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PETROLEUM GEOCHEMISTRY OF THE MIDCONTINENT U.S.A: IMPLICATIONS FOR FLUID MIGRATION PATTERNS

A Summary and Interpretation of Existing Information

by

Gerard W. James

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PURPOSE AND SCOPE OF REPORT

The purpose of this report is to summarize and interpret available geological and geochemical information which has a direct bearing on the origin of hydrocarbon accumulations in the Midcontinent petroleum province of Oklahoma and Kansas.

It is the author's intent to provide a reasonable and objective analysis of the proposition that "most of the oil found in Kansas came from Oklahoma"; the author hopes that this analysis will provide a fundamental framework through which Midcontinent petroleum exploration philosophies ranging in scope from "basin analysis" to "play definition" can be more carefully evaluated.

The seemingly simple proposition that "most of the oil found in Kansas came from Oklahoma" is actually quite complex geologically, and implies that (1) most potential hydrocarbon source sequences in Kansas are too immature thermally to have generated the oil found in Kansas reservoir rocks, (2) most of the oil present in Kansas was generated by the thermal maturation of source rocks in the Anadarko-Arkoma basins of southern Oklahoma, and (3) regional permeability patterns have allowed large-scale hydrocarbon migration over considerable distances (hundreds of miles). Consequently a critical evaluation of this proposition requires a considerable knowledge of petroleum geology and geochemistry, along with supporting data.

Accordingly, this report is organized in the following manner: Introduction and Statement of Problem, Conceptual Background Information, Midcontinent Petroleum Geology, Source Rock Geochemistry, Crude Oil Geochemistry, Source Rock-Crude Oil Correlations, Migration Pathways and Permeability Patterns, Conclusions, and Recommendations for Future Exploration and Research.

INTRODUCTION AND STATEMENT OF PROBLEM

In one of a series of rather remarkable, and highly controversial, papers written over fifty years ago, an independent Kansas geologist, John L. Rich, stated:

"One of the fundamental unsolved problems of petroleum geology is the source of the oil: whether formed close to the place where it is found or generated in certain areas under special conditions and later distributed widely to its present resting places. The problem is intensely practical, because on its solution depends an effective scientific search for regions most likely to produce oil." (Rich, 1927)

Fifty years later, the American Association of Petroleum Geologists sponsored a research symposium on "Problems of Petroleum Migration". The introductions to this symposium and its proceedings contain the following statements:

"In the business of petroleum exploration, it's hard to think of anything compared to migration which has enjoyed a greater bounty of ideas and opinions and at the same time suffered such a famine of facts." (Roberts and Cordell, 1978)

"The title of this volume might be taken as a confession of ignorance. The problems referred to are not problems of nature. They are problems of people. They are not problems in the geological world of rocks and time and fluids and space. Nature has solved those problems. Accumulations of hydrocarbons are a reality. Migration has occurred and the results are in place. The problems exist in our minds where fallibility has marked our explanations of how these things happen." (Roberts and Cordell, 1980)

The problem of understanding petroleum migration is still just as significant now as it was in Rich's time, and solutions or reasonable working hypotheses are just as practical in formulating basin or play analyses and exploration concepts.

Rich, like many modern petroleum explorationists, was intensely concerned with "the unsolved problems of the origin of oil, its method and time of generation, the extent of its migration, and the means by which its migration and accumulation have been accomplished". Rich proposed his own theories on the origin and migration of oil, and applied these concepts to explain the distribution of petroleum in Kansas and Oklahoma (Rich 1927, 1931a, 1931b, 1933). His work is well worth reviewing here, because, as stated by another independent Kansas Geologist, Robert F. Walters, "seldom have a geologist's predictions (Rich's), both negative and positive, been as abundantly confirmed" (Walters, 1958).

Rich, in his own words, argued that "the distribution of oil pools to be expected under the hypothesis that the oil of Kansas was generated, during the Appalachian revolution, in the deep geosynclinal basins of southern Oklahoma and has migrated northward through certain porous carrier beds and accumulated under the control of the structural and geologic conditions existing at that time - before the more recent westward tilting of the region - seems to agree fairly closely with actual distribution as now known. Whether this agreement indicates the correctness of the hypothesis or is due merely to coincidence remains an open question to be decided by future developments." (Rich, 1933)

Rich believed that most, if not all, of the known distribution of crude oil in Kansas* could be explained in the following manner.

*(1) lack of oil in southeastern corner counties of Kansas, (2) a wide belt of pools in Cherokee sands trending north-northeasterly from Montgomery county to Miami county, (3) oil at the top of the Mississippian in Greenwood, Woodson, and Coffey counties, (4) the belt of Cherokee "shoestring" sands in Cowley, Butler, and Greenwood counties, (5) a group of predominantly Arbuckle-Simpson pools overlying the crest of the Nemaha ridge from Oklahoma City north to Eldorado, (6) the concentration of oil pools associated with the Central Kansas Uplift, and (7) lack of oil in the Salina-Forest City Basins; Rich also felt the apparent scarcity of oil in western Kansas was due to inadequate testing.

1. Deep burial and/or orogenic regional metamorphism of a thick sedimentary accumulation of highly carbonaceous and bituminous Pennsylvanian rocks in the geosynclinal environments of southern Oklahoma generated a large source of petroleum hydrocarbons by large-scale distillation of organic material in a natural, geologic, "high pressure cracking still". The high subsurface temperatures, and the pressures due to the associated gas evolution led to the production of a highly mobile crude oil with a low viscosity and low surface tension.
2. Up-dip migration of crude oil occurred principally through main "carrier beds", in this case the widespread Simpson sands and the highly weathered and porous upper surface of the Arbuckle and Mississippian limestones. This up-dip migration occurred primarily due to the buoyancy of oil with respect to water (even in the absence of water movement), but may have been aided by artesian and gas pressures. Initial introduction of crude oil into the carrier beds was accomplished through fracture systems and associated faults and joints.
3. Anticlines, faulted anticlines, and fault structures acted as "localizers" of the upward migration of hydrocarbons and led to exceptionally large accumulations of oil on major structures such as the Nemaha Ridge and the Central Kansas Uplift, as well as smaller accumulations on minor structures on the south flank of the Chataqua Arch-saddle-Central Kansas Uplift structural trend which separated the Salina-Forest City Basins on the north from the geosynclinal shelves of the Anadarko-Arkoma basins to the south.

It was on this basis that Rich correctly predicted the lack of major hydrocarbon resources in the Salina-Forest City Basin, and the probable occurrence of oil in local structures on the south flank of the Central Kansas Uplift.

Rich also believed that secondary post-migration structural rearrangements had caused considerable remigration and/or flushing of reservoirs, particularly in eastern Kansas where tilting and erosion has allowed fresh-water influx.

As noted earlier, Rich's hypotheses were highly controversial and were met with considerable criticism from geologists who noted that local sources of hydrocarbons were the more likely sources of crude oil, particularly in the case of the Cherokee shoestrings, and that deep basinal sources and widespread migration pathways were not warranted, nor could be proved, on the basis of field evidence.

Indeed, substantial field evidence against the basin generation - shelf migration hypothesis was presented by T.E. Weirich, a geologist for Phillips Petroleum Company, in 1953, who based his "shelf principle of oil origin, migration, and accumulation" on a detailed subsurface analysis of the distribution of Atokan and Desmoinesian (Cherokee) oil accumulations in eastern Kansas and Oklahoma. Weirich observed that while oil accumulations occurred in both structural (anticlinal) and stratigraphic (shale enclosed sands) traps in the Cherokee petroleum province, these accumulations were limited to shelf positions north and northwest of the Arkoma basin hinge line. Weirich concluded that "except for the Bartlesville sand, no widely continuous porous avenues, inviting migration of oil, extend out of the basin (Arkoma) and over the shelf area. This indicates that oil originated in the shelf sediments, not in the basin or geosyncline . . . the abruptly diverging stratigraphy southeast of the hingeline in the adjoining basin performs no function in the process of oil generation." (Weirich, 1953)

Weirich's conclusion was further enhanced by Baker, Ferguson, and Claypool (1969), who conducted organic-geochemical studies of potential source rocks and crude oils from the Cherokee platform and concluded that "the geochemical results support the "shelf principle" of petroleum origin."

Rich's concepts, however, were significantly strengthened by the lucid work of another independent Kansas geologist, Robert F. Walters, who very precisely documented a pattern of differential entrapment of oil and gas in the Arbuckle rocks associated with the Central Kansas Uplift. Walters (1958) concluded "this pattern of differential entrapment of gas and oil accords closely with the theoretical distribution of hydrocarbons . . . and provides part of the evidence from which it is concluded that gas and oil migrated out of Oklahoma for more than 100 miles . . . the gas and oil spilled upward under an impervious roof of Ordovician Simpson shale and Pennsylvanian beds until differentially entrapped in Central Kansas."

The most recent advocate of Rich's concepts, Leigh Price, developed a predictive basin evaluation model based on the premise that "oil on the stable, shallow, shelves of deep basins could have originated in the deeper part of the basin and undergone long lateral migration to the traps where it is now found. Conduits for such migration could have been sandstones in delta-distributary systems (E Oklahoma and Kansas), reef trends (Alberta, Canada), or regional porosity and permeability in sheet carbonates (Anadarko basin, W Oklahoma and Kansas)." (Price, 1980)

However, with all due respect for Price's predictive model, the origin of hydrocarbons distributed in the Midcontinent petroleum province remains as controversial today as it was in Rich's time.

From a traditional geologic viewpoint, it is apparent that most, if not all, the major hydrocarbon reservoirs - structural and stratigraphic - in the Midcontinent are sealed by shale units that could have also been a reasonable local source of the reservoired hydrocarbons. One then has to ask the fundamental question of how were hydrocarbons expelled from, and yet retained or sealed by, the same unit.

On the other hand, many of these accumulations also lie in up-dip proximity to obvious major fluid pathways - unconformities, faults, and sheet porosity-permeability trends. One also has to consider the possibility that Midcontinent delta-distributary systems and reef systems also represent subtle, yet major, permeability pathways that could have allowed long-distance migration of hydrocarbons.

Obviously, the key question to consider is what specific rocks, or rock sequences, were the source of the reservoired hydrocarbons in the Midcontinent petroleum province. The answer to this question will require a detailed knowledge of the chemical characteristics of both potential "source rocks" and crude oils in the Midcontinent.

CONCEPTUAL BACKGROUND INFORMATION

While the current state of knowledge of petroleum geochemistry is the sum of many individuals and research organizations, the development of the fundamental principles of source rock maturity and crude oil generation and correlation is perhaps best displayed by the publications of G.T. Philippi (Shell Research) from 1965 to 1981.

In 1965, Philippi presented the first conclusive evidence of an oil source rock identification based on the comparison of the specific chemistry of shale and crude oil hydrocarbons. Philippi observed a very strong increase of hydrocarbon-to-organic carbon ratios at greater depths and temperatures for the equivalent shales in both the Los Angeles and Ventura basins, and noted that the temperatures at which the composition of shale hydrocarbons became nearly identical to the oil hydrocarbons were the same in each basin, although the depths differed by four thousand feet (due to differences in the geothermal gradients). These observations constituted the first documentation for the origin of natural petroleum by subsurface temperature-controlled, nonbiological chemical reactions which led to the generation of paraffinic crude oils from the thermal maturation of organic material present in source rocks.

Philippi (1974, 1975, 1977) subsequently demonstrated the influence of marine and terrestrial source material on the composition of petroleum, the deep subsurface temperature-controlled origin of the gaseous and gasoline-range hydrocarbons of petroleum, and the microbial transformation of paraffinic crude oils to heavy and medium gravity naphthenic crude oils.

In 1977, Philippi also introduced his concept of "primary" basin oils - paraffinic crude oils with gasoline-range hydrocarbon compositions, as well as heavy hydrocarbons boiling above 325°C, being very close or identical to that of hydrocarbons extracted from corresponding source beds. Philippi (1981) then correlated ten "primary" crude oils from different formations in four geologic provinces with their oil source formations, using high resolution gas chromatographic C6-C7 component analyses.

Paralleling the publications of Philippi's work, outstanding geologic applications of petroleum geochemistry for basin analysis were presented by geochemists at the Amoco and Imperial Oil research centers and the Institut Francais du Petrole (e.g., Evans, Rogers, and Bailey, 1971; Tissot et.al., 1971; Williams, 1974; Dow, 1974). These examples, like Philippi's work, relied very heavily on the use of specific hydrocarbon chemistry to relate the origin and occurrence of crude oils to source rock facies, and to determine source rock maturity.

More recent work, primarily published by research geochemists from Chevron, has focused on the extremely detailed examination of trace fossil "biomarkers" present in source rocks and crude oils to further determine maturation, migration, and source characteristics (e.g., Seifert, 1977; Seifert and Moldowan, 1978; Seifert, Moldowan, and Jones, 1979).

All these papers key on the fact that many specific hydrocarbons and hydrocarbon groups present in crude oils are either thermally generated from organic material initially incorporated in sediments, or are derived from recognizable biologic precursors.

The amounts and types of hydrocarbons generated in source rocks thus reflect both the initial organic source characteristics and the thermal history of the rock; these chemical characteristics are readily apparent in crude oils, and generally allow the specific correlation of a crude oil with other crude oils, as well as the specific source rock facies.

Applications of petroleum geochemistry to basin analysis (e.g. Dow, 1974) should thus allow (1) the characterization of oils into genetic types or families, (2) the relation of each type to specific source facies, and (3) reasonable interferences of migration pathways based on the stratigraphic and areal distribution of the major oil types, source beds, carrier beds, structure, reservoirs, and seals.

The migration of petroleum from a source rock to a reservoir rock generally requires two stages - an initial release and introduction of hydrocarbons to a carrier bed or permeability pathway (primary migration) and the movement of hydrocarbons along the carrier bed or permeability pathway to a trap (secondary migration). Most geologists agree that buoyancy is the major driving force of secondary migration; however, few agree upon the actual mechanisms of primary migration.

Current concepts of primary migration have been presented by many researchers in Roberts and Cordell (1978, 1980), and generally may be divided into two groups - those which require movement of a water phase (molecular or micellar solution), and those which are independent of water movement (hydrocarbon phase migration or diffusion).

While it is possible that all of these mechanisms may be operative, the strongest evidence, as summarized by Jones (1978) and Momper (1978), seems to favor continuous hydrocarbon phase migration as the most likely mode of initial hydrocarbon release from source rocks. Hydrocarbon phase expulsion appears to be the natural consequence of peak hydrocarbon generation - pore space saturation by hydrocarbons increases, continuous oil phases form, internal pore pressures increase from the volume expansion of gaseous and liquid hydrocarbons generated from kerogen, capillary pressures are overcome or continued pore pressure buildup causes microfracturing, and temporary or permanent migration pathways are created by the overpressuring of pore fluids.

Although documentation of hydrocarbon phase expulsion, or any other type of primary migration, is still mostly by inference, it seems reasonable to conclude that specific crude oil characteristics result from specific source rock characteristics, and that linkage of a crude oil to a source rock by detailed hydrocarbon chemistry is a very useful tool to document secondary migration pathways - based on buoyancy, geologic structure, and permeability patterns. Furthermore, in many cases, detailed hydrocarbon chemistry should allow the distinction between indigenous hydrocarbons and migrating hydrocarbons, thus providing a tool for the direct observation of migration pathways.

MIDCONTINENT PETROLEUM GEOLOGY

Introduction

The Midcontinent petroleum province consists of the Paleozoic oil and gas fields of Kansas, Oklahoma, and the Texas Panhandle, and is one of the oldest and most important oil and gas provinces in the United States. According to Rascoe and Adler (1983), "approximately 15% (19.4 billion bbl) of the oil and 23% (119 tcf) of the nonassociated gas resources of the 48 conterminous United States have been found in the Midcontinent, as of January 1, 1978 . . . approximately 5,500 oil fields and 1600 nonassociated gas fields have been delineated . . . however, the bulk of these oil and gas resources was concentrated in a few fields: about 14.2 billion bbl of oil and 103 tcf of nonassociated gas have been discovered in 111 large oil fields (greater than 25 million bbl) and 57 large gas fields (150 bcf) . . . these figures represent approximately 73% of the oil and 87% of the gas discovered in the Midcontinent . . . these large fields include 29 giant oil fields (greater than 100 million bbl) and 13 giant gas fields (greater than 600 bcf) which contain 9.6 billion bbl of oil and 92.2 tcf of gas . . . it is apparent that the giant fields of the Midcontinent account for about half of the oil and three-quarters of the gas resources discovered in the region."

