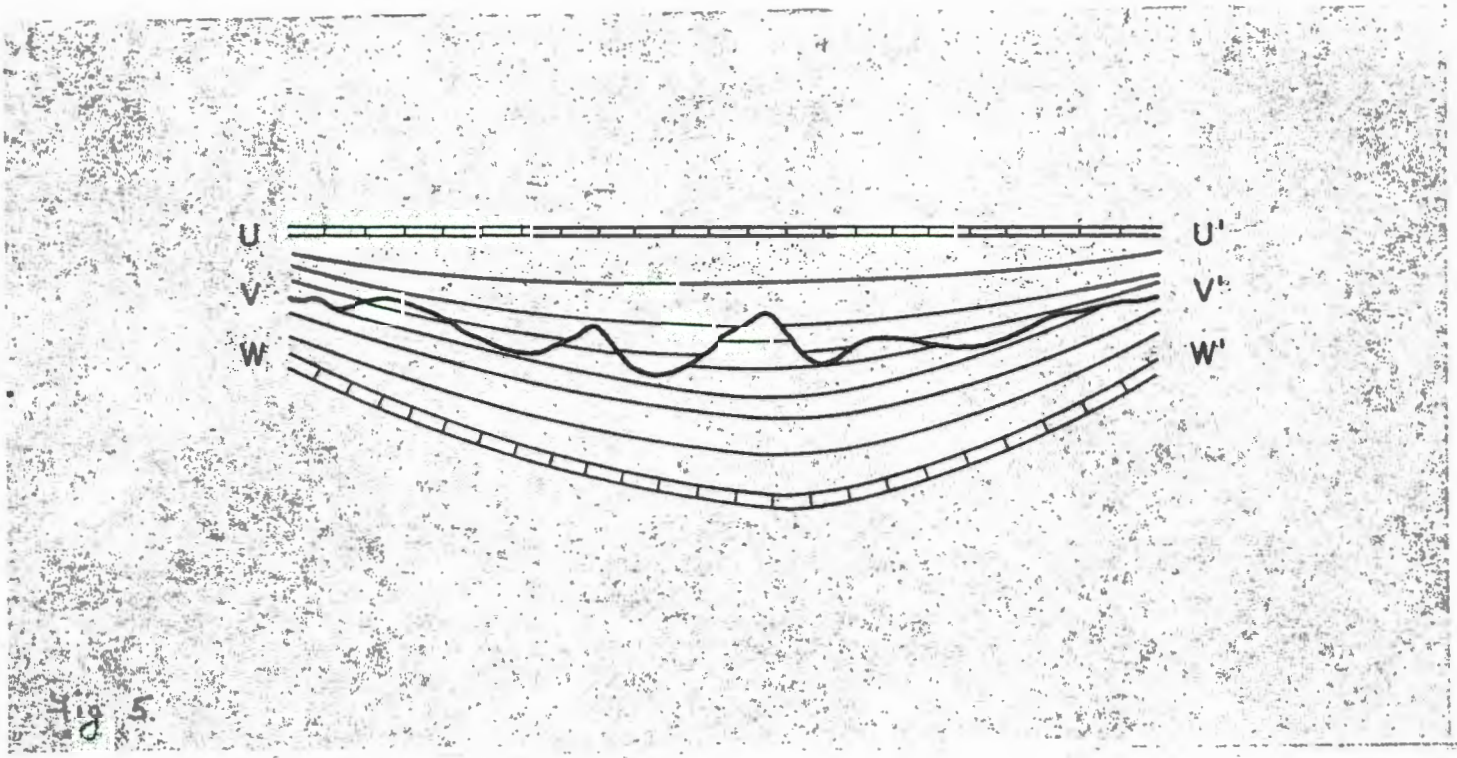


Fig 5.

Fig. 6.—Cross sections showing the effect on the thickness of a sequence between the originally flat surfaces N–N' and O–O' when folding represented by N–N' of cross section A was modified by later folding of another kind as shown by M–M' of cross section B. The over-all thickness between O–O' and N–N' shown in cross section C does not differentiate between the results of the two movements.

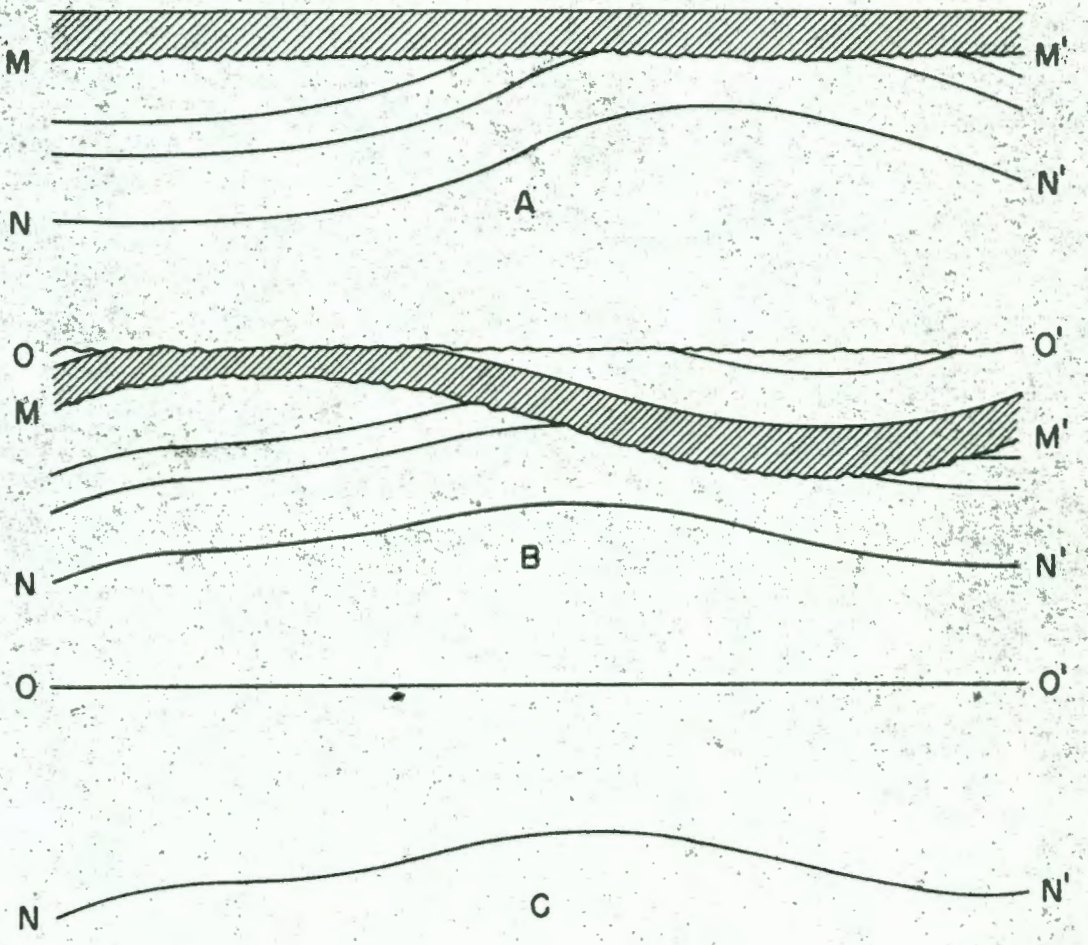


Fig 6.

Fig. 7.—Cross sections showing the erroneous interpretation of cross section A as a beveled syncline as in cross section B, on consideration of thickness alone. The relation of the sequence between X–X' and Y–Y' to the underlying formations, however, reveals a filled valley without deformation as shown in cross section C and Fig. 8.

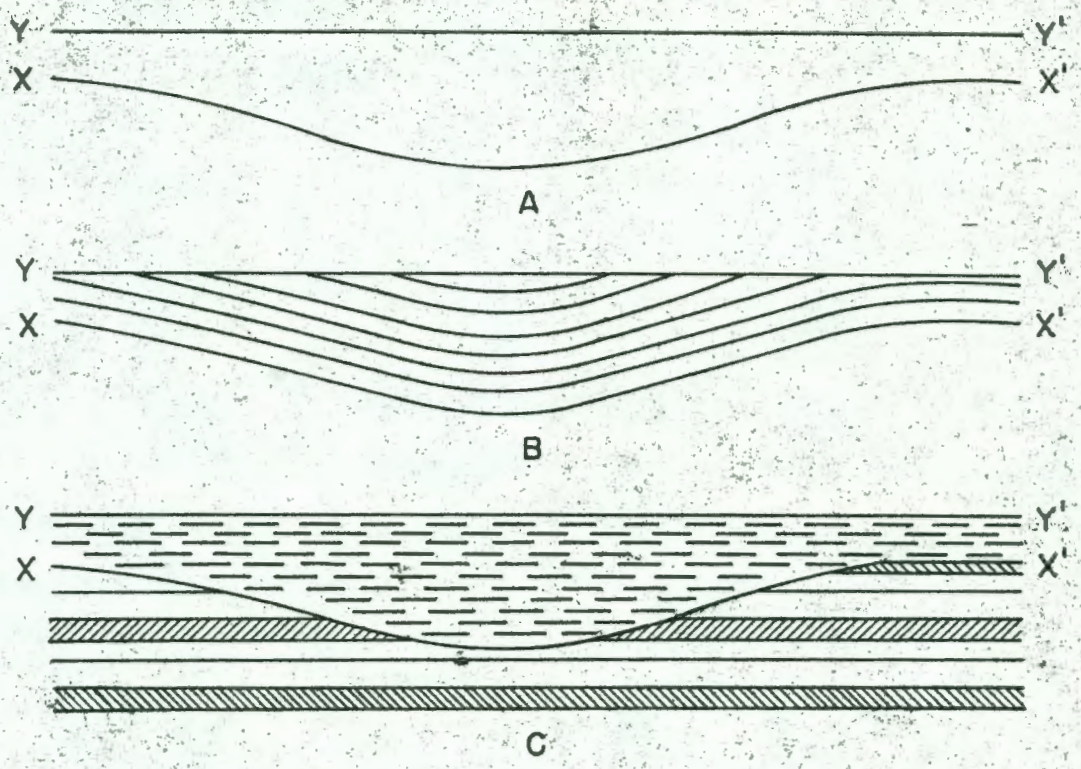


Fig. 7

Fig. 8.—Diagrammatic cross section of a pre-Chattanooga valley filled by later Chattanooga shale in McPherson County, Kans. The interval between A-A' and B-B' does not reveal structural movement. The interval between A-A' and C-C' indicates deformation.

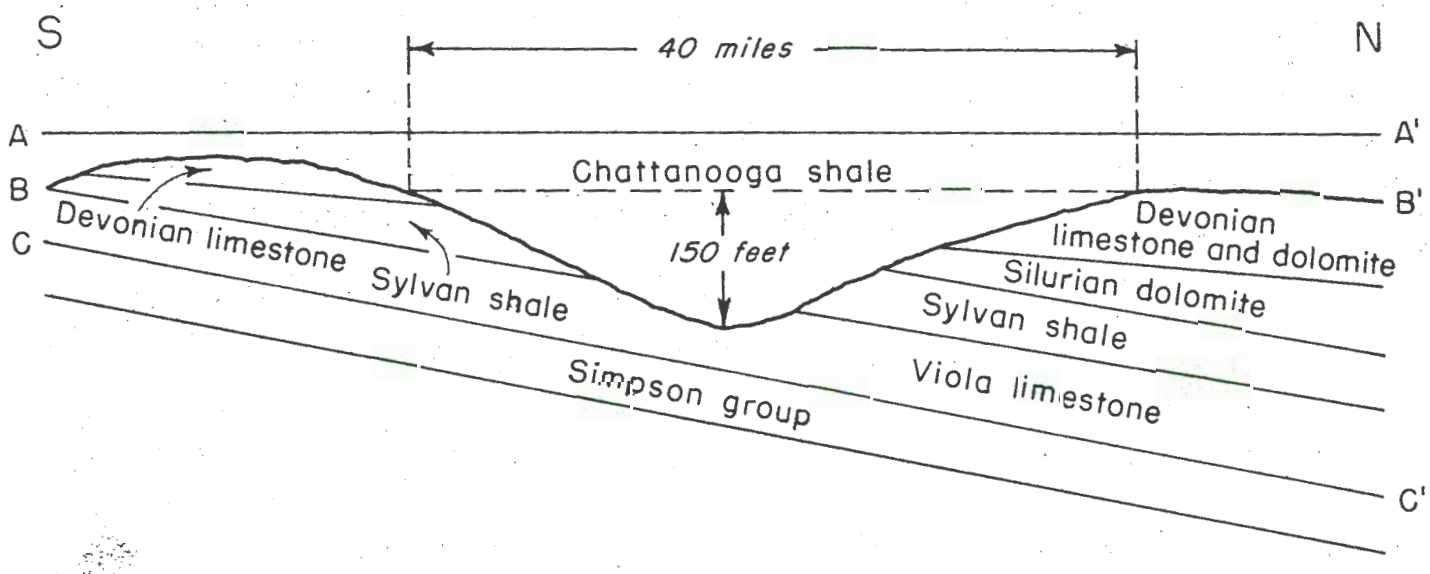


Fig. 9.—Diagrams illustrating surfaces, such as Y-Y', of value in preparation of thickness maps significant of structural movement.

Fig. 10.—Skeletonized columnar section, showing the relative position of stratigraphic units discussed in this paper. Due to unconformities and overlap, the full section is not found at any single locality in the area.

The column at the right indicates the sequences of rocks included in the thickness maps (Figs. 11 to 26).

Important unconformities are shown by heavy wavy lines.
The terminology of this report is that of the U. S. Geological Survey.

Fig. 11.—Map showing the thickness of the sedimentary rocks below the St. Peter sandstone; and in southern Missouri, the thickness of the rocks between the top of the Roubidoux formation and the top of the Lamotte sandstone.

Thickness lines spaced at 200-foot intervals.

A-A' shows the position of the cross section Fig. 12.

Fig. 12.—Cross section of Arbuckle and adjacent rocks from central Kansas to southeast Missouri on the line A-A' of Fig. 11.

Wells are correlated on the top of the Roubidoux formation.

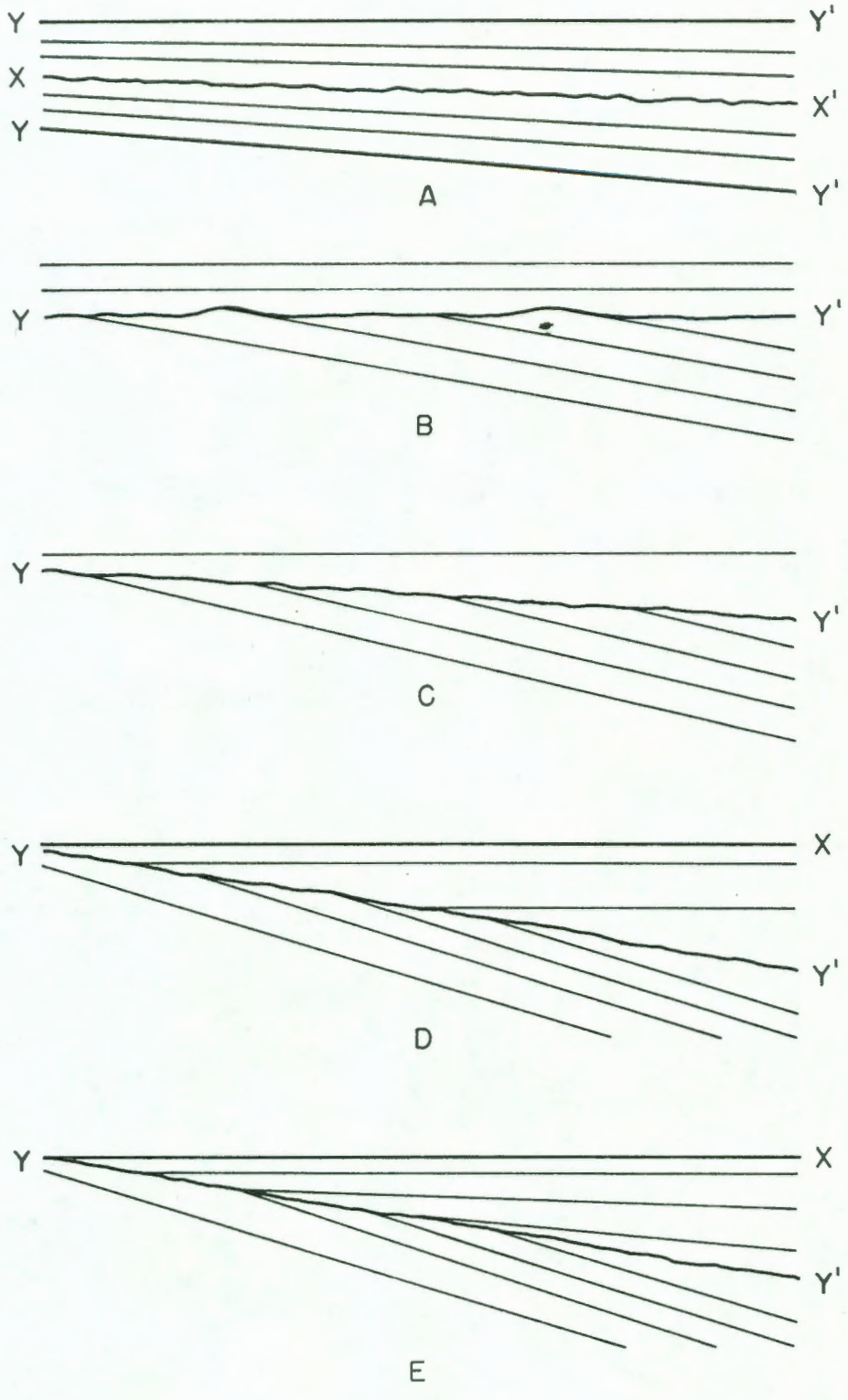


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System	Series	Group	Formation or correlative	
Quaternary	Recent Pleistocene			
Tertiary	Pliocene			Fig. 26 B
Cretaceous		Montana		
		Colorado		
			Dakota formation	
Jurassic				
Triassic				Fig. 26 A
Permian	Guadalupe			
	Leonard	Nippewalla		
		Sumner	Stone Corral dolomite	
			Wellington formation (Hutchinson salt member)	Fig. 25
Permian ?	Wolfcamp	Chase		
			Barneston limestone	
			Cottonwood limestone	
		Council Grove		Fig. 24
			Admire shale	
		Wabaunsee		
		Shawnee	Topeka limestone	

Carboniferous	Pennsylvanian	Douglas	[illegible]	Fig. 23
			Weston shale	
		Lansing		
		Kansas City	Hertha limestone	
		Pleasanton		Fig. 21
		Des Moines	Marmaton formation	
			Cherokee shale	
	Mississippian	Meramec		Fig. 20
		Osage		
		Kinderhook		
Carboniferous or Devonian			Boice shale	Fig. 17 / Fig. 18
			Chattanooga shale	
Devonian			Hunton limestone and dolomite	Fig. 16 / Fig. 18
Silurian				Fig. 18
Ordovician			Sylvan (Maquoketa) shale	Fig. 13 / Fig. 18
			Viola (Kimmswick) limestone and dolomite	Fig. 18
		Simpson	Platteville formation	Fig. 18
			St. Peter sandstone	Fig. 18
		Arbuckle		Fig. 11
			Jefferson City dolomite	
			Roubidoux formation	
			Van Buren formation	
Cambrian				
			Bonneterre dolomite	
			Lamotte sandstone	
Pre-Cambrian			Granite etc.	