A general feeling for the stratigraphic and regional distribution of these oil and gas accumulations can be obtained from the production and reserve data compiled by Adler et al. (1971) as part of a detailed review of Midcontinent geology to ascertain the petroleum potential of the region. A summary of this data is presented in Table 1, which compares the estimated ultimate recovery from known (as of 1967) oil and gas fields in Kansas and Oklahoma (which includes the Texas Panhandle) by geologic horizons. (For general information, Adler et al. concluded "Reserves of ultimately recoverable oil and gas in the Midcontinent (17.3 billion bbl and 130.0 trillion cu ft) are nearing depletion. Production through 1967 of 14.9 billion bbl of oil and 81.4 trillion cu ft of gas dictates this conclusion.")

	OIL - Billion BBLS			GAS - Trillion Cu. Ft.		
	<u>Total</u>	<u>KS</u>	<u>OK</u>	<u>Total</u>	<u>KS</u>	<u>OK</u>
PERMIAN	1.45	-	1.45	71.2	22.4	48.8
PENN	7.57	1.56	6.01	36.8	4.1	32.7
MISS	1.76	.64	1.12	6.8	3.3	3.5
SIL-DEV	.46	.06	.40	2.2	-	2.2
M+U ORD	3.87	.53	3.34	8.9	0.3	8.6
CAM-L ORD	<u>2.14</u>	<u>1.84</u>	<u>.30</u>	<u>0.9</u>	<u>0.6</u>	<u>0.3</u>
TOTAL	17.25	4.63	12.62	126.8	30.7	96.1

Table 1. Ultimate Recovery from Known Midcontinent Oil & Gas Fields.

(Based on production and reserve data through 1967)

(from: Adler et al., 1971)

According to this classification, the percent distribution of known ultimately recoverable oil is as follows:

1. Pennsylvanian (mainly Cherokee sandstones) of Oklahoma (35%)
2. Mid Ordovician (mainly Simpson sandstones) of Oklahoma (19%)
3. Cambro-Ordovician (Arbuckle carbonates) of Kansas (11%)
4. Pennsylvanian (mainly Cherokee sandstones) of Kansas (9%)
5. Permian (mainly Wolfcamp carbonates) of Oklahoma (8%)
6. Mississippian (mainly Springer sandstones) of Oklahoma (6%)
7. Mississippian (upper carbonate unconformity) of Kansas (4%)
8. Mid Ordovician (Simpson-Viola) of Kansas (3%)
9. Silurian-Devonian (Hunton carbonates) of Oklahoma (2%)
10. Cambro-Ordovician (Arbuckle) of Oklahoma (2%)

The percent distribution of known ultimately recoverable gas in major provinces is as follows:

1. Permian (mainly Wolfcamp carbonates) of Oklahoma (39%)
2. Pennsylvanian (sandstones & limestones) of Oklahoma (26%)
3. Permian (mainly Wolfcamp carbonates) of Kansas (18%)
4. Mid Ordovician (gas associated w/ Simpson oil) of Oklahoma (7%)

As noted, these estimates are based on 1967 production and reserve information; the more recent information presented by Rascoe and Adler (1983) indicate an additional 2.1 billion barrels of oil and 13 trillion cubic feet of gas had been discovered by 1978. Virtually all of these "new" oil accumulations were discovered in the Mississippian (0.4 billion bbl), the Pennsylvanian (1.1 billion bbl), and the Permian (0.5 billion bbl); most of the "new" gas has been discovered in Pennsylvanian rocks.

Most of the known oil accumulations have been discovered in upper Paleozoic stratigraphic traps on the shallow shelves of the Anadarko and Arkoma basins or in structural, combination, and truncated unconformity traps in lower Paleozoic rocks associated with the major uplifts - the Central Kansas Uplift-Pratt Anticline, the Nemaha Ridge, the Seminole Arch, and the Amarillo Arch.

Most of the known non-associated gas accumulations have been discovered primarily on the shallow shelves of the Anadarko and Arkoma basins. (Most of the associated gas accumulations have been found in the Arbuckle-Simpson structural reservoirs in Oklahoma.)

The geographic distribution of the Anadarko and Arkoma basins and associated shelves and the major structural uplifts is shown by the basement structure map (Figure 1), taken from Rascoe and Adler (1983).

The stratigraphic and areal distribution of most of the known hydrocarbons in the Midcontinent petroleum province are illustrated in a series of geologic horizon thickness maps and paleogeographic maps in Adler et al. (1971) and Rascoe and Adler (1983). For reader convenience, these maps are appended to this report.

From the information presented thus far, it is apparent that, in general, the overall distribution of petroleum in the Midcontinent has not significantly changed since Rich's time fifty years ago, and the role of permeability pathways - fracture-fault systems, unconformities, and porous carrier beds (sheet sands, eroded carbonate surfaces, and possibly reef trends and delta-distributary systems) - must definitely be considered by any hypothesis or combination of hypotheses which attempt to explain the origin, migration, and accumulation of petroleum in the Midcontinent.

Furthermore these hypotheses must be able to account for tremendously large concentrations of hydrocarbons, as well as for rather widespread minor accumulations, in both structural and stratigraphic settings.

The rest of this section will briefly review the geologic framework and the geologic history of the Midcontinent.

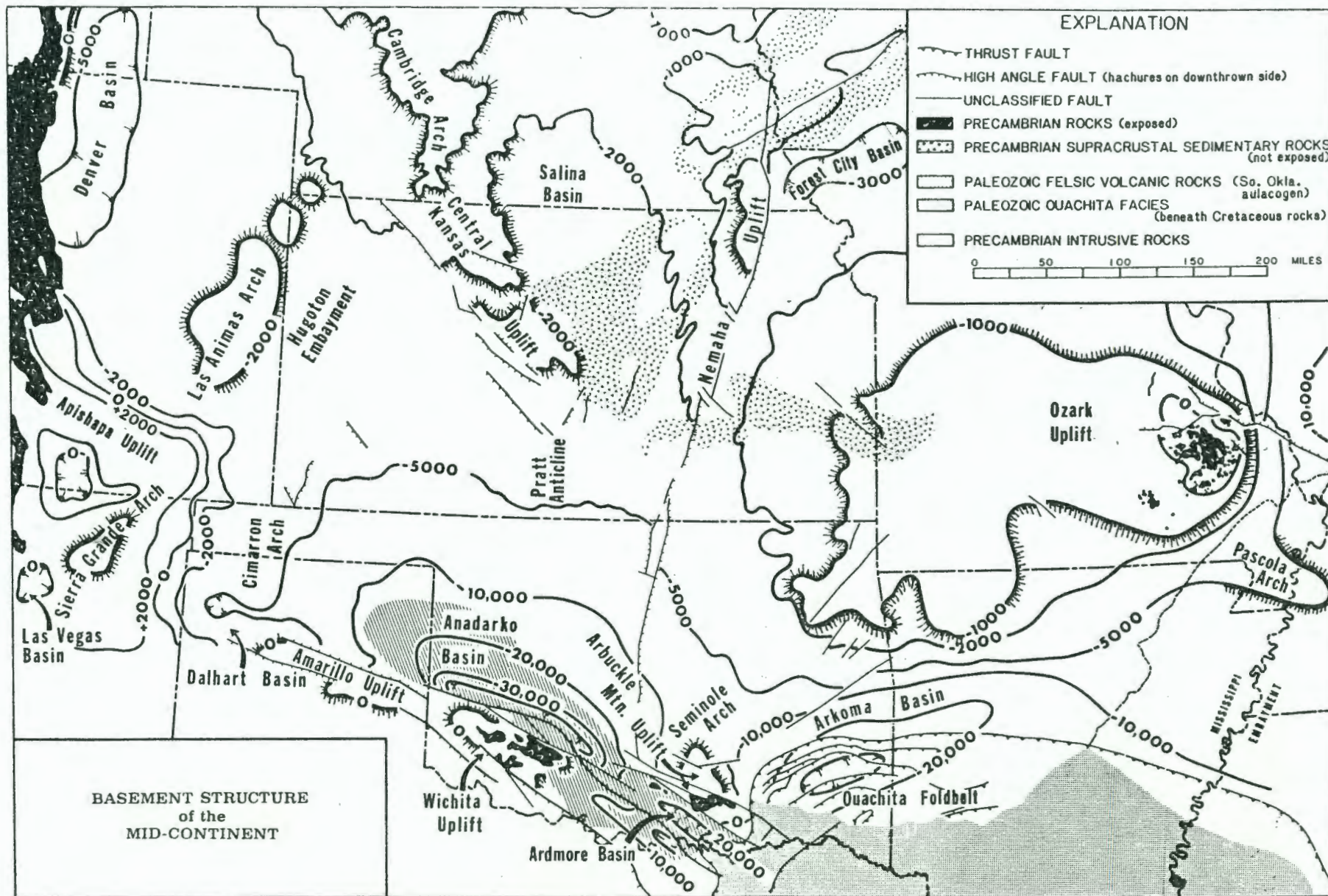


FIG. 1—Basement structure of the Mid-Continent (after Adler et al, 1971, Fig. 3).

Geologic Framework

The regional tectonic and stratigraphic framework of the Midcontinent has been well documented by Sloss (1963), Ham and Wilson (1967), Adler et al. (1971), Cook and Bally (1975), and Rascoe and Adler (1983). The review presented here and in the geologic history section will draw freely from their work.

The Midcontinent petroleum province of Oklahoma and Kansas essentially covers the south-central portion of the North American craton. As illustrated by the basement structure map (Figure 1), the area is divided into cratonic basins, cratonic uplifts, a transverse geosynclinal belt (the Anadarko-Ardmore basin and associated uplifts), and a marginal foredeep (Arkoma basin) associated with the Ouachita fold belt.

The Paleozoic sedimentary cover is normally less than 5000 feet thick in the structural uplifts, and reaches a thickness not exceeding 8500 feet in the shallow intracratonic basins. Sediment thickness of the Arkoma basin, which lies between the Ozark uplift of the craton and the frontal belt of the Ouachita system, however ranges from about 12,000 feet in the west to 26,000 feet in the east, and consists predominantly of Atokan and early Desmoinsian sediments.

The deep Anadarko basin of southern and western Oklahoma nearly divides the craton into separate segments and contains a column of late Cambrian through Permian sediments 38,000 feet thick. An additional 22,000 feet of sediments and layered flows and tuffs of questionable age (pre-Cambrian to Middle Cambrian) underly the Paleozoic rocks. Associated with the orogenic deformation of the Anadarko basin in late Paleozoic time was the formation of intensely folded marginal uplifts (the Wichita and Arbuckle Mountains), which were accompanied by movements along faults at least 400 miles long, with vertical displacements of at least 15,000 feet.

Over most of the Midcontinent, the Paleozoic tectonic record was epeirogenic, characterized generally by episodes of marine sedimentation which were terminated by periods of uplift, gently folding and relatively minor faulting, erosion, and subsequent onlap of younger strata over unconformable surfaces.

Ham and Wilson (1967) summarized the Paleozoic epeirogeny and orogeny of the central United States as follows:

"Following the craton wide deposition of Late Cambrian strata upon deeply eroded basement rocks, Paleozoic strata were epeirogenically uplifted and eroded over large areas of the craton during early, middle, and late Ordovician; early and middle Silurian; early, middle, and late Devonian; early Mississippian (two stages); and early Pennsylvanian (three stages).

Orogenic disturbances are confined to rocks of the Ouachita system and of the transverse Anadarko-Ardmore basin. The principal orogenic pulses are (1) early Atokan, especially pronounced as the Wichita orogeny in southern Oklahoma and represented by widespread epeirogeny upon the craton; (2) early-to-middle Desmoinsian, the major pulse in the deformation of the Ouachita Mountains, also represented by widespread epeirogeny upon the craton; and (3) middle Virgilian-early Wolfcampian, the major pulse of Marathon orogeny in west Texas and of Arbuckle orogeny in southern Oklahoma."

As noted by Ham and Wilson, "the study of Paleozoic tectonism upon the craton is mainly a study of unconformities in sedimentary sequences . . . The concept elucidated by Sloss (1963), that the pre-Middle Ordovician, pre-Middle Devonian, and pre-Pennsylvanian episodes of craton-wide uplift and erosion are the only three such Paleozoic episodes in the central United States, is here shown to be considerably oversimplified."

Ham and Wilson went on to demonstrate fourteen principal episodes of uplift and erosion that effected major parts of the craton during the Paleozoic, and noted the existence of sixteen additional Paleozoic disturbances of lesser distribution.

All of these episodes and disturbances represent some degree of relative breaks in sedimentation and structural deformation of the Midcontinent which created and/or enhanced regional patterns of porosity and permeability.

Adler et al. (1971) described the early Paleozoic structural framework of the Midcontinent as follows:

"The principal early Paleozoic tectonic features consisted of two large basins, the Iowa basin on the northeast and the Oklahoma basin on the southwest, separated by the Ellis-Chautauqua-Ozark arches . . . (which) were developed after Early Ordovician time.

Within each basin, smaller short-lived arches developed at different times. The northern part of the Nemaha ridge had an ancestral development as the Southwest Nebraska arch, which existed between the end of deposition of Lower Ordovician sediments and the beginning of deposition of lower Middle Ordovician sediments. That part of the Nemaha ridge in Oklahoma also had an earlier expression . . . which was effective primarily during early Middle Ordovician time. . . The Ellis arch is a pre-Middle Devonian expression of the Central Kansas uplift. . . The Ozark uplift has a history of recurrent activity; uplift occurred in post-Early Ordovician, post-Early Devonian, post-Mississippian, and post-Early Cretaceous times."

Adler et al. went on to note that most of the positive and negative structural features in the Midcontinent originated during Late Mississippian and Pennsylvanian time:

"The Cambridge arch and Central Kansas uplift are considered to be of Late Mississippian, "pre-Morrow" age because the unconformity beneath the Desmoinsian and Missouri beds over those features can be traced into western Kansas and southwestern Nebraska where Morrow rocks overlie this erosional surface.

The Salina basin, Nemaha ridge, and Forest City basin are related structural features of Late Mississippian, "pre-Morrow" age. The Iowa basin previously included the area now occupied by these features. The Nemaha ridge extends across Kansas into central Oklahoma, and the Oklahoma City uplift is located near the southern terminus of this regional feature. There it is possible to determine the probable age of the Nemaha ridge . . . over the

crest of the Oklahoma City structure, Desmoinsian beds unconformably overlie Ordovician rocks. As this unconformity is traced west and southwest, pre-Pennsylvanian rocks younger than Ordovician appear beneath the discontinuity and Pennsylvanian rocks older than Desmoinesian appear above it until, in the Anadarko basin, Morrow beds unconformably overlie Springer beds."

Adler et al. placed the origin of many other major structural features (the Anadarko basin - Hugoton embayment, and the Arkoma basin) in "post-Morrow, pre-Atoka" time, paralleling the development of the Wichita Mountains (the major pulse of which Ham and Wilson dated as culminating in Early Atokan time) and the early development of the Ouachita Mountains (the major pulse of which Ham and Wilson dated as culminating in Early-to-Middle Desmoinsian time).

Rascoe and Adler (1983) viewed the tectonic events which comprise the Wichita orogeny as the result of collision between the North American and South American plates from late Morrowan through Atokan, and into early Desmoinsian time. They felt this collisional episode was responsible for the folding and faulting of the Ouachita foldbelt; the drastic subsidence of the Arkoma basin; the emergence of the Amarillo-Wichita, Apishapa, and Nemaha uplifts; and the uplift of the Cimarron arch and small structures along the Las Animas arch. (They presented no evidence, however, which would indicate the Nemaha ridge is more of a post-Morrowan, rather than a pre-Morrowan, structural feature.)

They also felt that prior to Carboniferous time, oceanic crust of the North American plate was being subducted beneath the South American plate; and that by Early Pennsylvanian plate convergence had given up to collision, which continued through Atokan time and ceased during Desmoinsian time.

Post Paleozoic deformation of the Midcontinent (i.e., pre-Cretaceous westward tilting and post-Pliocene eastward tilting) is most likely to have been related to the Pacific plate movements and the massive Laramide orogenic deformations of Late Cretaceous to Early Eocene time; Midcontinent Cretaceous subsidence may have been also related to Mesozoic rifting in the Gulf of Mexico.

On a somewhat more speculative basis, Thompson (1976, 1978) interpreted the Paleozoic tectonic history of the Anadarko and Ardmore basins in terms of rifting, subsidence, and deformational stages of "aulacogen" development and destruction.

According to Thompson, the thermally related rifting stage lasted from latest Precambrian through Middle Cambrian time, and was accompanied by mafic intrusions and extrusions, siliceous igneous activity, and graben formation. During Late Cambrian through Early Devonian time, this igneous "basement" subsided (possibly in an isotatic response to crustal thinning and cooling of the thermal anomaly) below sea level and the aulacogen accumulated 5 to 10 times more shallow marine sediment than adjacent shelf areas, and formed a structural trough buried with sediment about 10,000 to 15,000 feet thick. The aulacogen was terminated by deep burial and intensive deformation from the Late Devonian to the Early Permian. Apparently guided by old normal faults, this deformation included lateral as well as prominent vertical displacements, both of which are reasonably well explained by compression related to plate convergence along the Ouachita orogenic belt.

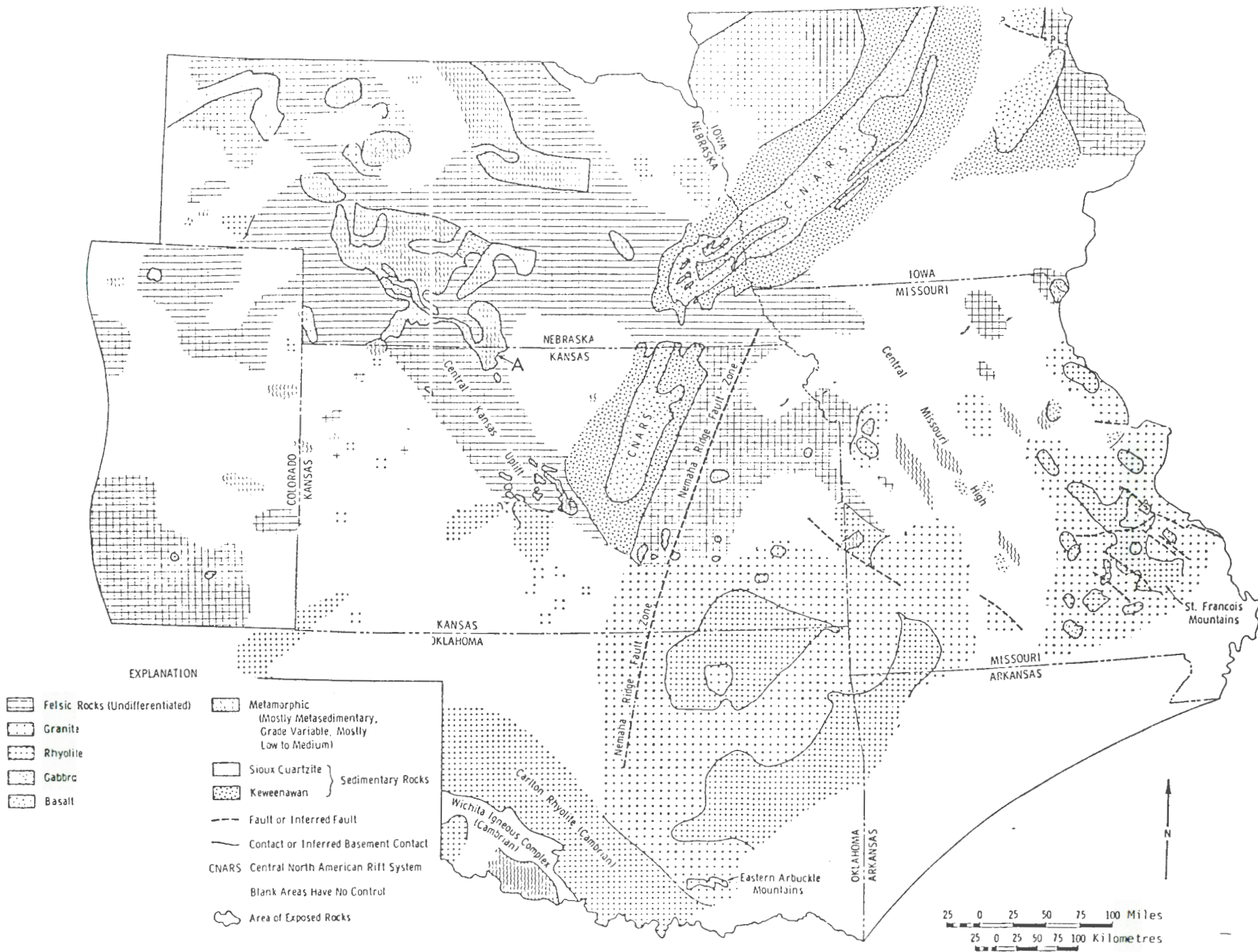
If indeed the early Anadarko basin was tectonically generated as a fragment of a newly formed oceanic basin (which aborted and remained as a long deep trough in the craton), crustal thinning and high paleotemperatures must have been associated with the Early Cambrian rifting. The relatively high rate of basin subsidence and deposition of thick sequences of Arbuckle-Simpson-Viola sediments in the basin (relative to the craton) may have been an overall isostatic response to the crustal thinning and cooling of the thermal anomaly; however the aulacogen and the craton must have been subsiding at roughly the same rate by Late Devonian time (and possibly as early as Late Ordovician) as is indicated by preserved thicknesses of middle Paleozoic rocks.

The origin of this Early Cambrian rifting may have been associated with a late Precambrian breakup of a "super-continent" landmass which left a south-facing passive continental margin on the southeast edge of the craton.

Thick sequences of Arbuckle-Simpson rocks (relative to the craton) are also present in the Arkoma basin "Arbuckle" foreland facies of the Ouachita fold-belt. Subsidence along this margin may have been in conjunction with the postulated Anadarko basin rift-related subsidence, or it might represent the early phases of underthrusting or subduction south of the Ouachita trend in early Paleozoic time. Recent COCORP deep seismic reflection profiles (Lillie et al., 1983) across the Ouachita Mountains indicate the presence of 39,000 feet of tectonically thickened Carboniferous flysch overlies relatively thin, lower to middle Paleozoic shelf strata in the Frontal thrust zone of the Ouachita foldbelt. This data strongly suggests that, at least by Mississippian time, a subduction zone can be inferred south of the cratonic margin; this data does not preclude the possibility of prior subduction in earlier Paleozoic time. The compressive forces associated with this subduction, and subsequent continental collision, probably dominated Midcontinent Paleozoic tectonic patterns, although forces related to the Mid-Ordovician Taconic and Mid-Devonian Acadian orogenic movements of the Caledonian-Appalachian Fold belt in the eastern United States probably made substantial contributions to the driving forces of earlier Midcontinent episodes of arching and uplifting.

Most of the Precambrian basement terrane in Oklahoma and southern Kansas (Figure 2) consists of undeformed and unmetamorphosed silicic volcanic rocks and related epizonal granitic plutons that formed 1370 to 1485 m.y. ago (Van Schmus and Bickford, 1981); this terrane may or may not be underlain by the orogenically deformed Mazatzal terrane (1625-1680 Ma) that appears to be coeval and on strike with the sheared-cataclastic mesozonal granites (1610-1650 Ma), metasediments, and metavolcanics that compose the basement terrane of northern Kansas. The presence of a number of 1380 to 1480 m.y. old undeformed epizonal to mesozonal granitic plutons emplaced in the older orogenic terrane certainly indicates zones of crustal weakness in these rocks during this period.

Superimposed on both these terranes, as well as older cratonic terranes to the north, are possible rift-related basement fracture patterns inferred from magnetic lineations associated with the 1100 m.y. old Central North American Rift System (Figure 3). The magnetic evidence presented by Yarger (1983) strongly suggests that block faulting associated with the rift system extends into the 1400 Ma crust of southern Kansas and Oklahoma.



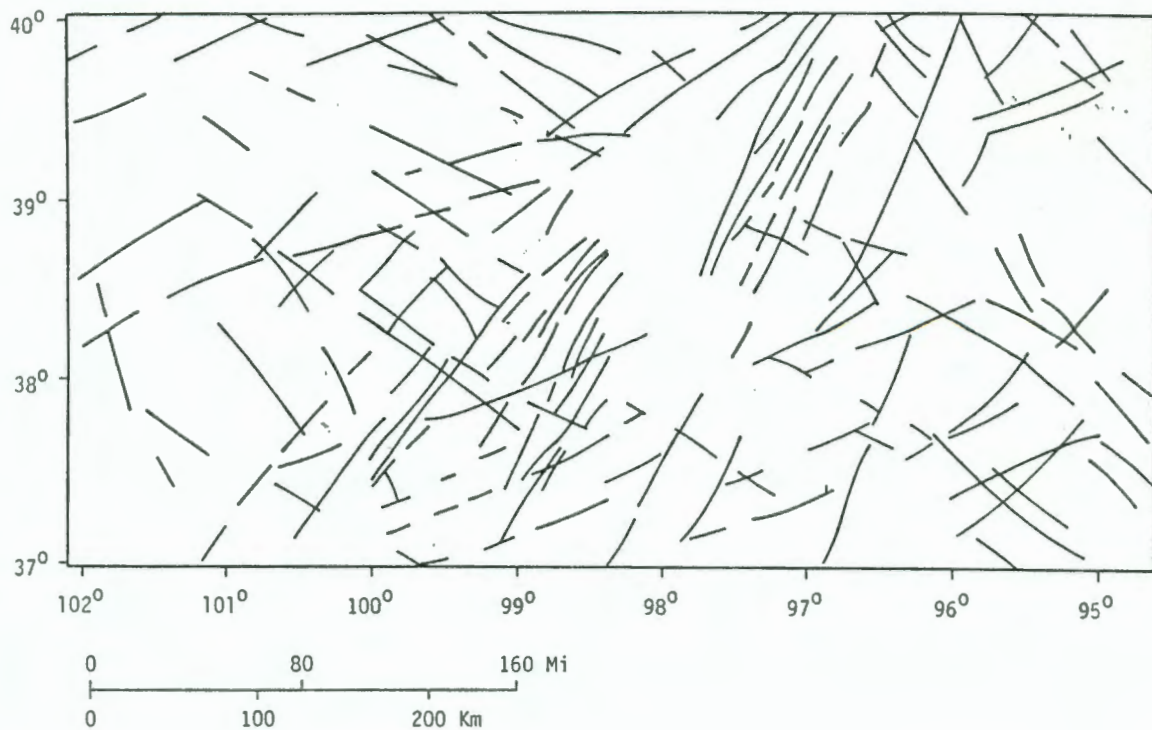


Figure 13. Magnetic lineations. The lineations were derived from Figures 2 and 5 through 9.

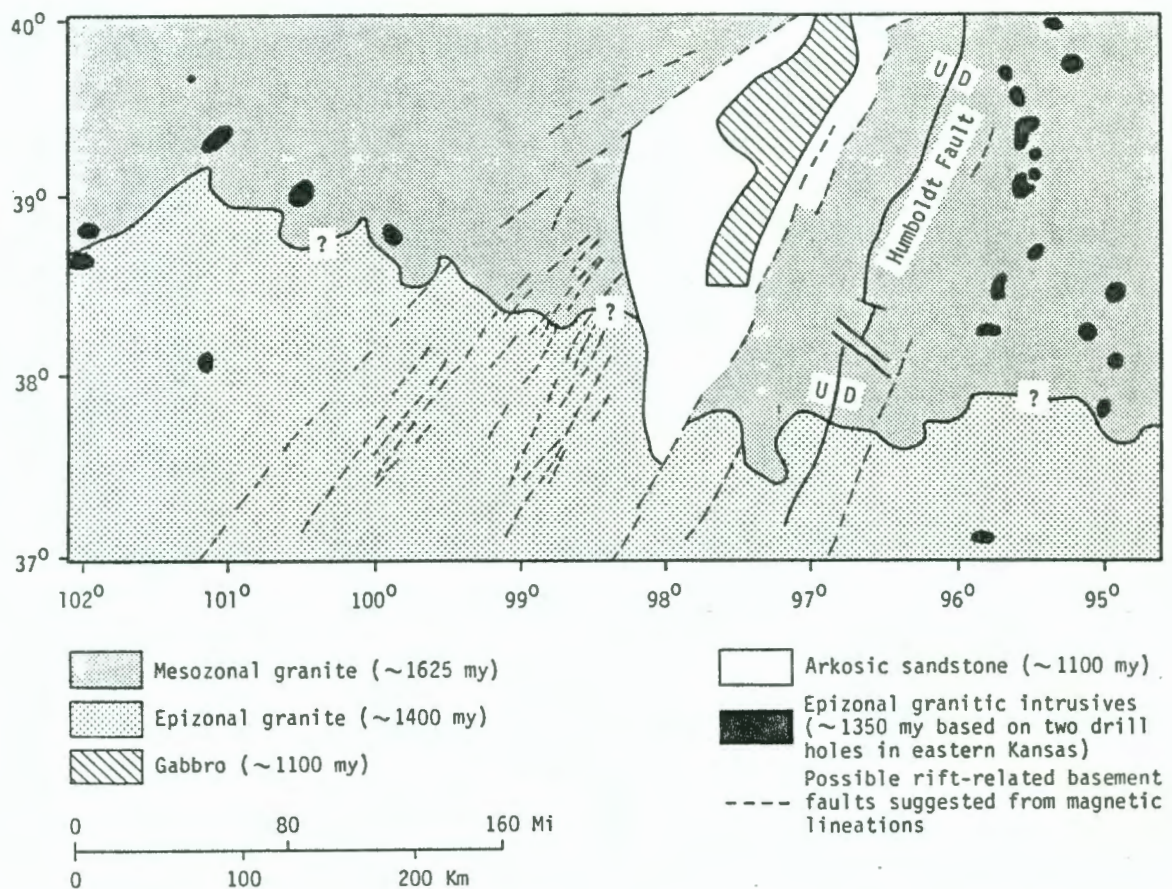


Figure 15. Precambrian terranes in Kansas. Inferred from magnetic data and age data of Bickford and others (1981).

Although fundamental relationships between the Central North American Rift System and the orogenic Grenville Belt (1000-1100 Ma) of eastern North America are not clear, both have roughly parallel trends (north-northeasterly) and regional extensional and compressional stress fields associated with these systems may have governed the distribution of most Midcontinent basement fracture systems; reactivation of these zones of crustal weakness during the Paleozoic could be the controlling influence on the spatial distribution of Paleozoic fracture systems in the Midcontinent petroleum province.

In summary, it appears that the geologic framework of the cratonic Midcontinent petroleum province probably has been controlled largely by peripheral tectonic forces associated with continental rifting, margin subduction, and plate collision. Extensional and compressional forces associated with the major orogenic events taking place on the cratonic-continental margins throughout Phanerozoic time most likely account for the numerous episodes of basinal subsidence and uplift recorded so frequently by sediment deposition, erosion, and unconformities in the Midcontinent. The key question to be considered when attempting to predict the occurrence of fracture patterns associated with these stress fields is to determine the probable effect of pre-existing Proterozoic zones of crustal weakness. Major structures such as the Central Kansas Uplift and the Nemaha Ridge contain many horst and graben fault block features (which may or may not have lateral motion) that almost certainly represent readjustment of ancient Precambrian zones of crustal weakness.

However, regardless of the primary origin of these basin forming and basin modifying forces, it is clear that there has been enough tectonic activity to suspect the creation and existence of large-scale fracture permeability patterns in the Midcontinent. The ability to detect these patterns should be limited only by the imagination and insight of the petroleum geologist, using the tools of lineament detection through areal photography and basement geophysics in combination with traditional subsurface mapping techniques.

Geologic History

The geologic history of the Midcontinent petroleum province can perhaps be best understood when viewed in the context of rock sequences bounded by major unconformities, regional tectonics, and absolute geochronological time.

Regional maps of sediment distribution patterns and thicknesses can be found in Ham and Wilson (1967), Adler et al. (1971), Cook and Bally (1975), and Rascoe and Adler (1983); as noted earlier, some of these maps are appended to this report for reader convenience.

All references to absolute geologic time dates are taken from Van Eysinga (1978), unless otherwise stated.