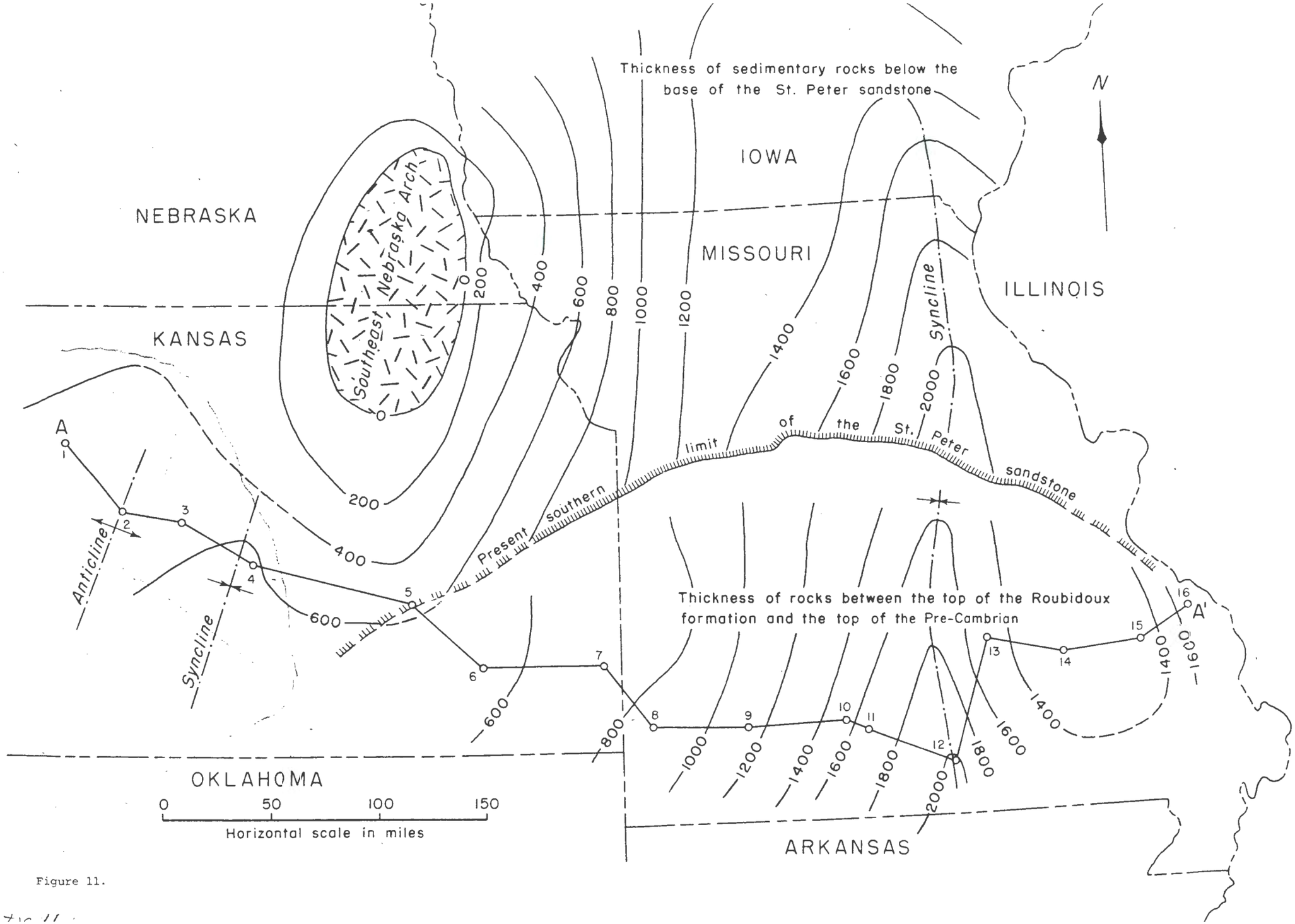

Thickness of sedimentary rocks below the base of the St. Peter sandstone
N
IOWA
NEBRASKA
MISSOURI
ILLINOIS
KANSAS
OKLAHOMA
ARKANSAS
Southeast Nebraska Arch
Syncline
limit of the St. Peter sandstone
Present southern
Anticline
Syncline
A
A'
Thickness of rocks between the top of the Roubidoux formation and the top of the Pre-Cambrian
0 50 100 150
Horizontal scale in miles

Figure 11.

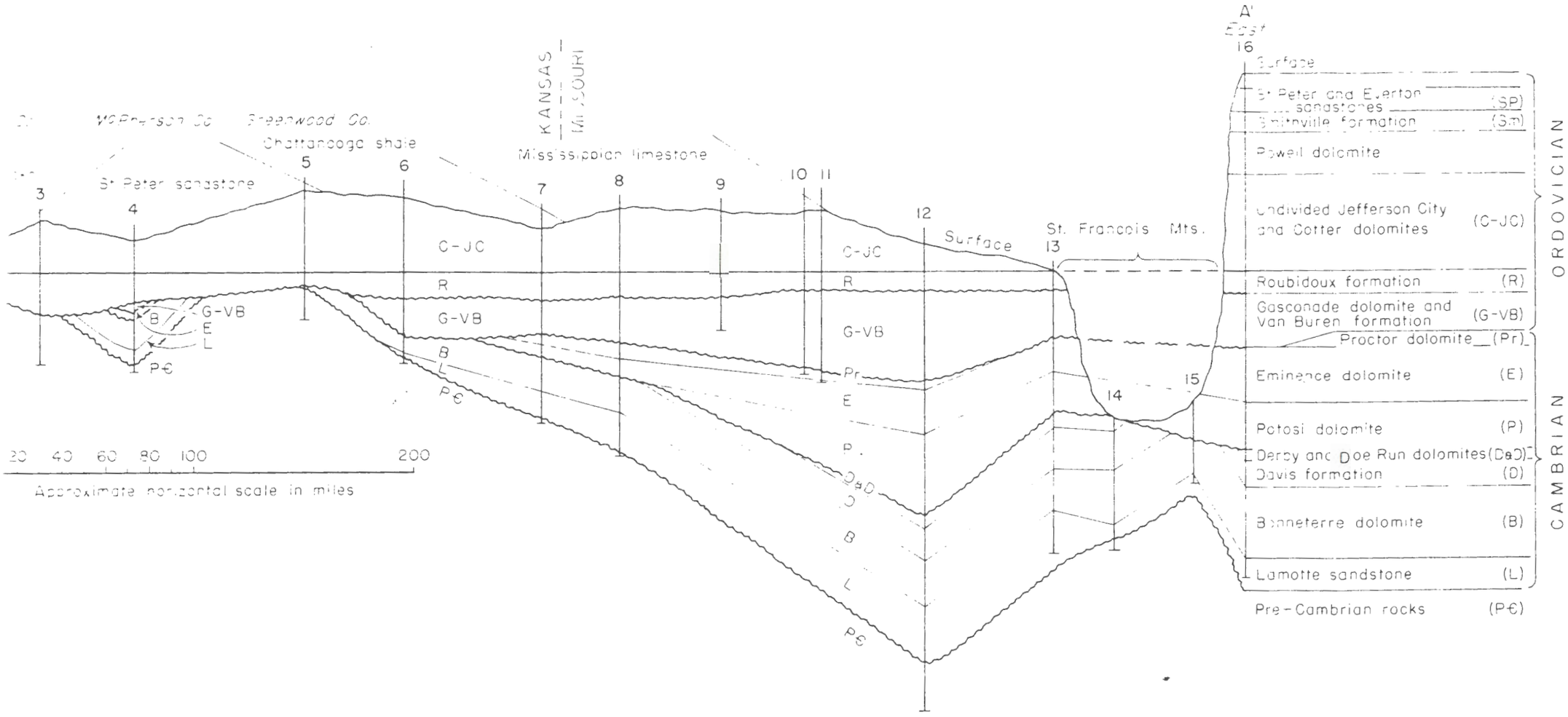

A'
East
16
Surface
St. Peter and Everton sandstones (SP)
Smithville formation (Sm)
Powell dolomite
Undivided Jefferson City and Cotter dolomites (C-JC)
Roubidoux formation (R)
Gasconade dolomite and Van Buren formation (G-VB)
Proctor dolomite (Pr)
Eminence dolomite (E)
Potosi dolomite (P)
Derby and Doe Run dolomites (DaD)
Davis formation (D)
Bonneterre dolomite (B)
Lamotte sandstone (L)
Pre-Cambrian rocks (P€)
ORDOVICIAN
CAMBRIAN
KANSAS
MISSOURI
Mississippian limestone
Chattanooga shale
St Peter sandstone
Surface
St. Francois Mts.
C-JC
R
G-VB
Pr
E
P
DaD
D
B
L
P€
3
4
5
6
7
8
9
10
11
12
13
14
15
20 40 60 80 100 200
Approximate horizontal scale in miles

Fig. 13.—Map showing the thickness of the sequence of rocks from the base of the St. Peter sandstone to the base of the Devonian dolomite and limestone.

Thickness lines spaced at 200-foot intervals.

Cross section A-A' is shown in Fig. 14.

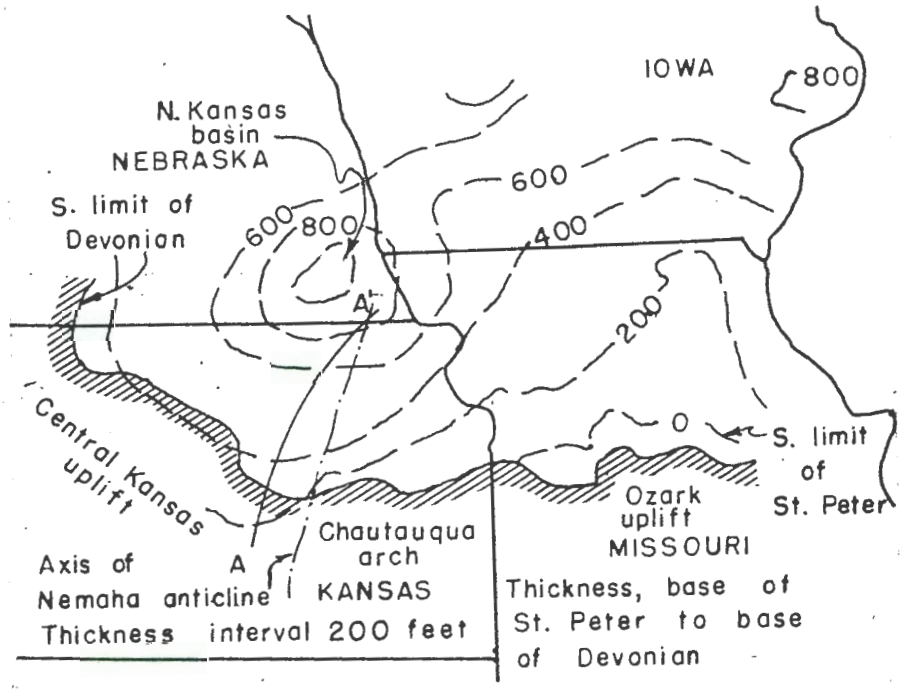
Fig. 14.—Cross section from Reno to Nemaha Counties, Kans., on line A-A' of Fig. 13.

Wells are correlated on the top of the St. Peter sandstone.

Fig. 15.—Map showing the pre-Devonian areal geology.

Fig. 16.—Map showing the present thickness of the Devonian limestone and dolomite.

Thickness lines spaced at 100-foot intervals. The interpolated 50-foot thickness line in eastern Kansas accentuates a belt of thinning extending southward from the southeastern corner of Nebraska. Thickness lines with long dashes are projected into areas from which all or part of the Devonian sequence has been eroded.



12

13

Figure 13.