The stratigraphic relationships and lithologic characteristics of the Paleozoic sediments of the Midcontinent are reasonably well known, as are the effects of tectonic events. However large spans of geologic time, not only in the Mesozoic and Cenozoic but also in the Paleozoic, are represented only by unconformities over widespread areas of the Midcontinent; hence cratonic patterns of subsidence-deposition and uplift-erosion can only be speculatively inferred from regional settings. In addition, and of a primary interest to this reviewer, the causative mechanisms of epeirogenic uplift and subsidence and orogenic movements are subjects that require tentative analyses. Stress fields associated with these mechanisms could have created regional fracture-permeability patterns that might very well hold an important key to future successful exploration efforts in the Midcontinent petroleum province.

As a working hypothesis, this review and interpretation of the geologic history of the Midcontinent will attempt to stress the possible significance and control of Precambrian zones of crustal weakness on Paleozoic tectonic patterns; furthermore this review will attempt to relate the formation of Midcontinent structural features to stress fields formed in response to complex plate interactions at convergent plate boundaries involved in the formation of the activation and collision orogenic belts on the eastern, southeastern and western margins of the central United States.

Late Precambrian - Middle Cambrian

(ca. 1650 - 515 m.y.)

From the work of Ham et al. (1964), Muehlberger et al. (1966, 1967), Bickford and Lewis (1979), Bickford et al. (1981), Van Schmus and Bickford (1981), and Harrison and Peterman (1984), it is clear that the major sequences of "basement terrane" ages in the Midcontinent are reasonably well known (with one critical exception), as are the principal rock types. Knowledge of the crustal structure and the tectonic significance associated with these rocks has been advanced by the geophysical work of Steeples (1982) and Yarger (1984).

As noted earlier, most of the Midcontinent in southern Kansas and Oklahoma is underlain by a vast undeformed rhyolitic and epizonal granitic terrane of early Middle Proterozoic age (1370-1485 m.y.). This terrane is bounded on the north by a fairly extensive orogenic terrane of mesozonal gneissoid granitic rocks and associated meta-sedimentary and meta-volcanic rocks. In northern Kansas, this terrane is very late Early Proterozoic in age (1610-1650 m.y.). The north-northeasterly trending Central North American Rift System (Keweenaw Trough - Midcontinent Geophysical Anomaly) cuts down through this sequence from the Lake Superior region into northern Kansas, where it appears to terminate fairly abruptly. Magnetic lineations (Yarger, 1984) indicate a possible extension of this feature into central Oklahoma. This system is approximately late Middle Proterozoic in age (1100 m.y.) and has the character of an intracontinental aulacogen-trough infilled with basic volcanics and intrusives, marginal fanconglomerates and alluvial sediments, and possibly some lake sediments associated with blocked drainage patterns.

Another aulacogen-type trough bounds the Midcontinent in southern Oklahoma. This feature contains the deepest and most geologically persistent sedimentary basin on the North American craton, the Anadarko basin, which accumulated 38,000 feet of Paleozoic sediments and is underlain by an additional 7,000 feet of Middle Cambrian rhyolitic flows, tuffs, and associated intrusives, which are 525 m.y. old. Beneath this sequence lies a major gabbroic complex of layered intrusives, possibly 10,000 feet thick, and of questionable age. Early to Middle Cambrian radiogenic ages of 535

m.y. may result from thermal overprints of later igneous events. Underneath this basic stratiform body lies an additional 15,000 feet (seismically estimated) of meta-greywackes and other layered rocks, known as the Tillman terrane, and also of questionable age. The latest U.S. Geological Survey Precambrian rock sequence charts (Harrison and Peterman, 1984) show the Tillman terrane as falling into a probable age range of 1200 to 1400 m.y. (mid Middle Proterozoic), which is slightly younger than the undeformed silicic terrane which underlies most of Oklahoma and southern Kansas.

Regardless of its age, the gabbroic complex probably marks the axial core of a rift-related system and demonstrates a significant zone of crustal weakness that is oriented almost perpendicular to the presumably older, but possibly coeval, Central North American Rift System.

The significance of these systems and terranes in terms of Precambrian continental tectonics and geologic history is not entirely clear. Understanding the possible geologic history of the Precambrian requires placing each of these terranes in its proper time frame, and then comparing terranes to establish the full extent of regions that have been subjected to similar geologic processes and sequences of events; as noted by Harrison and Peterman (1984), the time frame of seemingly parallel events may differ from region to region.

The 1600+ m.y. dates of the northern Midcontinent terrane reflect the approximate close of major intrusive and metamorphic events in the Lake Superior and Rocky Mountain regions and are coeval with extensive volcanic, volcano-sedimentologic, and magmatic rock assemblages of the southwestern United States and northern Mexico; these events may reflect the cratonization of a block welded to the North American plate about 1600 m.y. ago according to Harrison and Peterman (1980, 1984).

The tectonic significance of the extensive 1400 m.y. old belt of undeformed rhyolitic volcanic rocks and associated epizonal-to-mesozonal granitic plutons is an enigma. This vast terrane extends from the Texas Panhandle to Indiana and Ohio, and includes virtually no igneous rocks of mafic or intermediate composition, and with the possible exception of the Tillman terrane, no sedimentary or metamorphic rocks.

According to Van Schmus and Bickford (1981), "the question of the tectonic setting in which such a terrane could form is central with regard to the possible operation of plate tectonic processes in the Precambrian . . . we suggest that (following episodes associated with convergent plate tectonics) a period of crustal thickening and heating occurred (and) culminated with melting and production of silicic magmas in the lower crust. These magmas then rose buoyantly and produced widespread ignimbrite sheets that were invaded at shallow depths by granitic bodies of similar composition."

However, rifted continental settings also commonly produce abundant rhyolitic rocks; but typically include large volumes of basalt. It seems possible that basaltic magmas may have "ponded" beneath the crust (at the Moho interface) and caused general uplift and acid melt production, with or without observable attendant continental rifting or the appearance of surface basalts. It is interesting to note that a large rhyolitic province, which appears not to be associated with any other more basic eruptives, also occurs in western Bahia (Brazil). It is also possible that the gabbroic stratiform bodies and the Tillman metasediments are approximately coeval with these rhyolitic terranes, and as such represent a crustal rift axis of Mid-Proterozoic age.

In any event, knowledge of the origin and emplacement of the 1400 m.y. terrane is not sufficient to predict the occurrence and orientation of major zones of crustal weakness during this period of time. The northern contact of magnetic quiet zones (Yarger, 1984³) may represent a major paleo-plate tectonic boundary which is oriented approximately west-northwest across southern Kansas, but this has not been substantiated by deep seismic evidence.

Paleomagnetic evidence suggests that North America, South America, Africa, and parts of other continental cratonic areas behaved as a single coherent plate or "super-continent" during most of the Early and Middle Proterozoic. If this is true, the postulated supercontinent must have been subjected to continental rifting which began about 1200 to 1000 m.y. ago; the formation of the Central North American Rift System clearly indicates the superposition of a major extensional stress field on the Midcontinent basement terranes. The formation and development of this system is

approximately coeval with the main deformational events and basement reactivation of the Grenville orogenic belt of eastern North America, and the deposition of supracrustal sediments and volcanics of the upper Belt-Purcell Supergroup of western North America.

The southern Oklahoma aulacogen must have developed during Late Proterozoic time, if it had not begun earlier in conjunction with the Keweenawan trough. The lack of precise evidence for dating both the Tillman terrane and the basic intrusives below the Early to Middle Cambrian rhyolitic flows clearly prevents a chronological analysis of key stress fields in the Midcontinent Precambrian.

Rifting of the Grenville continental mass, which was accompanied by anorogenic igneous activity, began about 820 m.y. ago in Late Proterozoic time (Rankin et al., 1984), and probably marks the beginning of a series of tectonic events that must have exerted a profound and fundamental control over Midcontinent Paleozoic tectonic patterns - the opening of a "proto-Atlantic ocean (Iapetus), which was followed by its subsequent closure and attendant activation and collision tectonics of the Appalachian-Caledonian and the Ouachita-Hercynian orogens.

During the Late Proterozoic both the eastern and western margins of the craton, as well as possibly the southern margin, developed thick wedges of mioclinal sediments which are indicative of divergent continental margins formed by extension tectonics related to continental rifting and sea-floor spreading. Possible effects of this rifting are manifest in the Midcontinent by either initial, or continued, development of the southern Oklahoma aulacogen. However, development of rift-related fault patterns, if present, are obscured or masked by later tectonic patterns.

A rather interesting interpretation of filtered gravity patterns by Kinsland (1984), however, suggests that the Precambrian/Early Paleozoic rift passive margins underneath the Appalachians in south-central Alabama and the Ouachitas in central Arkansas can be re-aligned by a strike-slip (transform?) fault system with a five hundred mile displacement to the northwest; this fault system would also re-align the Central North American Rift System of central Kansas with the Hartville Uplift of southeastern Wyoming. The location of this proposed fault zone almost directly overlies

the southwest edge of the northwest trending series of basement highs observed by Muehlburger et al. (1967) that include the Central Kansas Uplift, the Chadron and Cambridge Arches of Nebraska, and the Black Hills. This proposed pre-rift re-alignment of major Precambrian features also places the Michigan and Illinois basins on trend with the Anadarko basin in a belt that runs almost parallel to the Central North American Rift System on one side, and the Grenville orogenic belt on the other side. While these alignments may be fortuitous, they are compatible with a rift-related origin of a proto-Atlantic ocean in the Late Proterozoic - Early Cambrian. It is also not inconceivable that the southern Oklahoma aulacogen represents a "pull-apart" Cambrian basin associated with a northwest trending strike-slip fault zone that was super-imposed on an earlier northwest trending rift system.

As one can readily see, the geologic history of the Precambrian of the Midcontinent is a fascinating subject that lends itself to a variety of interpretations. One result of this history, however, is clearly evident: the magnetic lineations observed by Yarger (1984) in the Kansas portion of the Midcontinent have origins that can be explained in terms of basement tectonics. Re-activation of these zones during Paleozoic time should be suspected and examined by petroleum geologists in search of migration-permeability pathways and solution-enhanced reservoir porosities.

Late Cambrian - Early Ordovician

(ca. 515 - 475 m.y.)

Over most of the Midcontinent, the first major depositional sequence overlying the deeply eroded basement terrane consists of a thin basal sand unit (Lamotte-Reagan) of early Late Cambrian age and a thick carbonate unit (Arbuckle) of middle Late Cambrian through Early Ordovician age. The combined thickness of these units over most of Kansas and Oklahoma ranges from less than 500 feet to over 2000 feet, and reaches a maximum thickness of about 8500 feet in the southern Oklahoma basin area.

According to Ham and Wilson (1967), the first Cambrian deposits above the basement-rock surface of the cratonic platform are Dresbachian in age and consist of arkosic conglomerates which grade upward into feldspathic and generally glauconitic sandstones. Following the initial transgression of the craton, a widespread regression occurred, marked either by a unit of coarser clastics, a glauconitic zone, or a very sharp break in sedimentation. The ensuing Franconian transgression began after a considerable gap in trilobite zonation (which is more complete in the southern Oklahoma basin) and widespread platform carbonate sedimentation developed and continued essentially without interruption from Late Cambrian into Early Ordovician time. Except for a distinctive lithologic boundary within the Canadian series (the base of the Roubidoux) Early Ordovician sedimentation was rarely marked by a pronounced unconformity, although many argillaceous beds represent minor stages of clastic influx.

Judging from the widespread distribution of the basal Late Cambrian sands, the topographic surface of the Precambrian over most of the Midcontinent during Late Cambrian time appears to have been a relatively featureless gently dipping plain, except for a belt of widely scattered "Precambrian hills" several hundred feet high in central and southeast Kansas, northeastern Oklahoma, and southwestern Missouri.

Structural features active during this time period include the rapidly subsiding southern Oklahoma basin area, the moderately subsiding Ozark basin area, and the mildly subsiding main platform shelf of the central Midcontinent.

Gentle upwarping of the Transcontinental Arch, the Southeast Nebraska Arch, the Central Oklahoma Uplift, and the Ozark Uplift probably began during the latter portion of Early Ordovician time (pre-Roubidoux).

Strong regional cratonic uplift occurred before the deposition of the overlying early Middle Ordovician (Chazyan) Simpson group, and created a major unconformity of craton-wide distribution. In the northern portion of the Midcontinent truncation and karst features indicate the magnitude of this uplift was on the order of a few hundred feet.

The tectonic events that led to the widespread cratonic subsidence and transgression of the Cambro-Ordovician sequence are most likely related to extensional stress fields associated with the main opening of the Iapetus (proto-Atlantic) Ocean. The subsequent cratonic uplift in late Early Ordovician time probably represents the initial indication of continental-ocean plate compression and the beginning phases of ocean closure which eventually led to the westward-directed thrusting, plutonism, and metamorphism associated with the Taconic orogeny in eastern North America.

The principal axis of stress at that time probably was approximately perpendicular to the strike orientation of the Transcontinental Arch, and compressional crustal folding and/or basement faulting most likely was responsible for the incipient development of that feature and the Southeast Nebraska Arch - Central Oklahoma Uplift (all of which roughly parallel the strike of the Central North American Rift System and the Taconide orogen). Alternatively, the origin of this uplifting could be isostatic activation of basement blocks in response to basinal sediment loads.

Sediments deposited during this time period include the widespread Simpson group of sands, shales, and carbonates, the Viola (and equivalent) carbonates, and the Maquoketa-Sylvan shale.

The early Middle Ordovician Simpson sediments are Chazyan in age and consist of clean sands grading into carbonates interbedded with shales and sands in the northern portion of the Midcontinent, and predominantly carbonates with some sands in the southern portion of the Midcontinent. Preserved sediment thicknesses average about one hundred feet over most of the Midcontinent, but attain maximum thicknesses on the order of two thousand feet in the southern Oklahoma basinal area.

The late Middle Ordovician Viola-Fernvale-Kimmswick carbonates are mainly Trentonian in age. Preserved sediment thicknesses average around one hundred feet over most of Kansas, but increase to about seven hundred and fifty feet in the southern Oklahoma basin area. The areal distribution of the Viola carbonates is somewhat more widespread than the Simpson group.

The Late Ordovician Maquoketa-Sylvan shale is predominantly a dolomitic green shale of Cincinnati age and is preserved mainly in basinal-shelf depressions of the northern and southern portions of the Midcontinent. Sediment thicknesses range from less than one hundred feet to slightly over three hundred feet.

Each of these units are bounded by unconformities of regional extent, although the early Chazyan (pre-Simpson) unconformity is the most widespread and easiest recognized. Basal conglomerates, sandstone transgressions, local channeling, karst features, overlap and truncation all provide evidence that the continental interior was emergent and slightly folded before Chazyan deposition. The sub-Trenton-Black River unconformity (Simpson-Viola) is present between sequences of carbonate rocks and is more difficult to recognize; it does, however, represent a low-angle slightly truncating unconformity. In Kansas, the widespread distribution of the basal non-cherty zone of the Viola indicates the probable low relief of the Simpson surface; however from central Oklahoma northwestward to Colorado, the Viola cuts progressively downward across stratigraphic units of the Simpson

group down to the Arbuckle. The Late Ordovician post-Trenton unconformity (pre-Maquoketa-Sylvan) is recognized mainly by erosional features on the surface of the Viola and by minor truncations of Middle Ordovician strata; these features are characteristic of most parts of the central craton, and as such represent widespread Late Ordovician epeirogeny.

Structural features active during Middle and Late Ordovician time include continuing major subsidence of the southern Oklahoma basinal area, coupled with differential subsidence (and possible uplift) of minor to moderate intensity on the central platform-shelf area of the Midcontinent. The combination of preserved Simpson and Viola rocks present in the "Nebraska Sag" of the Transcontinental Arch, coupled with the Viola truncation of Simpson-Arbuckle rocks from central Oklahoma to Colorado indicate probable differential and segmented uplift of the Transcontinental Arch during Middle Ordovician. The formation of the North Kansas-Iowa basin (and the disappearance of the Southeast Nebraska Arch) during the deposition of the Viola-Maquoketa sediments indicates differential subsidence of the cratonic platform (on the order of one hundred and fifty feet) was taking place in the northern Midcontinent during Middle and Late Ordovician time. The formation of this basinal area may also be indicative of incipient uplift of the Chautauqua-Ellis Arch. Due to the effects of several later periods of uplift and erosion, definitive ages for uplift of these two features can only be inferred from regional stratigraphic relationships and cannot be demonstrated with certainty. However, the strike of anticlinal folds on the Ellis Arch are aligned with the Chautauqua Arch (and differ from the features of the later Central Kansas Uplift), thus allowing the inference of tandem uplift. The strike of these features also parallel, but offset, the strike of the Nebraska Sag and may be indicative of a fundamental set of northwesterly trending basement fractures. It may also be significant that the belt of observed "Precambrian hills" in central and southeastern Kansas, northeastern Oklahoma, and southwestern Missouri roughly outlines the Ellis-Chautauqua Arch; this early Paleozoic "backbone" which separates the North Kansas-Iowa basin from the southern Oklahoma basinal area may represent a fundamental basement block reactivation.

The disappearance of the Southeast Nebraska Arch and the appearance of the North Kansas-Iowa basin indicates the primary stress field during Middle Ordovician may have been vertical and isostatic in nature, as it was in the subducted and block-faulted continental margin area of the Taconide orogenic zone. However during Late Ordovician, folding, thrusting, nappe transport (including basement rock), and regional metamorphism in the final phase of the Taconic Orogeny presumably resulted from continued subduction and compressional oceanic-continental plate interactions. These compressive stresses were oriented almost normal to the Transcontinental Arch (but roughly parallel to the strike of the Ellis-Chautauqua Arch) and may have aided the uplift of that feature. The deposition of the Maquoketa-Sylvan shales in the Midcontinent probably represents long distance transport of late orogenic fine-grained clastics eroded from the Taconide mountains during the final stages of Ordovician uplift on the eastern margin of North America.

Silurian, Lower Devonian, and Middle Devonian rocks of the Midcontinent, commonly known as the "Hunton group", are predominantly shallow water carbonate sequences bounded by Early and Middle Silurian and Early, Middle, and Late Devonian unconformities. These strata are preserved only in the North Kansas-Iowa basin and the basinal areas of southern Oklahoma; consequently over large areas of the Midcontinent that include the Chautauqua Arch and its flanks in Oklahoma and eastern Kansas, the unconformities that bound these units combine and give the appearance of a single unconformity. On the shelves flanking the Ellis Arch and the Transcontinental Arch, these unconformities are over-ridden by two additional Early Mississippian unconformities with the result that late Early Mississippian (Osagian) carbonates truncate units as old as the Early Ordovician Arbuckle.

Aggregate sediment thicknesses of Silurian strata attain a maximum of about five hundred feet in the northern basinal area and approximately eight hundred feet in the southern basinal area, and are indicative of subsidence levels of at least that range. Lower Devonian rocks reaching three hundred feet in thickness are present in the southern basinal area, but equivalent strata in the north are present only in the deepest portion of the Iowa basin and are less than one hundred feet thick; the apparent center of deposition of Lower Devonian strata in the Iowa basin shifted approximately two hundred miles to the northeast during Late Silurian - Early Devonian time. Middle Devonian strata are not present in the Oklahoma basin-shelf area, but are fairly widespread in the North Kansas-Iowa basin area.

The tectonic behavior of the Midcontinent during this time period is difficult to assess with certainty. In broad regional terms, the southern Oklahoma basin area continued to subside at a moderate, but declining overall rate throughout the Silurian and Early Devonian; however during Middle Devonian time the southern Midcontinent experienced major cratonic uplift and extensive erosion. The northern basinal area also continued to subside

during the Silurian but either stabilized during Early Devonian, or was uplifted and eroded prior to the subsidence and deposition of relatively thin, but widespread, strata during Middle Devonian time. Overall, the Midcontinent appears to have experienced a very significant uplift and tilt to the north-northeast during Early and Middle Devonian time.

The tectonic behavior of the Transcontinental Arch and the Ellis - Chautauqua Arch during this time period is even more difficult to assess. However it is this reviewer's opinion that each of the basinal unconformities represent periodic episodes of structural uplift or readjustment of these features, and that the relatively common interpretation of Siluro-Devonian "Hunton" strata representing a single depositional episode (affected only by Middle Devonian pre-Chattanooga-Woodford and Mississippian-pre-Atokan periods of erosion) is considerably simplified. The unconformities present in the carbonate sequences are frequently subtle, difficult to recognize, and are obscured by solution effects of varying ages on the flanks adjacent to positive areas. However, faunal hiatuses and physical evidence for unconformities clearly characterize periodic depositional phases that are tectonically controlled in both the northern and southern basinal areas of the Midcontinent.

According to Ham and Wilson (1967), the Early Silurian (pre-early Alexandrian) episode of uplift, regional folding, and erosion is characterized in the cratonic interior by truncation of underlying Cincinnati and Trentonian beds. The Middle Silurian (post-Alexander, pre-Niagaran) episode of uplift and erosion has been distinguished in Kansas and Oklahoma primarily by paleontologic evidence, but regionally Niagaran strata truncate lower units. Widespread epeirogenic uplift (on the order of three to five hundred feet), gentle folding, and erosion of Early Devonian age is clearly indicated by Oriskanian truncation of Silurian and Ordovician strata in southern Oklahoma. Over most of the Midcontinent, however, the Early Devonian unconformity cannot be distinguished from the early Middle Devonian (pre-Onondagan) unconformity. Truncation of Silurian and Ordovician strata by Middle Devonian strata is especially pronounced over much of the northern portion of the Midcontinent. The early Middle Devonian unconformity is time transgressive in southern Oklahoma, and is over-ridden by the more widespread Late Devonian pre-Chattanooga-Woodford unconformity.

The pre-Late Devonian unconformity marks a distinctive episode of major Paleozoic epeirogeny in the Midcontinent. Cratonic uplift and erosion of over five hundred feet of Devonian, Silurian, and Ordovician strata occurred in Oklahoma and southern Kansas during Middle Devonian time. Uplift and erosion in the North Kansas-Iowa basin area was not nearly so pronounced; over most of the area, the Middle Devonian carbonate units were only slightly beveled and a karst surface developed.

Stratigraphic and structural relationships of Upper Ordovician, Silurian, and Middle Devonian strata in the sag area between the Ellis and Chautauqua Arches are indicative of uplifting on the order of one hundred and fifty feet and probably represent Middle Devonian structural readjustments of fracture and fault patterns that began in the Early Ordovician with the development of the Ellis-Chautauqua Arch and the North Kansas-Iowa basin.

Preserved sediment thicknesses of Middle Ordovician through Middle Devonian strata in the North Kansas-Iowa basin indicate total downwarping of this area with respect to the crest of the Ellis-Chautauqua Arch must have been on the order of two thousand feet. The total depositional filling of the southern Oklahoma basin area, as measured by Upper Cambrian through Lower Devonian strata was on the order of eleven thousand feet.

Most of the Siluro-Devonian tectonic features of the Midcontinent could represent vertical isostatic adjustments of cratonic crustal blocks. However, a major orogenic deformation of the eastern margin of the North American craton - the Caledonian-Acadian orogeny - which apparently represents a major crustal plate subduction and continent-continent collision (North America-Europe), caused major westward compressive stresses on the craton. On the western margin, crustal plate movements which led to the Roberts Mountain thrust of the Antler orogeny presumably would have caused major eastward compressive stresses. Northward directed stresses related to Mid-Paleozoic plate movements in the Ouachita-Hercynian zone also occurred during Middle and Late Devonian and caused the Bretonic deformation. The combination and interplay of all these possible forces may have been responsible for the cratonic uplift and tilt observed in the Midcontinent.

Late Devonian and Mississippian strata of the Midcontinent record (1) a major transgression and deposition of the Chattanooga-Woodford dark shale sequence, (2) an Early Mississippian - Kinderhookian unconformity, (3) a second transgressive sequence of Kinderhookian dark shales and/or carbonates, (4) another significant Early Mississippian (pre-Osagian) unconformity, (5) a craton-wide blanket of Middle Mississippian (Osagian-Meramecian) carbonate units with minor breaks in sedimentation, and (7) a cyclical sequence of interbedded shales, thin carbonates, and sandstones of Late Mississippian (Chester-Springer) age. The deposition of these strata was followed in Late Mississippian-Early Pennsylvanian time by the development of many of the present major positive and negative structural features of the Midcontinent, including the Cambridge Arch-Central Kansas Uplift and the Nemaha Ridge-Forest City/Salina basins.

Although depositional thickness patterns of the Chattanooga-Woodford shale have been substantially modified by several episodes of Mississippian and Pennsylvanian erosion, this shale sequence covered most of the eastern portion of the Midcontinent, including the Chautauqua Arch, and the Oklahoma shelf-basin system to the south; presumably western Kansas and the Ellis Arch was also covered. Over most of the Midcontinent, the unit averages about one hundred feet in thickness, rarely exceeds two hundred feet, and reaches a maximum thickness of five hundred feet in southern Oklahoma. Differential subsidence patterns are difficult to detect, but some thickening into both the southern Oklahoma basin area and the North Kansas-Iowa basin area is evident. Facies changes in shale color and organic carbon/carbonate content probably reflect both depositional bottom topography and subsequent sub-aqueous/sub-areal erosion.

The Early Mississippian (pre/early Kinderhookian) unconformity represents eastward tilting of the cratonic platform and differential uplift of the Transcontinental Arch and its flanks, followed by erosion and regional beveling. Regionally this unconformity extends in a north-trending belt from western Oklahoma through Kansas and Nebraska into South Dakota, and in many areas Kinderhookian limestones and shales overlies previously eroded Ordovician strata.

In the eastern portion of the Midcontinent, this unconformity is typically marked by red shale and/or oolitic ironstones.

Older Kinderhookian strata are confined to the eastern portion of the North Kansas-Iowa basin area, and may record the initial movements of the Nemaha ridge/Forest City basin; however this may just reflect uplift of the Transcontinental Arch and cratonic tilt that occurred just prior to the deposition of Kinderhook sediments. Younger Kinderhookian strata, both east and west of the axis of the Nemaha Ridge, thicken to the north and indicate some differential subsidence was taking place.

Prior to the deposition of Middle Mississippian (Osagian-Meramecian) strata, a substantial amount of regional uplift and minor differential tilting occurred in the Midcontinent, particularly on the flanks of the Transcontinental Arch and the Ozark Uplift. Osagian strata of differing ages generally truncate Kinderhookian rocks (also of differing ages) and/or Late Devonian shales; this unconformity overrides older unconformities in the more severely tilted areas.

Regionally, the Middle Mississippian carbonates represent a vast blanket of sediments that probably covered most of the craton. The present distribution of these rocks reflects major episodes of erosion, particularly off of the Cambridge Arch-Central Kansas Uplift and associated flanks, in the Early Pennsylvanian. Sediment thicknesses average about two hundred feet over most of the eastern and central portions of the Midcontinent, and indicate cratonic stability, although several minor unconformities represent brief periods of structural adjustment and tilting and probably reflect the incipient development of several major structural features. Regional thicknesses of five hundred to two thousand feet in western Kansas and southern Oklahoma indicate a considerable amount of basinal subsidence took place and represent the expansion of hingelines and the overally deepening of the Anadarko basin-shelf system during this period.

Following the deposition of the widespread Middle Mississippian carbonates, over two thousand feet of Upper Mississippian Chester-Springer clastics were deposited in the Anadarko basin. Thin equivalents of these units may have covered most of the shelf areas of the Midcontinent, but

are not preserved. These rocks represent a major cratonic regression and reflect southward tilting of the Midcontinent and uplift centering on the Cambridge Arch-Central Kansas Uplift.

Total Mississippian sediment thicknesses in the Anadarko basin reached a maximum of about five thousand feet; these sediments overlie about five hundred feet of Late Devonian shales, and are in turn overlain by about fifteen thousand feet of Pennsylvanian sediments. Equivalent Mississippian strata in the Ouachita trough have a maximum thickness of twenty-two thousand feet, and represent a vast accumulation of pre-orogenic dark shales and turbidites in a rapidly subsiding basinal area marginal to the south edge of the craton.

The repeated cratonic fluctuations and tilting from Late Devonian through Mississippian time probably represent responses to major crustal plate movements on three sides of the North American plate. The dominant eastward tilting in Late Devonian-Early Mississippian time probably reflects pulses of the Antler orogeny in the American Cordilleran system. The apparent Middle Mississippian structural readjustments in the northern portion of the Midcontinent, and the dominant southward cratonic tilting in Late Mississippian time probably occurred in response to sediment loading in the Anadarko-Arkoma basin area and the Ouachita trough.

The Cambridge Arch-Central Kansas Uplift clearly had substantial development associated with this Late Mississippian southward cratonic tilting, as is evidenced by the presence of Early Pennsylvanian (Morrowan) age strata in southwestern Nebraska and Kansas which overlie the erosional unconformity that can be traced over these structural features. One has to wonder if the Chautauqua Arch was also a positive feature at this time. Evidence for the development of the Nemaha Ridge does not clearly verify its development during the Mississippian time, although the incipient development of this feature may have been related to the stress fields that produced the eastward cratonic tilting in Late Devonian - Early Mississippian time. The Oklahoma City uplift, which lies near the southern terminus of this feature, is, however, overlain by an unconformity which can be traced west-southwestward into the Anadarko basin where Morrow beds unconformably overlie Springer beds.

Early Pennsylvanian (Morrowan)

(ca. 310 - 305 m.y.)

A widespread unconformity which covers all parts of the craton except the Anadarko basin trough clearly developed in Late Mississippian - Early Pennsylvanian time. Erosion before and during deposition of Morrowan strata exposed large areas of Precambrian basement rocks along the Transcontinental Arch and the Cambridge Arch-Central Kansas Uplift.

Clastic Morrowan sediments record a dominant pattern of marine transgression with brief stillstands and minor regressions which caused a variety of constructive and destructive alluvial and deltaic environments in a discontinuous arc extending from southern Oklahoma northwestward across the Panhandle region into eastern Colorado, western Kansas, and southwestern Nebraska. Over four thousand feet of sediments were dumped into the Anadarko and Arkoma basins, but sediment thicknesses in the western Midcontinent range from less than two hundred feet to over five hundred feet.

The major orogenic pulse of the Wichita orogeny occurred in Early Pennsylvanian time. Early Morrowan and early Atokan conglomerates exposed in the Criner Hills segment of the Wichita Uplift indicate ten to fifteen thousand feet of structural uplift occurred prior to Atokan time. COCORP deep reflection profiles recorded across the Wichita Mountains and Anadarko Basin suggest that significant crustal shortening occurred during this time period with the result that crystalline rocks of the Wichita Mountains were thrust over sedimentary rocks of the Anadarko Basin along a series of faults as deep as twenty plus kilometers; listric thrust faults and hanging-wall anticlines developed in the sedimentary rocks of the basin. These features suggest that Pennsylvanian downwarping of the Anadarko Basin was at least partially due to thrust loading. Stress orientation during uplift appears to have been north-northeasterly.

The present Anadarko and Arkoma basins formed in response to this uplift, as did several other positive structural elements associated with the Wichita system; in the northern Midcontinent, the formation of the Nemaha Ridge and the associated Forest City-Salina basins may in large part be due to stresses associated with this crustal deformation.

Middle Pennsylvanian (Atokan-Early Desmoinsian)

(ca. 305-295 m.y.)

The Morrowan uplift and deformation of the Wichita orogeny created a pre-Atokan unconformity which probably reflects the greatest intensity of uplift and erosion that is associated with any Midcontinent cratonic unconformity. By the time of the next major orogenic pulse in early to middle Desmoinsian time, the Wichita Mountains had been stripped of at least fifteen thousand feet of covering rocks above the Wichita granite.

The Arkoma basin-Ouachita trough subsided rapidly during Atokan and early Desmoinsian time. The Ouachita frontal belt contains about nineteen thousand feet of sediments, some of which may be tectonically thickened, but the undeformed foredeep (the Arkoma basin) contains well over ten thousand feet of Atokan strata plus an additional seven thousand feet of early Desmoinsian strata.

Most of the Atokan strata in the Arkoma basin reflect deep-water sedimentation and turbidite basinal filling fed by deltaic systems on the north-eastern shelf ("pre-Mississippi Embayment") and on the north-western shelf (the Cherokee platform-McAlester basin and the Forest City basin area).