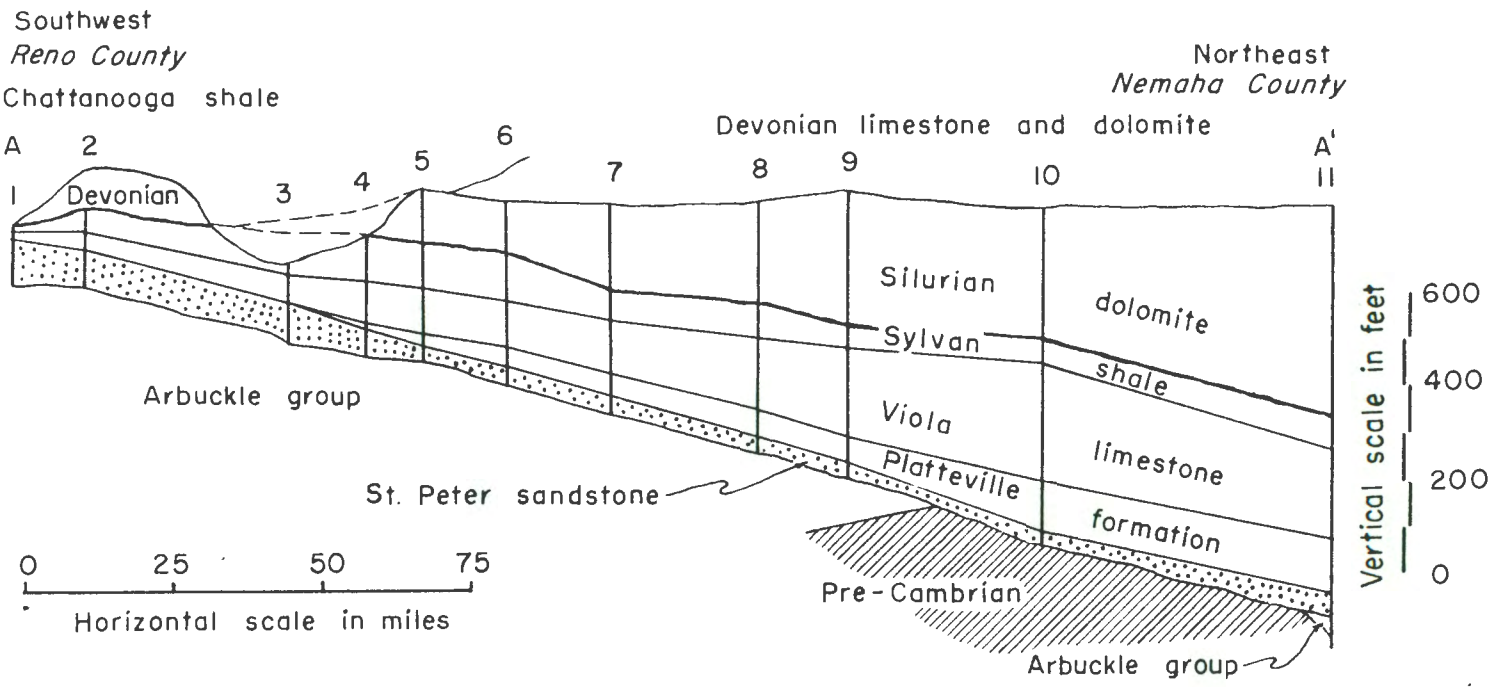

Southwest
Reno County
Chattanooga shale
Northeast
Nemaha County
Devonian limestone and dolomite
A
1
2
Devonian
3
4
5
6
7
8
9
10
A'
11
Silurian
dolomite
Sylvan
shale
Arbuckle group
Viola
limestone
Platteville
St. Peter sandstone
formation
Pre-Cambrian
Arbuckle group
0
25
50
75
Horizontal scale in miles
Vertical scale in feet
600
400
200
0

Figure 14.

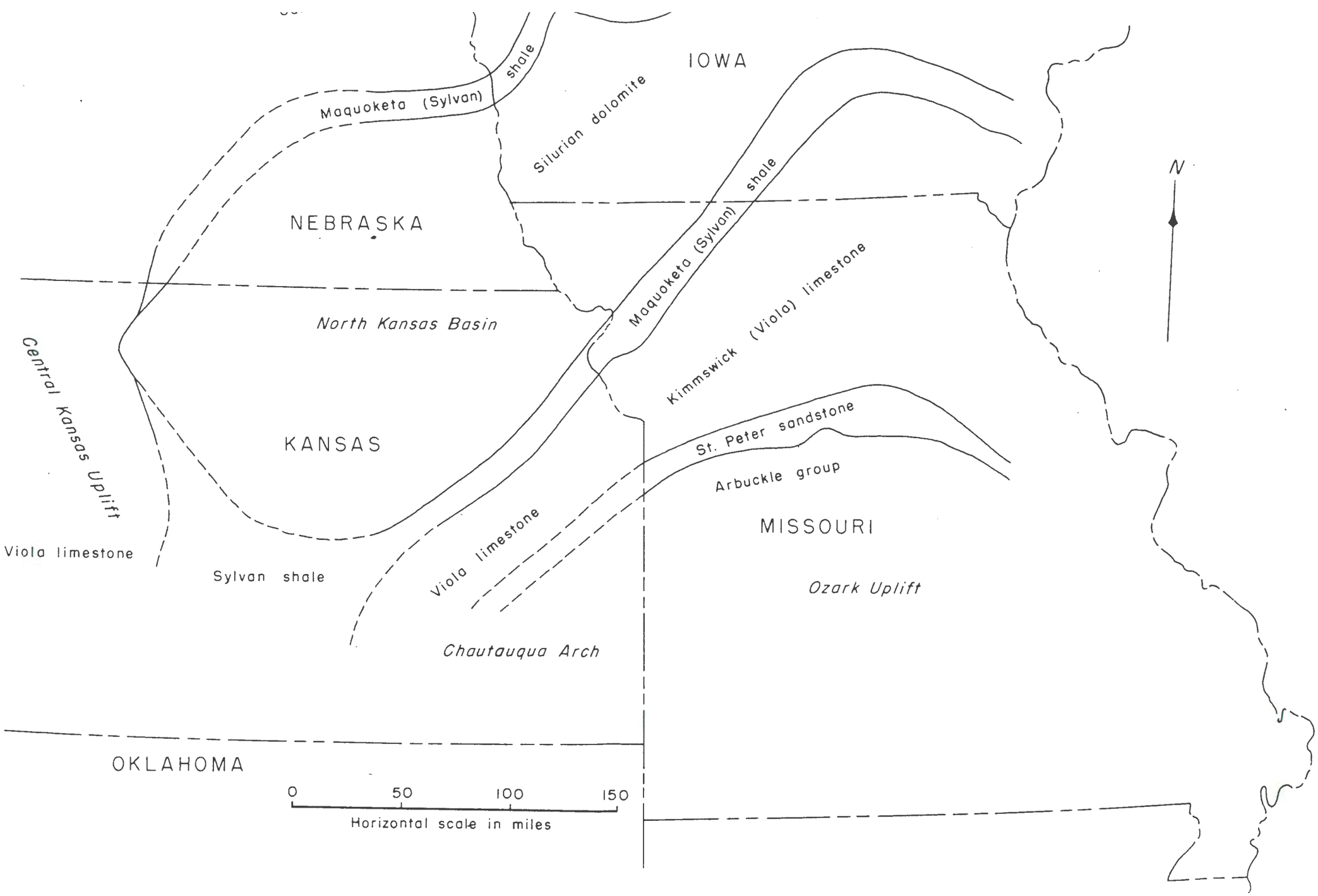

IOWA
Maquoketa (Sylvan) shale
Silurian dolomite
NEBRASKA
Maquoketa (Sylvan) shale
North Kansas Basin
Kimmswick (Viola) limestone
Central Kansas Uplift
KANSAS
St. Peter sandstone
Arbuckle group
MISSOURI
Viola limestone
Sylvan shale
Viola limestone
Ozark Uplift
Chautauqua Arch
OKLAHOMA
0 50 100 150
Horizontal scale in miles
N

Figure 15.

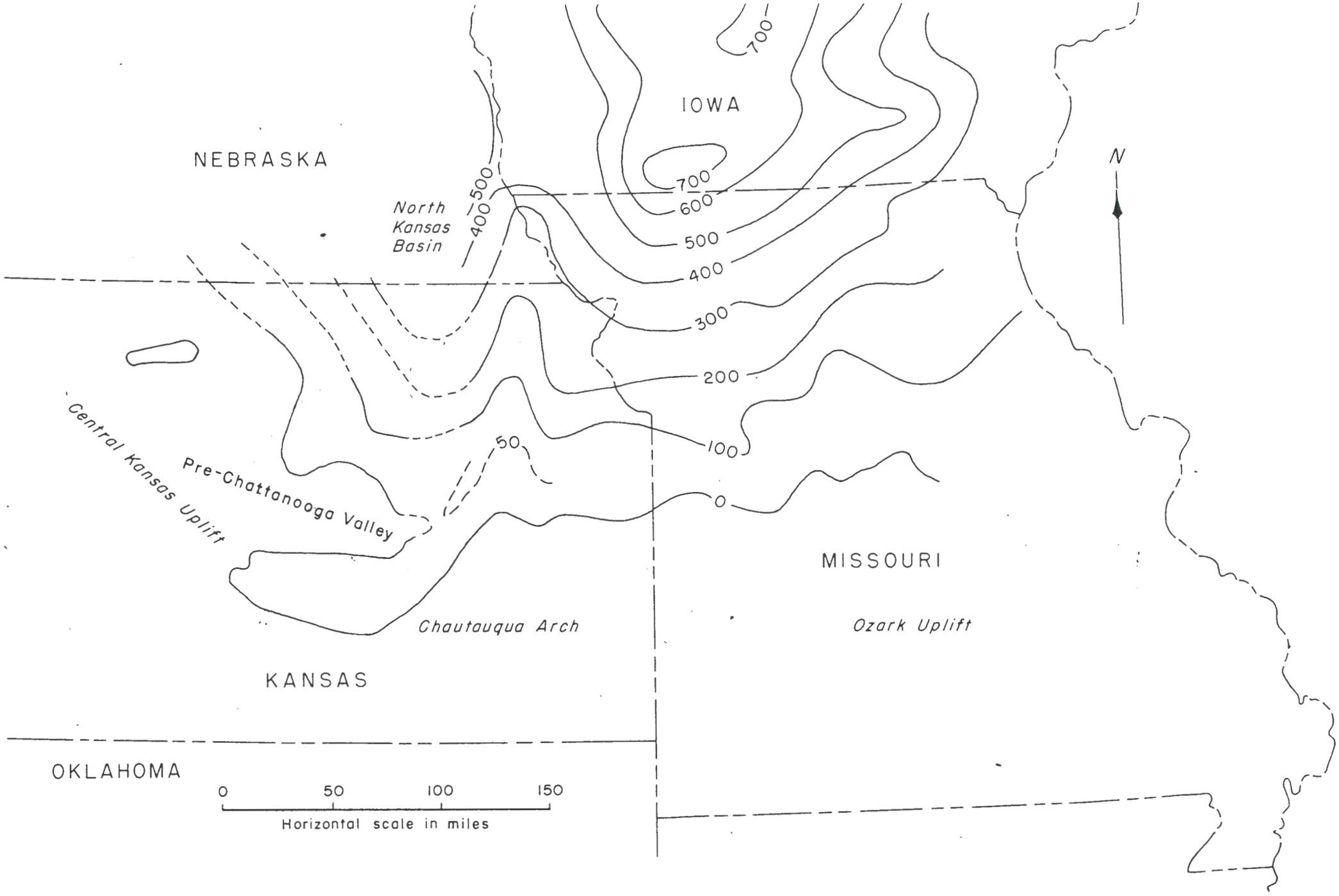

IOWA
NEBRASKA
North Kansas Basin
700
600
500
400
300
200
100
50
0
N
Central Kansas Uplift
Pre-Chattanooga Valley
MISSOURI
Chautauqua Arch
Ozark Uplift
KANSAS
OKLAHOMA
0 50 100 150
Horizontal scale in miles

Figure 16.

Fig. 17.—Map showing the present thickness of the shale sequence (Boice and Chattanooga shales) between the top of the Devonian limestone and dolomite and the base of the Mississippian limestones. Includes Louisiana limestone and Hannibal shale of northeastern Missouri.

Full thickness lines spaced at 100-foot intervals. Interpolated 50-foot thickness line is shown by short dashes. Thickness lines shown by long dashes suggest thickness and distribution of the shale sequence before post-Mississippian erosion.

Fig. 18.—Map showing the thickness in eastern Kansas of the sequence of rocks from the base of the St. Peter sandstone to the base of the Mississippian limestones.

Thickness lines spaced at 100-foot intervals. Dashed lines suggest probable original thickness in areas from which part of the sequence has been eorded.

Cross section A-A' is shown in Fig. 19.

Fig. 19.—Cross section from Rice County northeast to Nemaha County, Kans., on the line A-A' of Fig. 18.

The wells are correlated on the base of the Mississippian limestones.

Formations removed by pre-Pennsylvanian erosion at wells 10 and 11 have been restored.

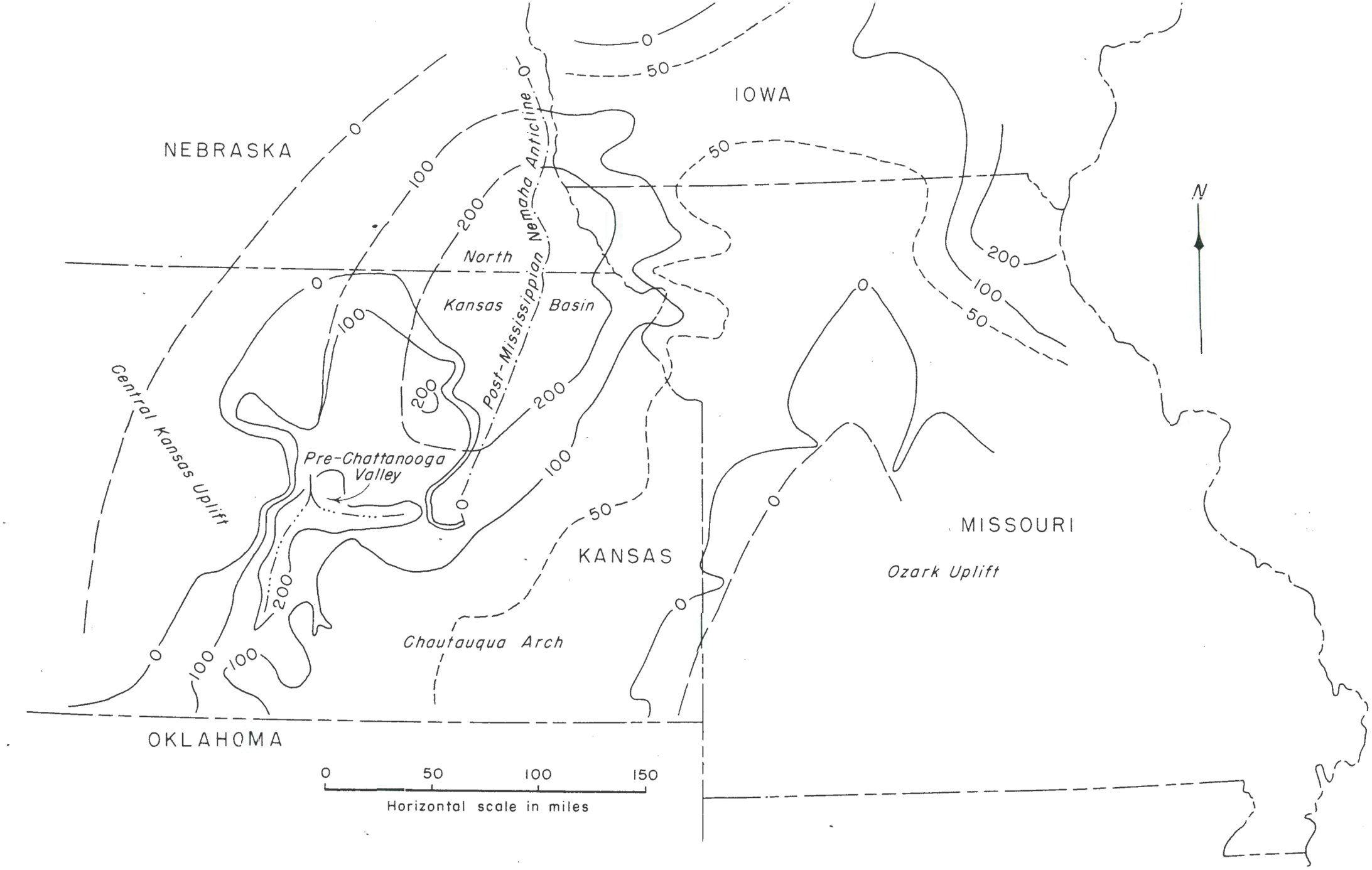

NEBRASKA
IOWA
MISSOURI
KANSAS
OKLAHOMA
North Kansas Basin
Nemaha Anticline
Post-Mississippian
Central Kansas Uplift
Pre-Chattanooga Valley
Chautauqua Arch
Ozark Uplift
N
0
50
100
150
Horizontal scale in miles

Figure 17.

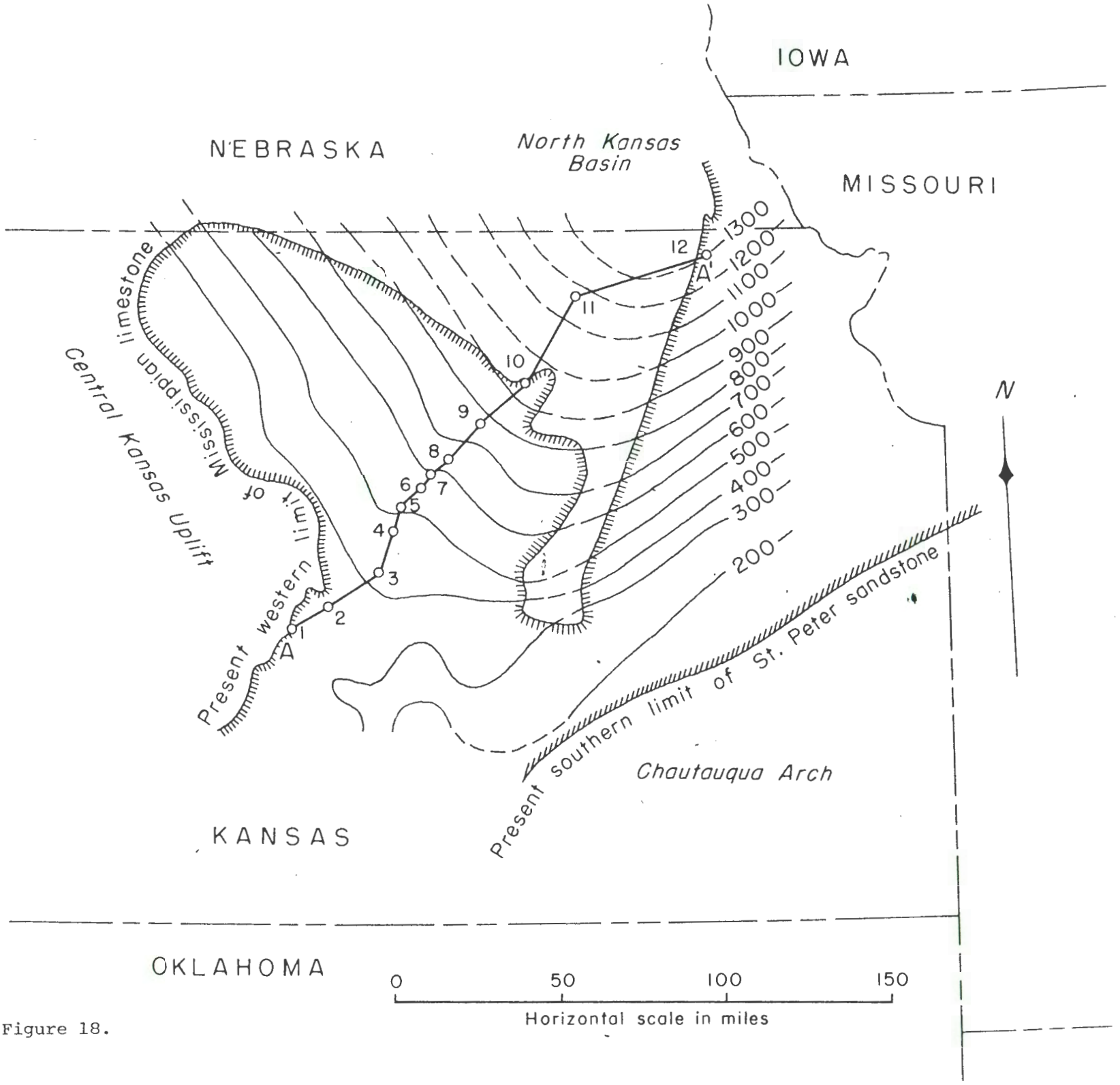

IOWA
NEBRASKA
North Kansas Basin
MISSOURI
1300
1200
1100
1000
900
800
700
600
500
400
300
200
12
11
10
9
8
7
6
5
4
3
2
1
A'
A
N
Central Kansas Uplift
Mississippian limestone
Present western limit of
Present southern limit of St. Peter sandstone
Chautauqua Arch
KANSAS
OKLAHOMA
0
50
100
150
Horizontal scale in miles

Figure 18.