The late Atokan-early Desmoinsian sea gradually transgressed the cratonic platform until only the topographically highest parts of major structures remained emergent, and covered most of the Midcontinent with a thin veneer of paralic sediments which are mainly fluvial and deltaic in origin in the Forest City basin - Cherokee platform area east of the Nemaha Ridge system, but are considerably more marine in origin in the Anadarko basin - Hugoton embayment shelf system south and west of the Nemaha Ridge-Central Kansas Uplift highlands. Sediment thicknesses in the Anadarko basin attained a maximum of five thousand feet in the deepest portion of the basin, but thin rapidly to less than one thousand feet near hingelines, and average only a few hundred feet over large areas of the Hugoton embayment and the Salina basin shelf extension; sediment thicknesses east of the Nemaha Ridge are approximately double those to the west of the ridge system. With the exception of the Deese strata in the Anadarko-Ardmore basin are, most Atokan and early Desmoinsian strata had a northerly source area and represent prograding deltaic sedimentation over a shelfward migrating hingeline system.

Tectonic deformations during Atokan and early Desmoinsian time include a second episode of uplift and probable thrusting of the Wichita Mountains, which contributed extensive orogenic conglomerates to the Desmoinsian Deese strata of the Anadarko basin, and the major episode of complex uplifting, thrust faulting, and folding of the Ouachita system. Tectonism in the Ouachitas is dated by the presence of thick chert conglomerates of early Desmoinsian age in the adjoining parts of the Ardmore basin, which increase in coarseness, number of beds, and thickness towards the Ouachitas. Stratigraphic dating of the Ouachita orogenic complex as early Desmoinsian is also supported by the presence of chert conglomerates (derived from the Ouachita Mountains) in gently folded early Desmoinsian foredeep strata in the Arkoma basin north of the highly deformed frontal Ouachita belt.

Structural movements of the Ouachita foldbelt associated with the earlier pre-Atokan Wichita thrusting probably caused the enormous downwarping of the Arkoma basin during Atokan time. COCORP profiles strongly suggest the thick Middle Mississippian-Lower Pennsylvanian flysch strata were simultaneously deposited and involved in foreland deformation. Major thrusting of the Ouachitas probably began in late Atokan time and continued into the early Desmoinsian. This deformation is coeval with the Alleghenian phase of the Appalachian orogeny and the Asturic phase of the Hercynian orogeny, and probably is due to continental collision of the North American and African plates.

Stress fields associated with the north/north-easterly thrusting of the Wichitas and Ouachitas probably account for the northeasterly shift of the axis of the Central Kansas Uplift and the downwarping of the Salina-Forest City basins, and should strongly indicate the possibility of lateral movements on northeasterly trending fractures in the northern Midcontinent. Vertical movements of major structures such as the Central Kansas Uplift-Cambridge Arch-Transcontinental Arch and pre-existing fracture zones of all orientations should have occurred in isostatic response to the tremendous sediment crustal loads of the Anadarko-Arkoma basins of southern Oklahoma.

Late Pennsylvanian (Late Desmoinesian - Virgilian) (ca. 295-280 m.y.)

Late Pennsylvanian age strata record a major marine transgression which inundated the Midcontinent and deposited a thin veneer of cyclic shelf sediments. Early Desmoinesian cratonic tilt and erosion had eliminated almost all northerly sources of clastic sediment supply, and the Ouchita foldbelt and the older Wichita Mountains became the source area for most of the Late Pennsylvanian alluvial and fluvial-deltaic systems. The last phases of orogenic deformation - the Arbuckle orogeny - occurred during late Virgilian time, and regressive semi-continental clastics encroached on the Midcontinent from the north and east.

Thickness patterns of upper Desmoinesian strata barely outline the Central Kansas Uplift and the Nemaha Ridge (features which are clearly delineated by patterns of lower Desmoinesian strata), and average about two hundred feet over most of the Midcontinent, increase to five hundred feet on the Anadarko-Ardmore basin shelf hingeline-margins, and reach a maximum of one thousand feet in the Anadarko basin. Missourian age strata cover the Central Kansas Uplift and the Nemaha Ridge, and are approximately double the thicknesses of the Upper Desmoinesian strata. Cyclic shelf deposits of carbonates and shales were widely distributed over most of the Midcontinent, but interfinger with a fluvial-deltaic facies derived from the Ouachitas in northeastern Oklahoma and deeper water clastics derived from the Wichitas in the Anadarko basin. Westward the carbonate shelf units interfinger with arkosic paralic units derived from the Apishapa uplift of southeastern Colorado. Virgilian age strata display many of the lithologic and thickness characteristics of the Missourian strata, but a constructional clastic-carbonate shelf system with thick deltaic wedges developed along the eastern margin of the Anadarko basin and prograded westward into the basin; cyclic sedimentation in the eastern and northern portions of the Midcontinent also became more terrigenous in nature.

The third and final major pulse of Pennsylvanian orogenic deformation occurred during late Virgilian time. The deformational style of the Arbuckle orogeny is complex, but again records strong compressional thrust and/or lateral movements and is stratigraphically dated by orogenic conglomerates derived from the Arbuckle anticline. Boulder beds and conglomeratic strata range in age from late middle Virgilian to latest Virgilian-early Wolfcampian and overlies steeply folded rocks that range in age from Virgilian to Precambrian.

Structural uplift of the Arbuckle Mountains has generally been characterized as the result of lateral movements of a wrench fault system, particularly since the advent of plate tectonic concepts. However, many features, both in the Wichita as well as the Arbuckles, are equally consistent with folds and reverse faults formed under normal lateral compression, as is particularly well evidenced by the COCORP profiles which strongly support thrusting with lateral compression normal to the Wichita trend. These profiles do not preclude, however, "Arbuckle" age (late Virgilian) wrenching along fault trends established by earlier thrusting, nor do they preclude an oblique slip (combined wrenching and thrusting) of "Wichita" and/or "Ouachita" age.

Coeval with the Arbuckle orogenic movements were the main deformational thrusting phase of the Marathon orogeny (latest Pennsylvanian/pre-Wolfcampian) of the Ouachita segment in West Texas and the cratonic deformation of the Tobosa basin which created the Midland-Delaware basin/Central Basin platform complex. The deeper portions of the Anadarko basin and the northern portions of the Midcontinent were relatively unaffected by this deformation; however an episode of northwest-directed thrusting in the Arbuckle region appears to have cut some of the "Arbuckle" orogenic conglomerates in late Virgilian time, and is probably the result of an over-riding of the Arbuckle segment by the frontal Ouachitas along a low angle thrust that is related to thrust movements in the Marathon region.

Permian - Early Jurassic

(ca. 280 - 180 m.y.)

Late Paleozoic-Early Mesozoic age strata of the Midcontinent region reflect a long period of relative cratonic stability with mild epeirogenic movements marked by cratonic tilting, minor structural reactivation movements, low-angle unconformities, and minor development of new basinal areas; sedimentation in the Midcontinent records a major regression of oscillating marine seas with attendant evaporitic and continental facies.

Many of the structural features that originated with the Wichita, Ouachita, and Arbuckle orogenies remained prominent during Early Permian time, and disconformities between Pennsylvanian and Permian strata are associated with the Arbuckle, Wichita, Apishapa, and Front Range uplifts, as well as the Transcontinental Arch. Over most of the Midcontinent, however, a low-angle unconformity is barely discernable.

Arkosic clastics were shed from the uplifts in the southwest, but overall Wolfcampian strata record a gradual transistion from predominantly marine cyclic sedimentation to paralic-marine and semi-continental sedimentation, and infilled the deeper portions of the Virgilian-starved Anadarko basin. Sediment thicknesses record an overall subsidence to the southwest, and range from over fifteen hundred feet to less than five hundred feet. Subsidence was slow, and shallow-water depositional environments persisted and fluctuated over wide areas of the Midcontinent; sediment supplies, even in the eastern portions, were predominantly derived from the westerly and south-westerly uplifts. Thickness patterns indicate differential subsidence occurred in the Salina basin, with respect to the Central Kansas Uplift and the Nemaha Ridge; early development of the structural Hugoton and Sedgwick embayments also occurred during this time, along with the ancestral Las Animas arch.

Leonardian strata include uplift-associated arkoses and sequences of cyclic redbeds and evaporites indicative of semi-continental and restricted marine environments associated with late stages of marine regression. Downwarping, with no apparent hingeline, continued in the Anadarko basin - Hugoton-Sedgwick embayment area. In the western areas

not affected by Mesozoic beveling, Leonardian strata generally grade in thickness from less than one thousand feet southward to over three thousand feet. Clastic sediment sources were generally derived from the westerly and south-western uplifts and the Transcontinental Arch, but deltaic deposits in eastern Oklahoma were derived from the east and south-east and may be indicative of eastern-most Permian paleo-sea margins being positioned not too far east of the present outcrop belt. Lithofacies patterns reflect the development of subsiding salt basins in central and southwestern Kansas with centers of deposition migrating west-southwest from early to late Leonardian time. The thickest salt, marking the greatest subsidence of the salt basin, overlies a portion of the crest of the Central Kansas Uplift, and is indicative of the cessation of structural uplift of this feature. Leonardian strata reflect overall tilting of the Central Kansas Uplift-Salina basin area to the southwest and differential subsidence of the Hugoton embayment shelf-extension of the Anadarko basin.

In marked contrast to the huge massive reefs of the west Texas-New Mexico Permian basin, Guadalupian-Ochoan sequences of clastic redbeds were deposited across widespread dolomitic mudflats, and probably represent to the final filling of the Anadarko basin-Hugoton shelf. In areas not severely affected by Triassic erosion, Guadalupian sediment thicknesses of over five hundred feet are common, and reach over one thousand feet in the Anadarko basin area.

Sedimentation in the Midcontinent was interrupted in Late Permian and Early Triassic time by accelerated westward tilting and the formation of the ancestral Denver basin to the northwest. Channels cut into Permian strata infer a Triassic or pre-Triassic age drainage system to the west and southwest. Although a continuous sequence of deep-red fluvial beds were deposited in the Denver basin area, most of the Midcontinent in Early Triassic time was characterized by erosion and non-deposition. In marked contrast to the westward tilted Permian surface of Early Triassic time, Late Triassic coarse westward-derived continental redbeds of the Dockum group were deposited in southwestern Kansas and western Oklahoma, and suggest some tectonic uplifting to the southwest. Much of the Midcontinent was again subjected to westward tilting, erosion, and non-deposition during latest Triassic and Early Jurassic time.

Permo-Triassic tectonic events in the Midcontinent were predominantly epeirogenic in nature and include cratonic warping and tilting, although some movements on northeasterly trending fault zones occurred in previously deformed areas. Relatively minor truncation unconformities suggest some periodic uplift of the Arbuckle-Wichita-Amarillo trend and the Apishapa-ancestral Rocky Mountain trend. The Anadarko basin continued its persistent sinking well into Permian time, apparently without an active hingeline, and essentially became filled during Late Permian time. Middle Permian time records the cessation of positive structural arching of the Central Kansas Uplift and the brief development of a major depositional salt basin over much of the same area. Late Permian-Early Triassic time reflects cratonic tilting to the west, which was repeated again in Late Triassic-Early Jurassic time.

The relative continental stability during Permian time probably can be related to the fusion of the North American, African, and South American plates during Pennsylvanian time. The Late Permian-Early Triassic westward tilting of the Midcontinent region probably reflects compressive orogenic crustal forces related to the large eastward-directed Golconda thrusting episode of the Late Permian-Early Triassic Sonoma orogeny of western North America. The Late Triassic wedge of sediments may reflect a complex interplay between compressive forces on the west and extensional forces on the east, which are related to the first stages of continental rifting on the east and southeast and the initial opening of the Atlantic ocean and the Gulf of Mexico during Late Triassic-Early Jurassic time.

Middle Jurassic - Cretaceous

(ca. 180 - 65 m.y.)

The stratigraphic and tectonic history of the Midcontinent during Late Mesozoic time primarily reflects major geologic events associated with (1) the formation of the Western Interior Seaway and attendant major cyclic marine patterns of sedimentation, (2) cratonic warping and westward tilting related to episodes of major eastward-directed thrusting of the Sevier orogeny and the formation of the Rocky Mountain Overthrust Belt, and (3) cratonic uplift and eastward tilting associated with the massive vertical basement uplifting and block-faulting of the Laramide orogeny.

Late Mesozoic sedimentation patterns in the Midcontinent are related to the evolution of the Western Interior Seaway southward from the Arctic Ocean and northward from the Gulf of Mexico. The cyclicity evident in these patterns probably reflects Rocky Mountain-Midcontinent foredeep deformation-foreland warping by a series of major craton-directed thrust events of the Sevier orogeny during Late Jurassic and Cretaceous time, as well as worldwide eustatic changes in sea level related to changes in sea-floor spreading rates associated with the opening of the North Atlantic Ocean and the formation of the Tethyan Seaway.

Throughout this time period, the Midcontinent region essentially evolved from a highly eroded continental foreland to an epi-continental shelf system of the Western Interior Seaway.

Beginning in Middle Jurassic time, four successive marine transgressions from the north culminated in Late Jurassic time with the deposition of Swift-Sundance sediments which grade into the overlying regressive coastal-, flood-, and alluvial-plain deposits of the Morrison formation. Prior to the deposition of the Morrison, several hundred feet of Permo-Triassic sediments had been removed from the Midcontinent by pre-Late Jurassic erosion. Jurassic formations older than the Morrison have not been recognized in the Midcontinent, primarily as a result of a rejuvenated Transcontinental Arch which controlled the eastward depositional limits of strata until Late Jurassic time. Jurassic seas from the Gulf of Mexico apparently did not

connect with the northern invasions. Remnants of Jurassic deposits exist in central Iowa, however, and suggest that the areal extent of Jurassic deposition may have been far greater than indicated by the preserved wedge of Sundance-Morrison deposits across the Rocky Mountain area, which are three hundred feet thick in the northwestern portion of the Midcontinent, but which were truncated to a feather-edge by Lower Cretaceous sediments in the north-central area of the Midcontinent.

Following the widespread deposition of the continental Morrison strata, northward flowing fluvial drainage systems developed during Early Cretaceous (Neocomian) time and formed a valley system that is reflected in the thickness and distribution of clastic facies of the overlying Lower Cretaceous strata. Early Cretaceous seas advanced from both the Arctic and the Gulf of Mexico and inundated the Midcontinent by mid-Albian time. These seas deposited the extensive Lower Dakota (Lakota)-Cheyenne sands and the organic-rich Skull Creek-Kiowa shales over a truncated Midcontinent terrain that had been heavily eroded in Late Permian-Early Triassic time, Early and Middle Jurassic time, and again in Early Cretaceous time. The Skull Creek-Kiowa seas regressed and a complex of alluvial and fluvial-deltaic "Dakota" sediments prograded westward across the Midcontinent into the Denver basin area, where the deltaic "J" sands developed. Marine waters again invaded the Denver basin - western Midcontinent during late Albian time and deposited the Mowry-Huntsman shales, but coastal and deltaic environments soon prograded again across the Midcontinent into the Denver basin and deposited the "D" sand complex. These clastics represent the last major contribution of sediments derived eastward from the Midcontinent during Cretaceous time.

In Late Cretaceous time (early Cenomanian) the Mowry sea again expanded, and connected with marine waters invading from the south to form the epicontinental Greenhorn seaway. The initial transgressive Greenhorn shale sedimentation was followed by the widespread development of the Greenhorn chalky carbonate sequence during Cenomanian and early Turonian time. The Greenhorn sea began to regress during middle Turonian time and deposited the Carlisle shales and silty sands; however, as sediment supplies dwindled

and base-levels readjusted, a widespread non-depositional unconformity developed during late Turonian time. A second Late Cretaceous transgression deposited the massive chalky carbonates of the Fort Hays member of the Niobrara formation during latest Turonian and early Coniacian time; the regressive episode of this cycle is represented by the protracted deposition of the marly Smokey Hill chalk sequence from late Coniacian through Santonian into early Campanian time. The Smokey Hill marls grade conformably into the overlying basal units of the Pierre shale, which represents the final major cycle of Cretaceous marine sedimentation and lasted into early Maestrichtian time. Deposition of the organic-rich Late Cretaceous shales was terminated by the increased tectonic activity of the Laramide orogeny and the final major thrusting event of the Sevier orogeny, which uplifted the entire Denver basin area and began to elevate and tilt the Midcontinent area.

Prior to Tertiary and Recent erosion, a relatively thick sequence of Cretaceous strata must have covered most of the Midcontinent. Preserved thicknesses of three thousand feet in northwestern Kansas and two thousand feet in southeastern Oklahoma thicken rapidly into the Denver basin and Gulf Coast-Mississippi Embayment areas, where total Cretaceous strata are approximately ten thousand feet thick. Paleogeographic maps of the Rocky Mountain region suggest that Cretaceous strata eroded from the Midcontinent might have been on the order of two thousand feet thick. The present section in northwestern Kansas contains ammonitic age equivalent strata of most of the section found westward, and places a probable maximum limit of eroded thicknesses removed from much of the Midcontinent.

Tectonic stresses affecting the Midcontinent during Late Mesozoic time are probably most directly related to the Sevier and Laramide orogenies of the western American Cordilleran system, but are probably also related to world-wide crustal plate movements that affected many parts of continents simultaneously. Major changes in sea-floor spreading rates and directions of both Atlantic and Pacific ocean plates at 135 m.y., 80 m.y., and 50 m.y. are recorded in the Cordillera by the onset of thrusting and plutonism associated with the Sevier and Laramide orogenies, and the rather abrupt end of the Laramide orogeny.

Initial major tectonic activity in the Rocky Mountain Overthrust belt began with a cratonic-directed thrusting event in Late Jurassic time, which probably contributed to the widespread regressive Morrison phase of the Sundance cycle. Renewed thrust movements during Early Cretaceous (Albian) time correlate well with the Dakota regressive phases of the Skull Creek-Kiowa cycle, and subsequent major thrusting episodes in Late Cretaceous mark the end of transgressive sedimentation phases in middle to late Turonian (Carlisle-Frontier regression and Niobrara disconformity) and early Maestrichtian time (termination of Pierre shale deposition). The combined effects of these thrusts probably not only played a significant role in flexing and uplifting the cratonic crust of the Midcontinent (in response to western basin loading), but probably contributed a significant compressive stress field that either created joint patterns or reactivated existing fractures in the Midcontinent.

Massive emplacements of batholithic intrusions and vertical uplifting associated with the beginning of the Laramide orogeny in very late Cretaceous time were nearly coeval with the culminating phases of Sevier thrusting, and mark the beginning of Rocky Mountain uplifting and structural basin formation, and presumably began to tilt the Midcontinent region to the east.

Tertiary - Recent

(ca. 65 - 0 m.y.)

Structural deformation of the Rocky Mountain Laramide orogeny continued from Late Cretaceous time well into Tertiary time. Block faulted intermontane basin sedimentation began in Paleocene time and continued into Eocene time in well defined structural basins. Over most of the area, a major erosional and/or nondepositional hiatus between Eocene and Oligocene sediments indicate a major episode of broad regional uplifting, which was followed by erosional channel cutting and deposition during the Oligocene and Miocene on the western fringes of the Midcontinent. In late Miocene and early Pliocene time renewed activity in the Front Range was followed by extensive regional crustal adjustments in middle and late Pliocene time which led to the widespread alluvial deposition of the Plio-Pleistocene Ogallala sediments of the Great Plains.

The major episode of broad regional uplifting that occurred in late Eocene time marks the culmination of Laramide deformation, and tilted the Denver basin and adjacent areas of the Midcontinent eastward. This deformation is also nearly coeval with the widespread early Miocene bimodal eruptions of basalt and rhyolite that occurred throughout the Rocky Mountain and Great Basin region, and may be responsible for deep basement fracturing in the Midcontinent which most likely occurred at this time and/or earlier at the end of Cretaceous time.

Summary and Implications of Geologic History

From the preceding review and analysis of regional geologic data, it is clear that the stratigraphic and tectonic history of the Midcontinent petroleum province can be related to major tectonic events and crustal processes that affected the southern portion of the North American craton and its margins on the east, south, and west. The observed patterns of sedimentation and orientations of structural features demonstrate a significant amount of basement control and involvement. Although the nature of the causative processes of cratonic and intra-cratonic control are speculative, the coeval timing of major orogenic events with the formation and development of cratonic structures cannot be ignored.

In order to provide a basis for modeling the generation and migration of Midcontinent hydrocarbons, these events can be summarized by the following Precambrian, Paleozoic, and Mesozoic-Cenozoic sequences.

Precambrian

1. Formation of northern Midcontinent granitic basement terrane at approximately 1625 m.y. by orogenic processes. Structural grain unknown, but possibly approximately east-west.
2. Formation of southern Midcontinent rhyolitic basement terrane at approximately 1400 m.y. by anorogenic processes of unknown origin. Similar, possibly coeval, rhyolitic terranes on South American craton in Brazil.
3. Formation of layered Proterozoic basin marginal to Midcontinent. Inferred from COCORP profiles. Fault bounded on north edge, with downthrow to south. Character of layering suggests depositional and/or layered igneous bodies. Either predates, or is filled by Tillman greywacke/metasediments. Relationship to 1400 m.y. terrane unknown; possible remnant of rift basin? possible rifted continental margin?

4. Formation of Central North American Rift System (CNARS) at approximately 1100 m.y. Basic igneous intrusions and extrusions, block faulting, rift sedimentation. North-northeasterly strike in northern Midcontinent with probable transform off-sets; possible extension into southern Midcontinent. Related to Grenville orogeny? and/or breakup of Proterozoic supercontinent?
5. Formation of southern Oklahoma aulacogen trough with intrusion of gabbroic layered complex (unknown age, possible range 1400 to 550 m.y.) and rhyolitic extrusions (Early/Middle Cambrian). Oriented almost normal to CNARS. Possible rift-related system and/or pull-apart wrench basin. Probable association with formation of proto-Atlantic/Iapetus ocean.
6. Formation of Late Precambrian - Early/Middle Cambrian passive continental margins with mioclinal clastic sedimentation on eastern and western (and probably the southern) margins of the North American craton.

* * Paleozoic * *

1. Deposition of Cambro-Ordovician carbonate sequence, with minor depositional break in Early Ordovician time (pre-Roubidoux) indicating incipient uplift of Transcontinental Arch, Southeast Nebraska Arch, Central Oklahoma Uplift, and Ozark Uplift. Major subsidence (8000'+) in Anadarko-Arkoma basin region of southern and southeastern cratonic continental margins, with less than 1000' of equivalent strata on Midcontinent platform. Rapid basin subsidence probably due to isostatic response to crustal thinning and cooling of rift-related thermal anomalies associated with the main opening of the Iapetus (proto-Atlantic) Ocean.

2. Major regional cratonic uplift and development of Transcontinental uplift during Early Ordovician time led to major pre-Middle Ordovician (pre-Chazyean) unconformity. Cratonic uplift probably in part due to isostatic response of marginal basin sediment loading, and in part represents an indication of continental-ocean plate compression and initial phase of ocean closure.
3. Early Middle Ordovician Simpson seas transgressed the Midcontinent in possible response to change in sea-floor spreading rates and a possible world-wide eustatic change in sea-level. Differential subsidence continued in the southern basinal areas and the development of the Nebraska sag in the Transcontinental Arch coupled with movement on the Southeast Nebraska Arch suggests an early development of northwesterly oriented basement zones of weakness that might indicate a major cratonic transform lineament associated with the CNARS.
4. After a minor break in sedimentation, due in part to differential uplift on the Transcontinental Arch and the Ozark Uplift, Viola-Kimmswick carbonate sedimentation continued in late Middle Ordovician time. Depositional patterns changed significantly and indicate (1) an overall differential tilt of the Midcontinent to the north, with only relatively minor subsidence in the southern Oklahoma basinal area, (2) the development of a basinal area in the northern Midcontinent (the North Kansas-Iowa basin), and (3) the development of a transverse northwesterly oriented Midcontinent "backbone" consisting of the Ellis-Chautauqua arch system; these structural features in the Midcontinent are coeval with the main thrusting phases of the Taconic orogeny on the eastern margin of the craton, which continued into the Late Ordovician.

5. Sedimentation patterns of the Maquoketa-Sylvan shale indicate continued relative uplift of the Ellis-Chautauqua arch "backbone", with the result that nearly complete separation of the North Kansas-Iowa basin and the Oklahoma basin areas took place in Late Ordovician time. This time period is coeval with the culminating phases of the Taconic orogeny, which represents major crustal compression and uplift on the eastern continental margin. Middle and Late Ordovician time reflects major epeirogenic movements in the Midcontinent which probably created sets of major fracture patterns in the carbonate sequences that could be related to basement zones of weakness; the porosity and permeability associated with these fracture zones near the structural backbone could have been enhanced considerably before the deposition of the Maquoketa-Sylvan shales, which represent the first major potential Midcontinent petroleum province hydrocarbon "source-seal" system (although certain facies distributions of the interbedded shales of the Simpson formation probably represent the first potential major Paleozoic source rock).
6. Depositional patterns of the Siluro-Devonian "Hunton" carbonates are masked by several unconformities (Early and Middle Silurian, Early, Middle, and Late Devonian), but indicate continued (yet slowing) differential subsidence of the North Kansas-Iowa basin and the Oklahoma basin areas. Depositional patterns and preserved sediment thicknesses on Middle Ordovician through Middle Devonian strata in the North Kansas-Iowa basin indicate total downwarping of this cratonic area with respect to the crest of the Ellis - Chautauqua arch system must have been on the order of two thousand feet. Middle Devonian strata present in the northern Midcontinent are not preserved in the southern Midcontinent, and indicate the Midcontinent experienced a significant uplift and tilt to the north-northeast during Early and Middle Devonian time.

The relatively frequent breaks in sedimentation on the flanks of the Ellis-Chautauqua backbone probably represent a complex combination of tectonic and/or isostatic adjustment of crustal blocks (by Middle Devonian time, the Anadarko-Ardmore basin area contained about eleven thousand feet of Paleozoic sediments). Middle and Late Devonian time represents a major orogenic period of deformation and uplift on the eastern margin of the North American craton (the Caledonian-Acadian orogeny) which apparently represents a major crustal plate subduction and North American-European continent-to-continent collision, and caused major westward-directed compressive stresses on the Midcontinent. On the western margin, crustal plate movements led to the eastward craton-directed Roberts Mountain thrusting of the Antler orogeny; and Mid-Paleozoic plate movements in the Ouachita-Hercynian zone caused the Bretonic deformation which probably placed additional north-northwestward stresses on the Midcontinent. The creation (and enhancement of existing) fracture zones, coupled with horizontal and vertical shear movements, must have been inevitable.

7. Deposition of the organic-rich Chattanooga-Woodford records a major transgression of the Midcontinent, and may reflect worldwide eustatic changes in sea-level, or the aftermath of complex continental crustal adjustments to multiple plate convergences. Regardless of its origin, the Chattanooga-Woodford sedimentation created the second major potential hydrocarbon source-seal system of the Midcontinent.
8. Pre/early Kinderhookian and pre-Osagian Early Mississippian unconformities record a major eastward tilting of the cratonic platform and differential uplift of the Transcontinental Arch and its flanks, followed by erosion and regional beveling. These regional unconformities probably reflect the culminating phases of the Antler orogeny and western plate movements.

9. A craton-wide blanket of Middle Mississippian (Osagian-Meramecian) carbonates record a time of relative tectonic quiescence, but subtle variations in northern Midcontinent sedimentation patterns and thicknesses indicate incipient structural activity of the Central Kansas Uplift and the formation of the Salina-Forest City basin and Nemaha ridge system.
10. Late Mississippian time records the initial stages of filling of the Ouachita trough. Approximately 22,000 feet of sediments were dumped into the rapidly subsiding Ouachita system marginal to the Midcontinent; approximately 2,500 feet of equivalent Chester-Springer dark shales were deposited in the Anadarko basin, which constitute the third major potential hydrocarbon source-seal system of the Midcontinent. The relatively rapid cratonic subsidence of the Anadarko basin is probably related to the extremely rapid subsidence of the Ouachita trough, and coeval structural activity on the Cambridge Arch-Central Kansas Uplift can be established by an unconformity that can be traced to a Springer-Morrow unconformity in the Anadarko basin. Uplift on the southern portion of the Nemaha ridge (the Oklahoma City uplift) can also be established in the same manner.
11. Late Mississippian - Early Pennsylvanian (pre-Morrow) time is represented over most of the Midcontinent by a widespread unconformity. This unconformity probably not only reflects differential uplift on the Transcontinental Arch and the Cambridge Arch-Central Kansas Uplift, but probably reflects an overall cratonic uplift and tilt due to crustal events taking place on the southern margin of the craton. The amount of movement on the Nemaha ridge during this time is unknown and masked by later events.
12. Early Pennsylvanian Morrow time records a major downwarping of the southern Midcontinent. Over four thousand feet of clastics were dumped into the Anadarko and Arkoma basin areas, much of which came from a large fluvial-deltaic system in the western portion of the Midcontinent and the rising Wichita Mountains in the southern area.

13. The major pulse of the Wichita orogeny occurred in late Morrowan-early Atokan time. The present Anadarko and Arkoma basins formed in response to this event, as did several other positive structural elements in the Wichita system. The Morrowan uplift and deformation of the Wichita orogenic system thrust crystalline rocks of the Wichita Mountains northeastward over sedimentary rocks of the Anadarko basin, and suggests that Pennsylvanian downwarping of the Anadarko basin was at least partially due to thrust loading. This period of deformation possibly reflects the greatest intensity of uplift and erosion that is associated with any Midcontinent cratonic unconformity, and major movement on the Nemaha ridge must have taken place during this time.
14. Structural movements of the Ouachita foldbelt associated with the pre-Atokan Wichita thrusting probably caused enormous downwarping of the Arkoma basin during Atokan and early Desmoinesian time. The Ouachita frontal belt contains about 19,000 feet of sediments (which may be tectonically thickened), but the undeformed foredeep (the Arkoma basin contains well over 10,000 feet of Atokan strata plus 7,000 feet of early Desmoinesian strata. Most of this strata reflects deep-water sedimentation and turbidite basinal filling fed by deltaic systems on the northeastern shelf ("pre-Mississippi Embayment") and on the northwestern "Cherokee" shelf of the Arkoma basin area.
15. Major thrusting of the Ouachita system began in late Atokan time and continued into the early Desmoinesian time. This deformation is coeval with the Alleghenian phase of the Appalachian orogeny and the Asturic phase of the Hercynian orogeny, and is probably due to continental collision of the North American and African plates. This deformation created the Ouachita Mountains of the southeastern Midcontinent, and caused new and/or renewed uplift in the Wichita-Amarillo, Apishapa, Front Range trend to the south and southwest.

Deformational movements of the Central Kansas Uplift-Cambridge Arch - Transcontinental Arch, and downwarping of the Salina - Forest City basin area can all be documented as responding to the Ouachita thrusting during early-to-middle Desmoinesian time. Patterns of fracture permeability and porosity again were either substantially created or enhanced as a result of both the Wichita and the Ouachita orogenies, and the deposition of the relatively widespread Cherokee shales constitutes the fourth major potential hydrocarbon source-seal system of the Midcontinent.

16. Late Pennsylvanian age strata record a major marine transgression which inundated the Midcontinent and deposited a thin veneer of cyclic shelf sediments over most of the positive structural features that had not been covered by Cherokee sedimentation, including the Central Kansas Uplift and the Nemaha Ridge. Widespread systems of cyclic carbonate banks developed over large areas of the Midcontinent. Late Desmoinesian through Virgilian sediments created a fifth major potential hydrocarbon source-seal system, and contains many internal units that could have created localized systems in combination with porous reef-bank facies.
17. The third and final major pulse of orogenic deformation marginal to, and in, the southern Midcontinent occurred during late Virgilian time, and caused major deformation in the Arbuckle Mountains. Coeval with the Arbuckle orogenic movements were the main deformational thrusting phases of the Marathon orogeny in the western segment of the Ouachita belt, which created the Midland-Delaware basin/Central Basin Platform complex. The deeper portions of the Anadarko basin and the northern Midcontinent appear to be relatively unaffected by this deformation.
18. Sedimentation in Permian time in the Midcontinent records a major regression of oscillating marine seas with attendant evaporitic and continental facies, and reflects a period of basin filling tectonic quiescence probably due to continental fusion of cratonic North American, African, and South American plates.