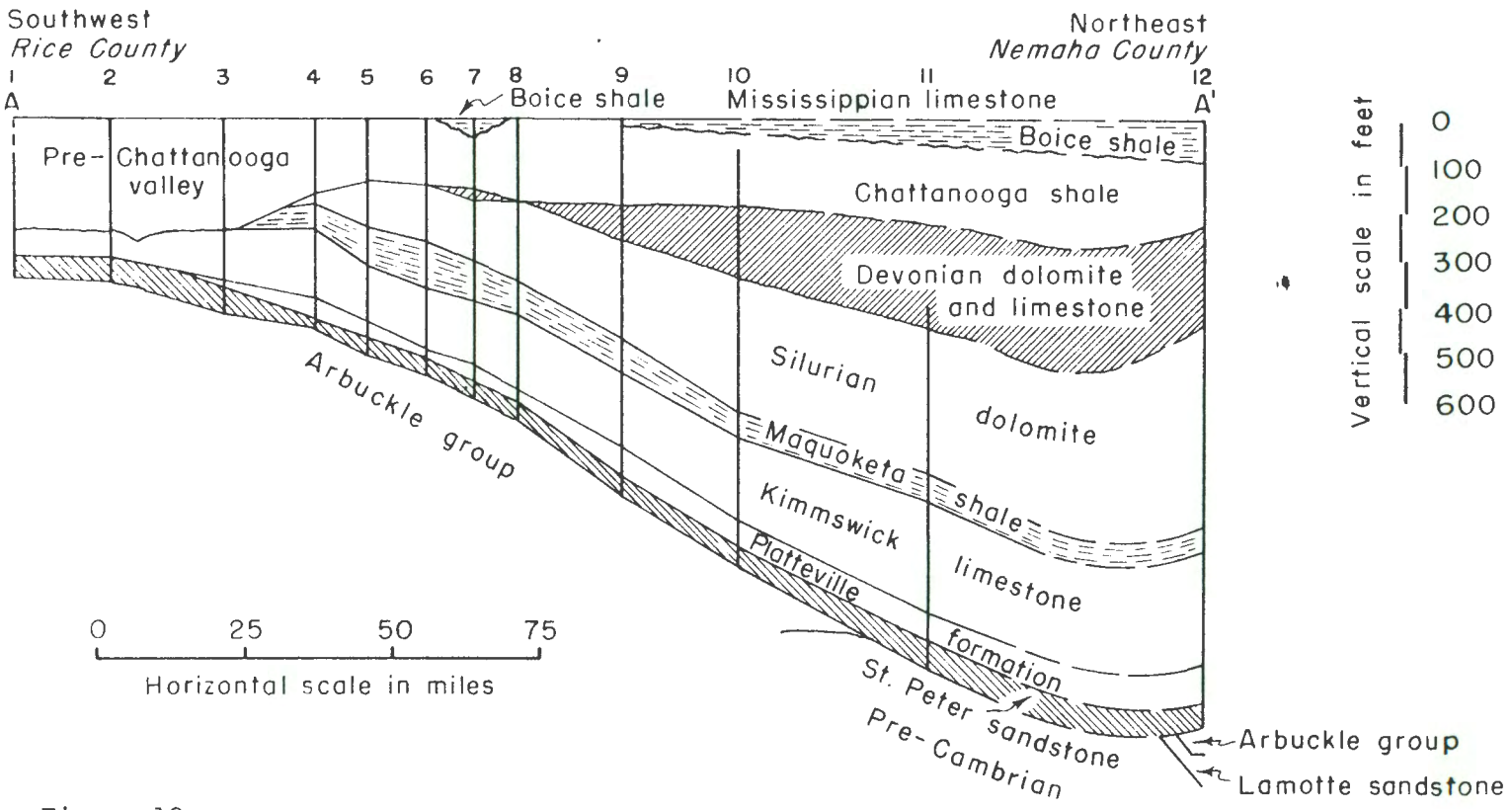

Southwest
Rice County
Northeast
Nemaha County
1 2 3 4 5 6 7 8 9 10 11 12
A
A'
Boice shale
Mississippian limestone
Pre-
Chattanooga
valley
Boice shale
Chattanooga shale
Devonian dolomite
and limestone
Silurian
dolomite
Arbuckle group
Maquoketa
shale
Kimmswick
limestone
Platteville
formation
St. Peter sandstone
Pre-Cambrian
Arbuckle group
Lamotte sandstone
0 25 50 75
Horizontal scale in miles
Vertical scale in feet
0
100
200
300
400
500
600

Figure 19.

Fig. 20.—Map showing the present thickness of Mississippian limestones.

Thickness lines spaced at 100-foot intervals.

Small areas on the Nemaha anticline in which the thickness of the limestone is less than 100 feet or absent are approximately shown in black. The deepest parts of the structural basins are shown by hachured lines.

Fig. 21.—Map showing the thickness of the Pennsylvanian rocks below the Hertha limestone at the base of the Kansas City group.

Thickness lines spaced at 100-foot intervals.

The deepest parts of the structural basins are shown by hachured lines.

Areas never covered by Hertha limestone are cross hatched.

Axes of only the more important anticlines are shown.

Fig. 22.—Diagrammatic cross sections west to east from Salina, Kans., to Kansas City illustrating; A, the deformation of the Mississippian and older rocks and the eorsional beveling that followed Mississippian deposition, and B, the revived structural movements that had deformed the beveled surface and rejuvenated the earlier folds by the beginning of Kansas City time.

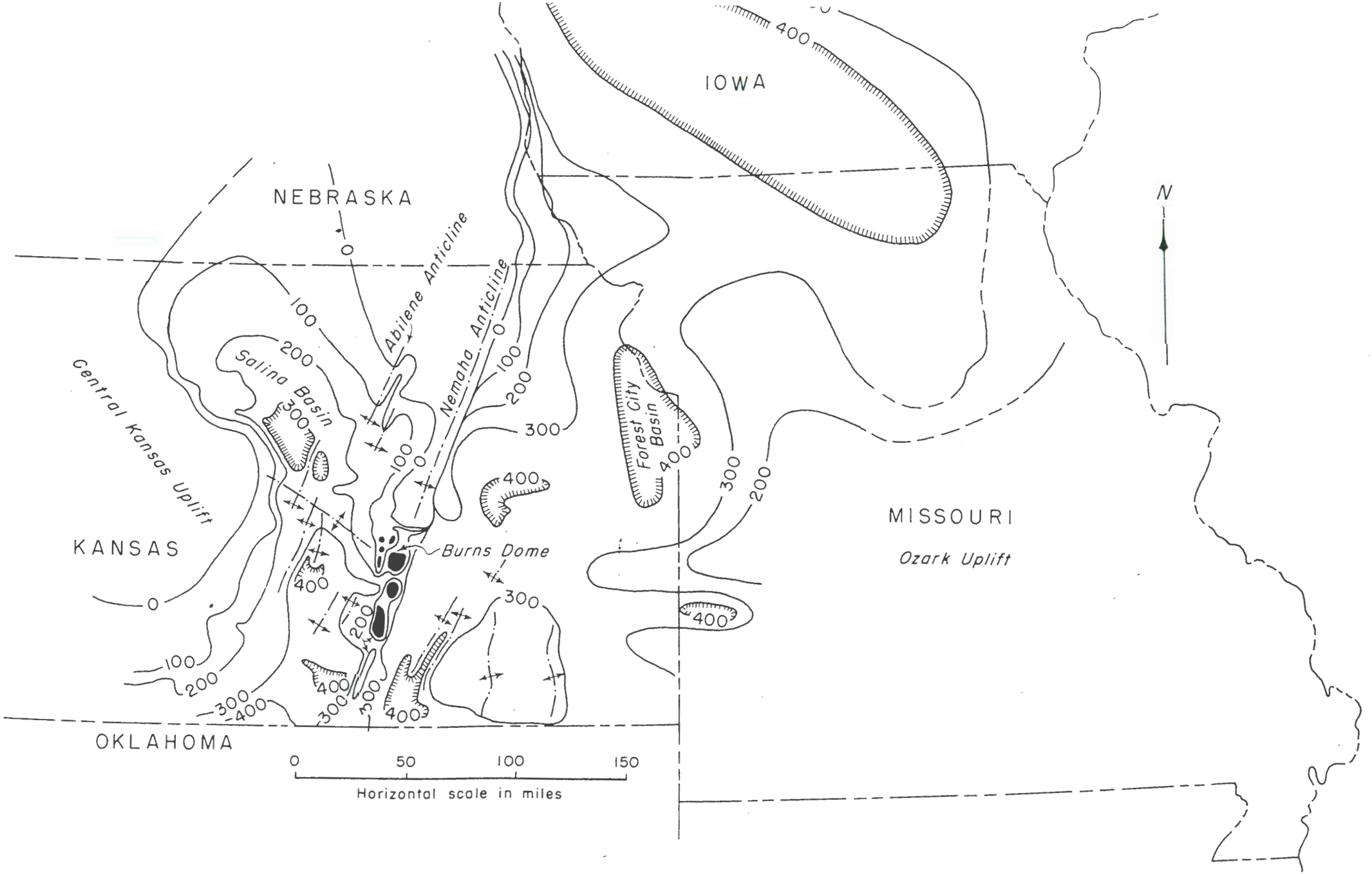

IOWA
NEBRASKA
KANSAS
OKLAHOMA
MISSOURI
Ozark Uplift
Central Kansas Uplift
Salina Basin
Abilene Anticline
Nemaha Anticline
Forest City Basin
Burns Dome
N
0
100
200
300
400
0
50
100
150
Horizontal scale in miles

Figure 20.

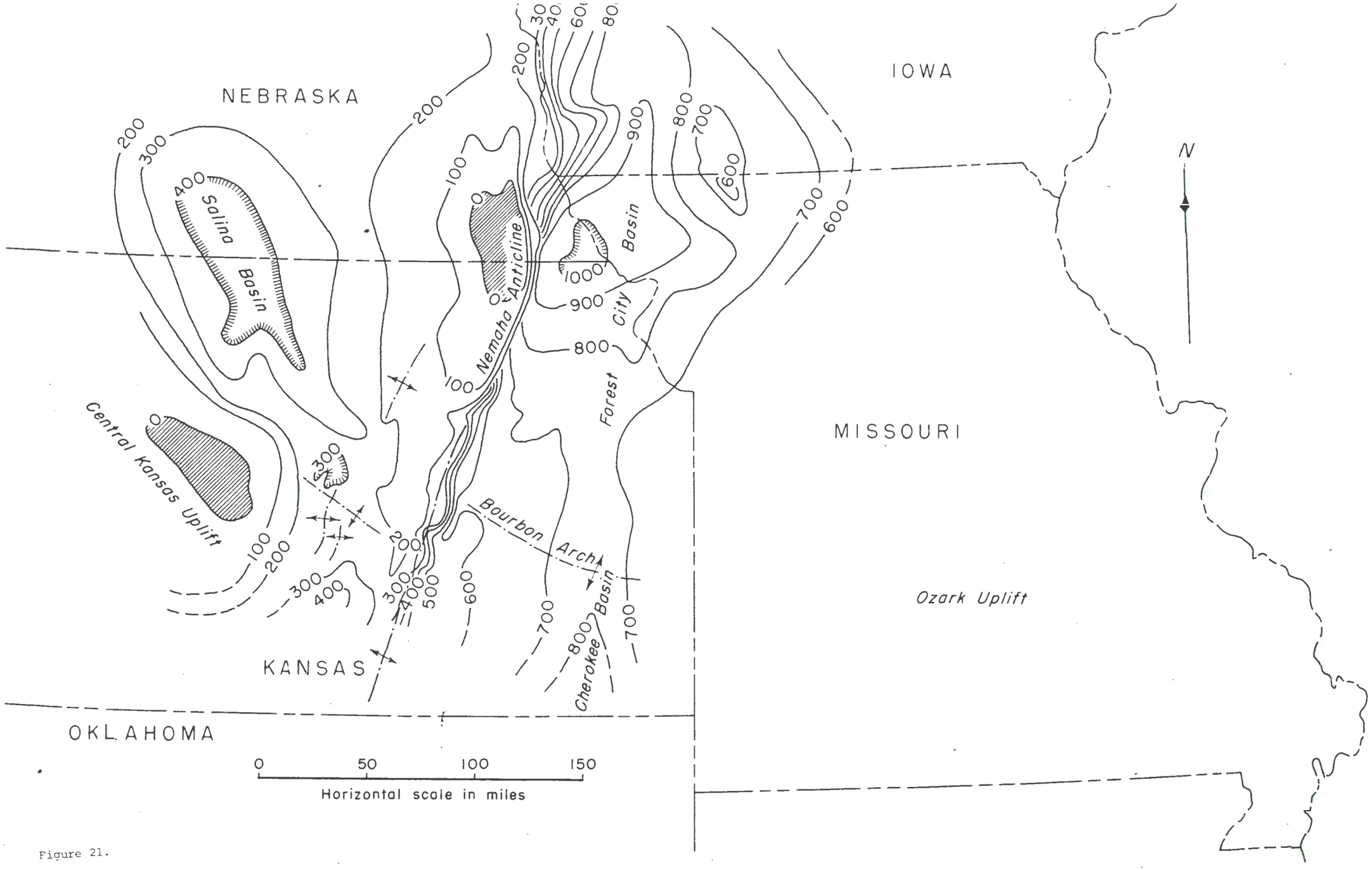

NEBRASKA
IOWA
MISSOURI
KANSAS
OKLAHOMA
Salina Basin
Central Kansas Uplift
Nemaha Anticline
Forest City Basin
Bourbon Arch
Cherokee Basin
Ozark Uplift
N
0 50 100 150
Horizontal scale in miles

Figure 21.

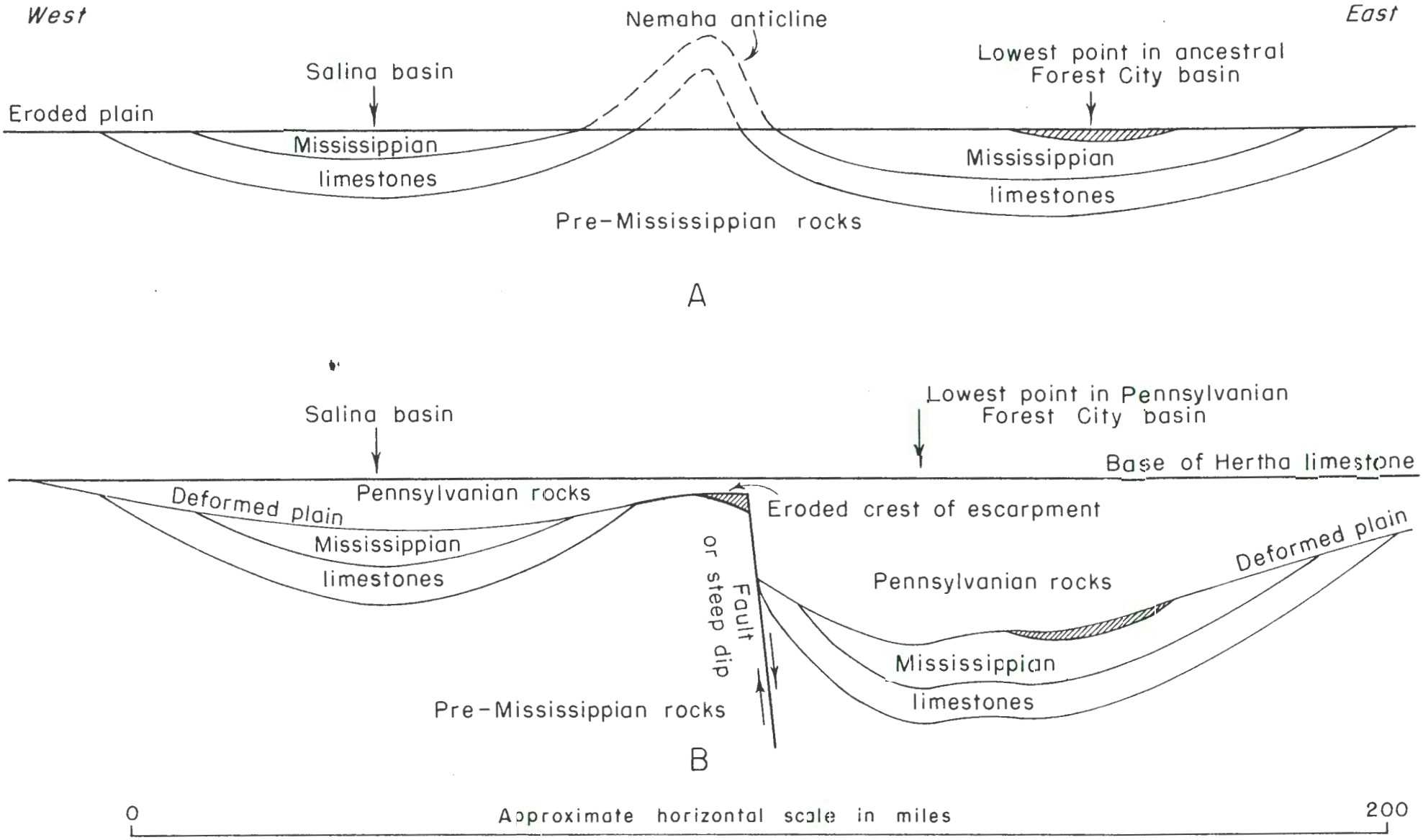

West
East
Nemaha anticline
Salina basin
Lowest point in ancestral Forest City basin
Eroded plain
Mississippian limestones
Mississippian limestones
Pre-Mississippian rocks
A
Salina basin
Lowest point in Pennsylvanian Forest City basin
Base of Hertha limestone
Deformed plain
Pennsylvanian rocks
Eroded crest of escarpment
Mississippian limestones
Fault or steep dip
Pennsylvanian rocks
Deformed plain
Mississippian limestones
Pre-Mississippian rocks
B
0
Approximate horizontal scale in miles
200

Figure 22.

Fig. 23.—Map showing the thickness in eastern Kansas of the sequence of rocks between the base of the Hertha limestone and the top of the Topeka limestone. The upper part of this sequence is no longer present in Missouri.

Thickness lines spaced at 100-foot intervals.

Fig. 24.—Map showing the thickness in central Kansas of the sequence of rocks between the top of the Topeka limestone and the base of the Barneston limestone.

Thickness lines spaced at 100-foot intervals.

Fig. 25.—Map showing the thickness in central Kansas of the sequence of rocks from the base of the Barneston limestone to the top of the Stone Corral dolomite.

Thickness lines spaced at 100-foot intervals.

Fig.26.—Structure maps showing post-Permian deformation in central and western Kansas. Contour interval 250 feet.

A. Structure at top of Stone Corral dolomite at end of Dakota time (datum assumed).

B. Present structure at the top of the Dakota formation referred

to sea level (after Bass, 1926).

C. Present structure at the top of the Stone Corral dolomite referred to sea level.

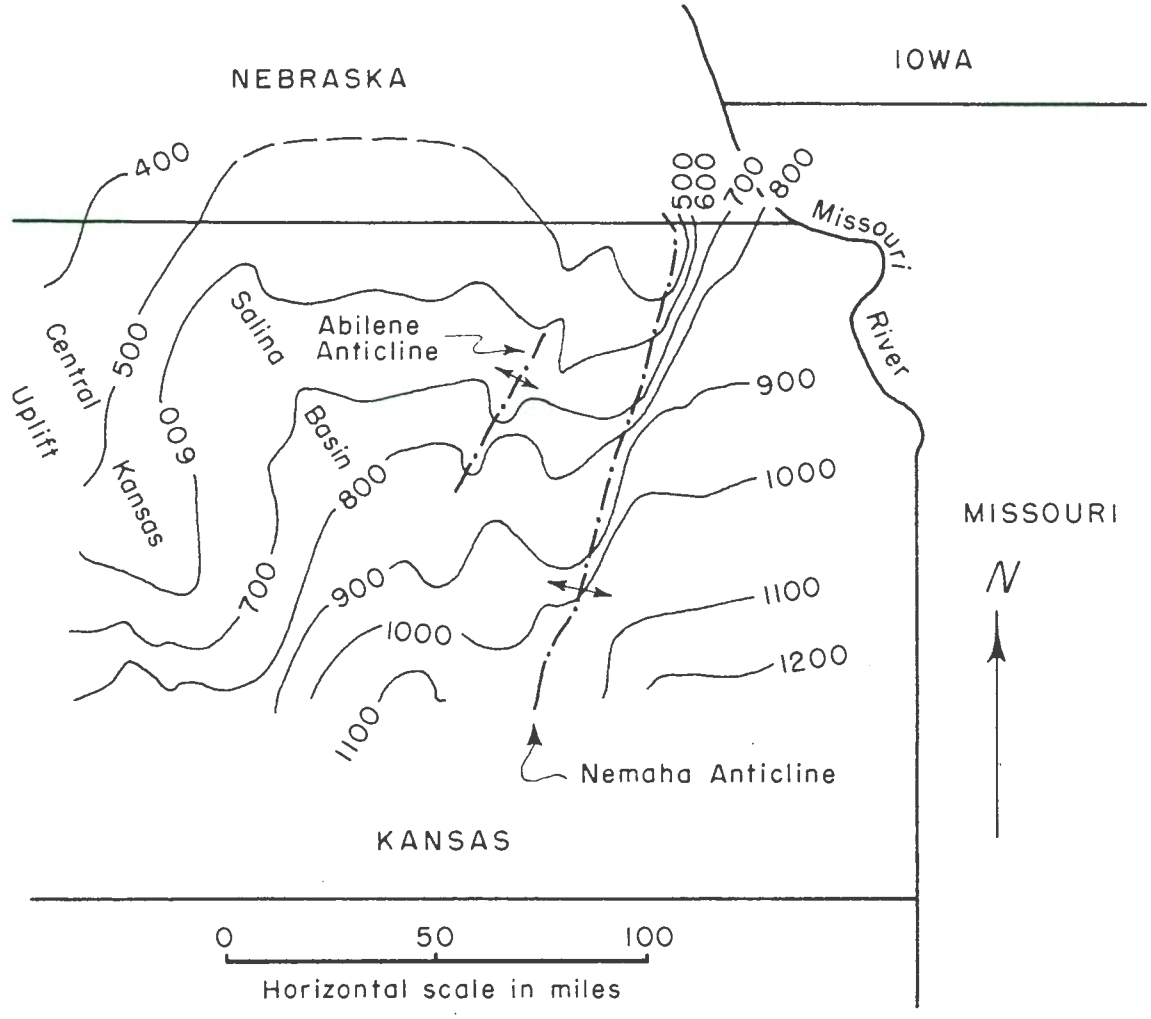

NEBRASKA
IOWA
MISSOURI
KANSAS
400
500
600
700
800
900
1000
1100
1200
Missouri River
Salina Basin
Central Uplift
Kansas
Abilene Anticline
Nemaha Anticline
N
0
50
100
Horizontal scale in miles

Figure 23.

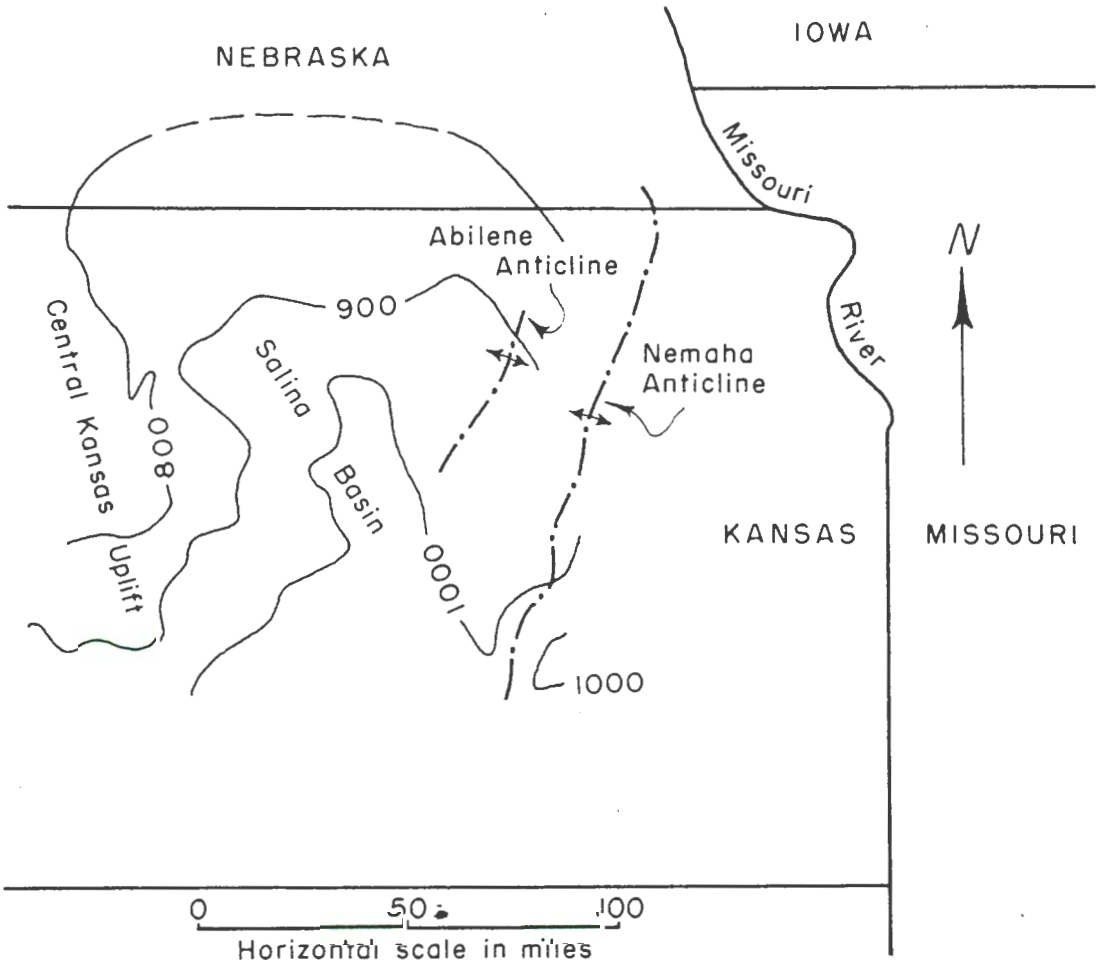

NEBRASKA
IOWA
Missouri
River
N
Abilene
Anticline
Nemaha
Anticline
900
800
1000
1000
Central Kansas
Uplift
Salina
Basin
KANSAS
MISSOURI
0
50
100
Horizontal scale in miles

Figure 24.

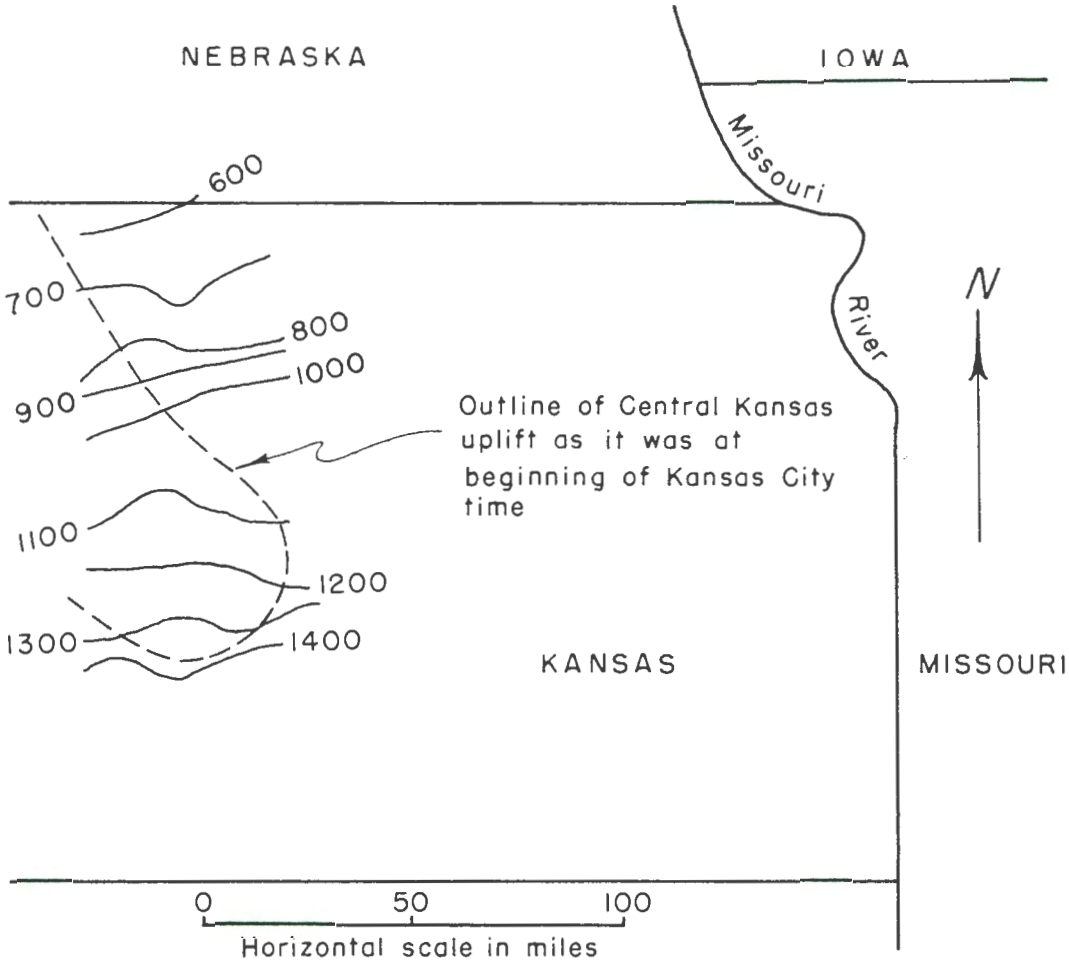

NEBRASKA
IOWA
Missouri
River
N
600
700
800
900
1000
1100
1200
1300
1400
Outline of Central Kansas uplift as it was at beginning of Kansas City time
KANSAS
MISSOURI
0
50
100
Horizontal scale in miles

Figure 25.

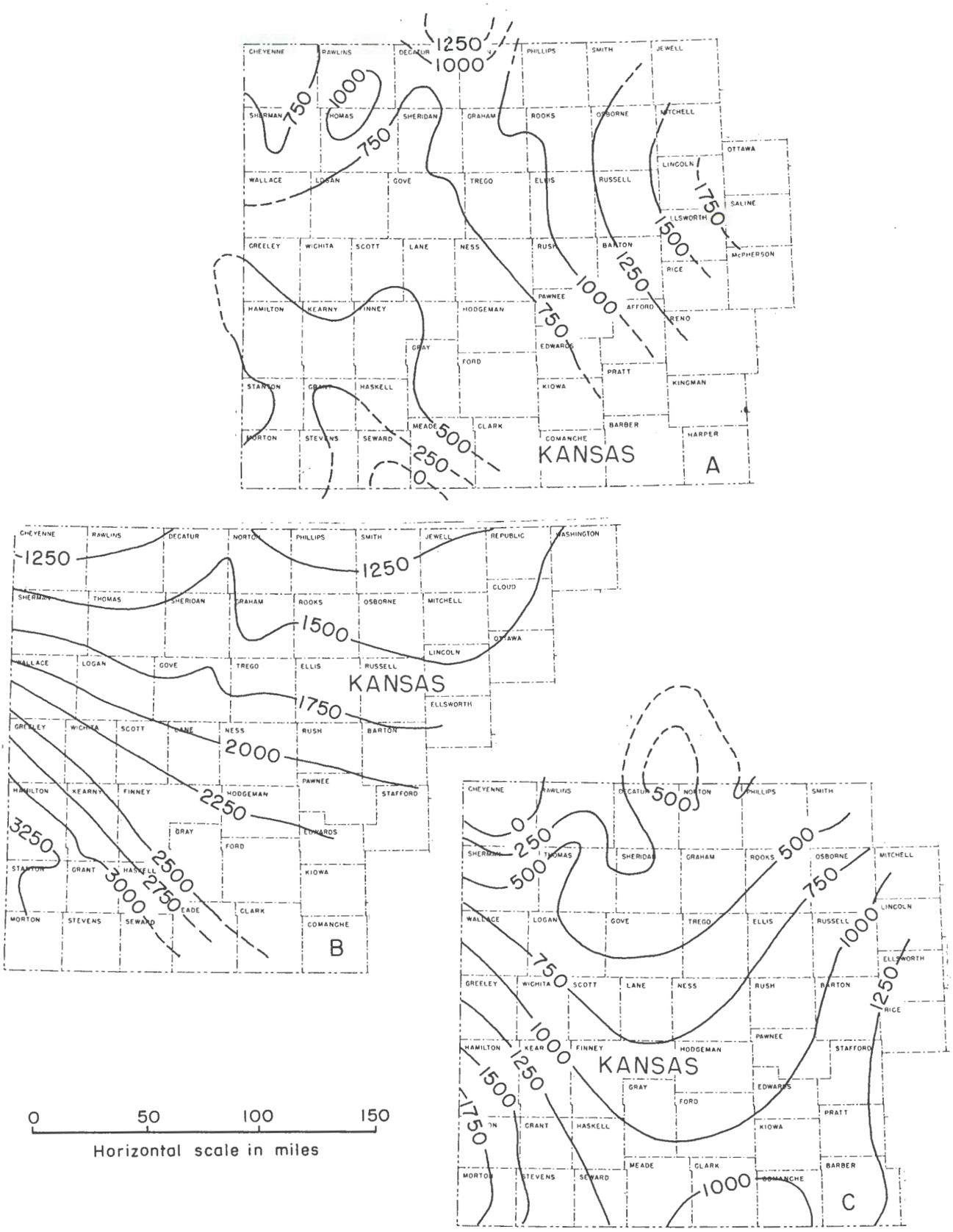

KANSAS
A
KANSAS
B
KANSAS
C
0
50
100
150
Horizontal scale in miles

Figure 26.