* * Mesozoic - Cenozoic * *

1. Midcontinent sedimentation was interrupted in Late Permian and Early Triassic time by accelerated westward cratonic tilting, marked by an incised channel drainage pattern infilled with coarse westward-derived continental beds of the Late Triassic Dockum group. This westward tilting probably reflects a cratonic response to the thrusting event (Golconda) of the Late Permian-Early Triassic Sonoma orogeny of the western Cordilleran.
2. Following the deposition of the Late Triassic wedge of sediments, another long period of erosion continued to remove massive amounts of Permo-Triassic sediments from the Midcontinent.
3. Beginning in Middle Jurassic time, marine transgressions from the Arctic culminated in Late Jurassic time, and deposited the regressive coastal and alluvial plain sediments of the Morrison formation.
4. Early Cretaceous seas advanced from both the Arctic ocean and the Gulf of Mexico and inundated the Midcontinent by mid-Albian time. A transgressive-regressive cycle of lower Dakota-Cheyenne sands, organic-rich Skull Creek-Kiowa shales, and alluvial-fluvial-deltaic Dakota-J sands truncated a heavily eroded Midcontinent terrain.
5. After another brief transgressive-regressive cycle (which deposited the Mowry-Huntsman shales and the "D" sand complex), marine seas invaded the Midcontinent from both the north and the south and formed the epi-continental "Greenhorn" seaway in Late Cretaceous time. Another cycle of sediments (Graneros shale-Greenhorn chalky carbonates-Carlile shales/silty sands) were deposited widely over the Midcontinent before an extensive non-depositional disconformity developed during late Turonian time. A second Late Cretaceous transgression deposited the massive chalky carbonates and marls of the Niobrara formation and the organic-rich Pierre shale.

The development of the Western Interior Seaway and attendant major cyclic marine patterns of sedimentation probably reflects a combination of worldwide eustatic changes in sea-level related to the opening of the Atlantic ocean and Tethyan seaway, as well as cratonic warping and westward tilting related to thrust loading episodes of the Late Jurassic - Late Cretaceous Sevier orogeny and the formation of the Rocky Mountain Overthrust Belt.

The Late Permian to pre-Cretaceous westward tilting, and the northwest tilting of Cretaceous time, probably led to significant fluid redistribution in Midcontinent migration pathways and reservoir rocks. The major Late Jurassic-Late Cretaceous sediment cycles of the western Midcontinent and the Denver basin area constitute several additional potential hydrocarbon source-seal systems.

6. Massive emplacements of batholithic intrusions and vertical uplifting associated with the beginning of the Laramide orogeny in very Late Cretaceous time, coupled with the culminating phases of Sevier thrusting, mark the beginning of Rocky Mountain uplifting and structural basin formation and presumably began to tilt the Midcontinent region to the east. Structural deformation continued into Eocene, and a major erosional and/or nondepositional hiatus between Eocene and Oligocene sediments in the intermontane basins indicate a major episode of broad regional uplifting and the culmination of Laramide deformation, which was followed by erosional channel cutting and deposition during Oligocene and Miocene on the western fringes of the Midcontinent.
7. Late Miocene-early Pliocene structural activity in the Front Range was followed by extensive regional crustal adjustments in mid and late Pliocene which led to the widespread alluvial deposition of the Plio-Pleistocene Ogallala sediments of the Great Plains, and finalized the basic structural attitude of the Midcontinent.

* * * * *

Although the fundamental mechanisms of the structural evolution of the Midcontinent must be considered speculative and controversial, the regional stratigraphic associations and lithologic characteristics of time-equivalent rock units clearly delineate major and minor unconformities which mark episodes of Midcontinent orogeny and aperiogeny. The traditional tools of geologic basin assessment - stratigraphic analysis and structural geology - can be combined with both surface and subsurface geologic and geophysical lineament analysis to provide a regional framework of potential permeability pathways for hydrocarbon fluid flow.

However, before an attempt can be made to discern or infer possible Midcontinent migration patterns throughout the geologic evolution of Oklahoma and Kansas, the observed distribution of hydrocarbon accumulations has to be clearly related in a genetic sense to "source rocks" or sequences of source rocks. Furthermore, if it can be demonstrated that a particular family of crude oils is related to a specific set of distal sources, the timing of the generation, expulsion, and migration of hydrocarbons has to be determined with respect to the lithologic and structural development of potential permeability patterns and pathways that existed during that time.

The following sections of this report will focus on (1) definition of Midcontinent source rocks and source-rock maturation, (2) identification of genetic families of Midcontinent crude oils, and (3) correlation of crude oils to source rock facies. These geochemical assessments will then be combined with regional stratigraphic and structural geologic information to infer past and present migration patterns and permeability patterns of hydrocarbon fluid flow.

* * * * *

A P P E N D I X I

MIDCONTINENT PALEOGEOGRAPHIC AND UNIT THICKNESS MAPS

Adler, F.J., W.M. Caplan, et al, 1971, Future petroleum provinces of the Mid-Continent region, in Future petroleum provinces of the United States - their geology and potential: AAPG Memoir 15, v.2, p. 985-1120.

Rascoe, B., Jr., and F.J. Adler, 1983, Permo-Carboniferous hydrocarbon accumulations, Mid-Continent, U.S.A.: AAPG Bulletin, v.67, p. 979-1001.

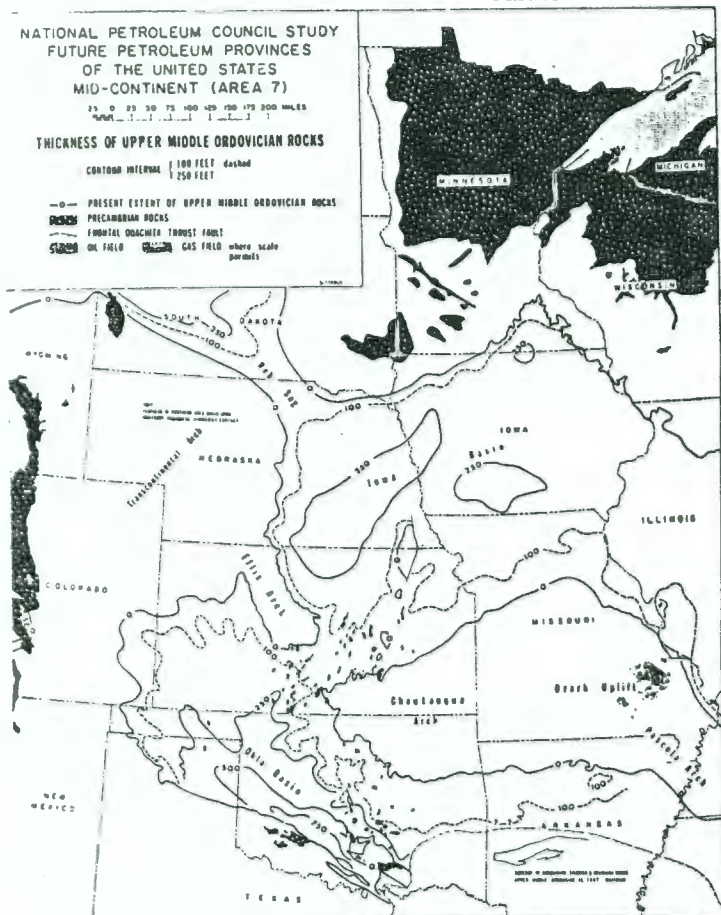
NATIONAL PETROLEUM COUNCIL STUDY
FUTURE PETROLEUM PROVINCES
OF THE UNITED STATES
MID-CONTINENT (AREA 7)

25 0 25 50 75 100 125 150 175 200 MILES

THICKNESS OF UPPER MIDDLE ORDOVICIAN ROCKS

CONTOUR INTERVAL: 100 FEET dashed
250 FEET

- 0 — PRESENT EXTENT OF UPPER MIDDLE ORDOVICIAN ROCKS
- PRECAMBRIAN ROCKS
- FRONTAL OZARKIA THRUST FAULT
- OIL FIELD GAS FIELD where scale permits



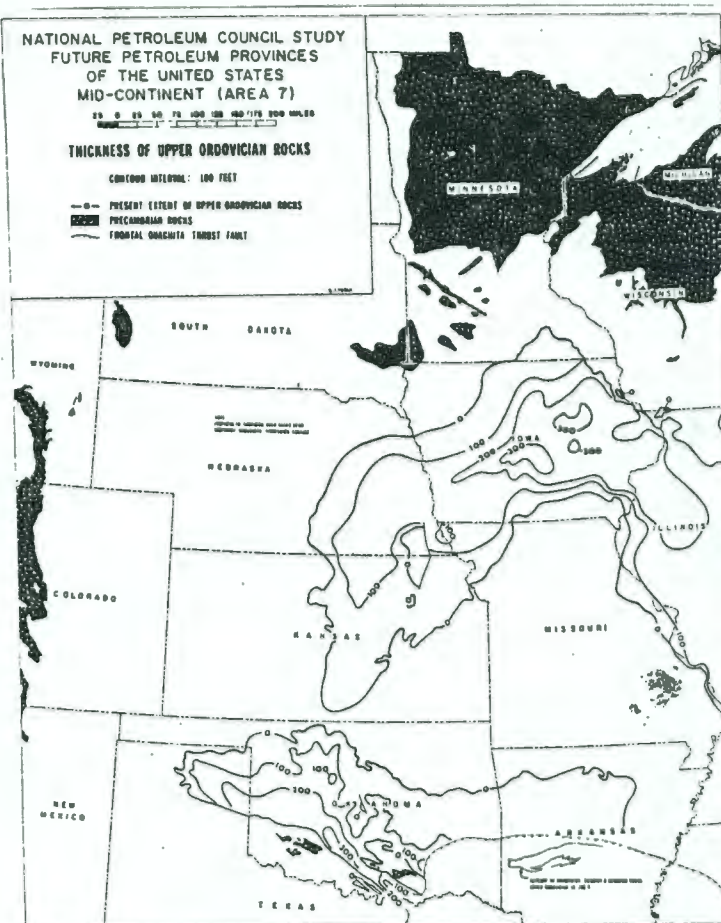
NATIONAL PETROLEUM COUNCIL STUDY
FUTURE PETROLEUM PROVINCES
OF THE UNITED STATES
MID-CONTINENT (AREA 7)

25 0 25 50 75 100 125 150 175 200 MILES

THICKNESS OF UPPER ORDOVICIAN ROCKS

CONTOUR INTERVAL: 100 FEET

- 0 — PRESENT EXTENT OF UPPER ORDOVICIAN ROCKS
- PRECAMBRIAN ROCKS
- FRONTAL OZARKIA THRUST FAULT



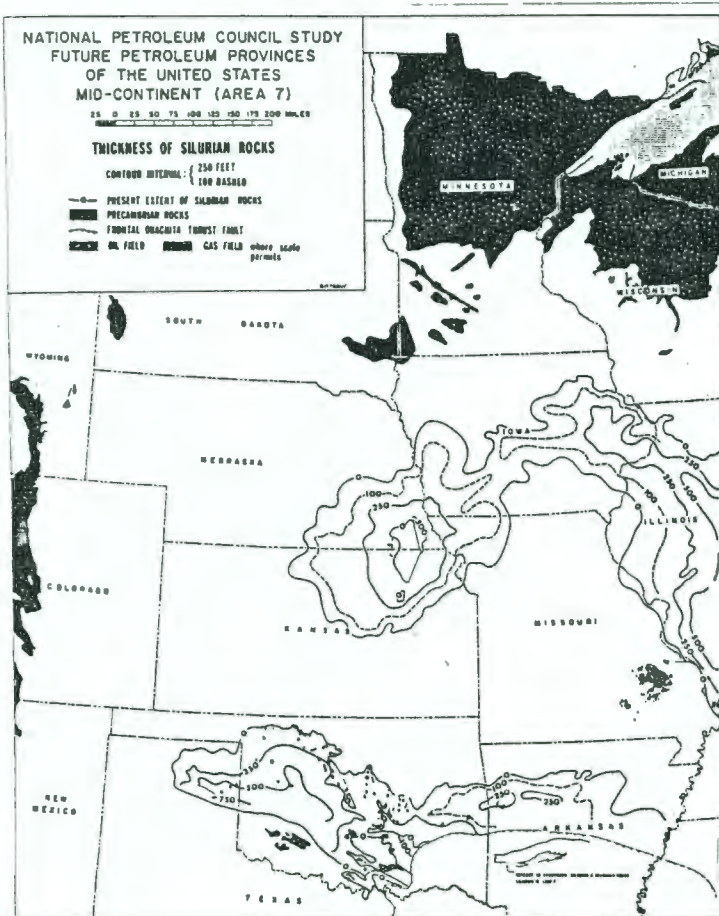
NATIONAL PETROLEUM COUNCIL STUDY
FUTURE PETROLEUM PROVINCES
OF THE UNITED STATES
MID-CONTINENT (AREA 7)

25 0 25 50 75 100 125 150 175 200 MILES

THICKNESS OF SILURIAN ROCKS

CONTOUR INTERVAL: 250 FEET
100 DASHED

- 0 — PRESENT EXTENT OF SILURIAN ROCKS
- PRECAMBRIAN ROCKS
- FRONTAL OZARKIA THRUST FAULT
- OIL FIELD GAS FIELD where scale permits



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MID-CONTINENT (AREA 7)

25 0 25 50 75 100 125 150 175 200 MILES

THICKNESS OF LOWER DEVONIAN ROCKS

CONTOUR INTERVAL: 100 FEET

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- PRECAMBRIAN ROCKS
- FRONTAL OZARKIA THRUST FAULT
- OIL FIELD GAS FIELD where scale permits



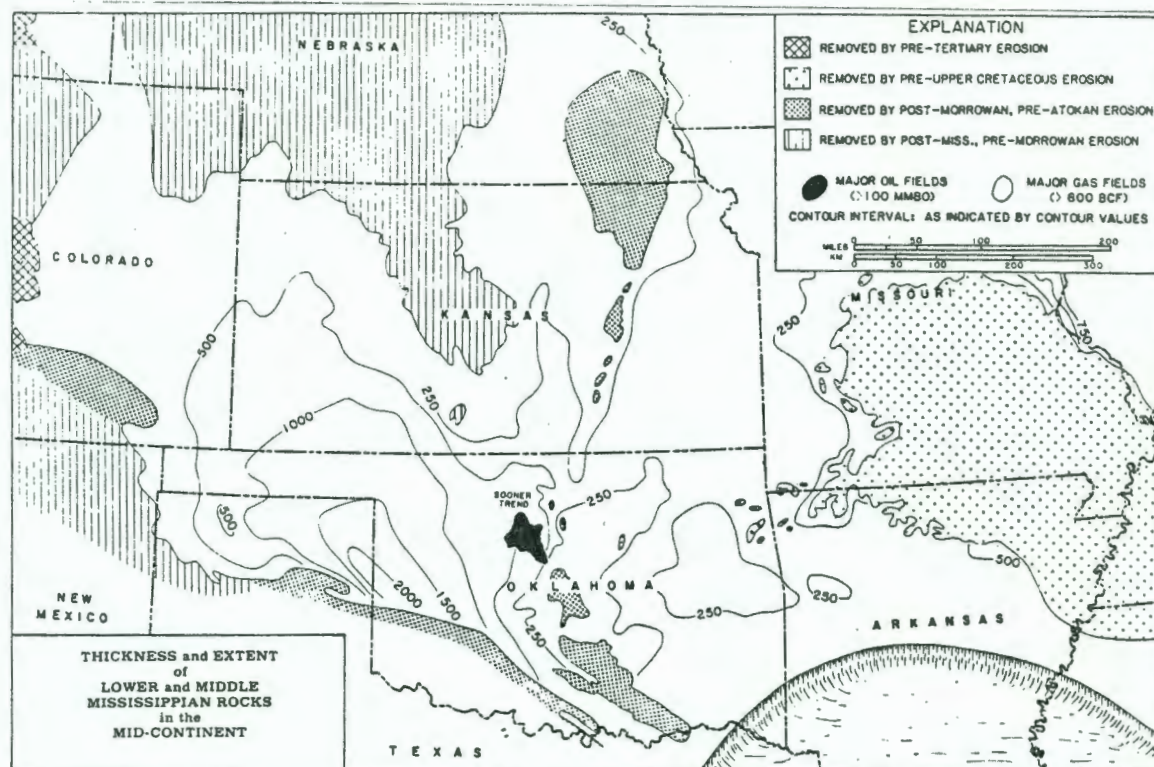
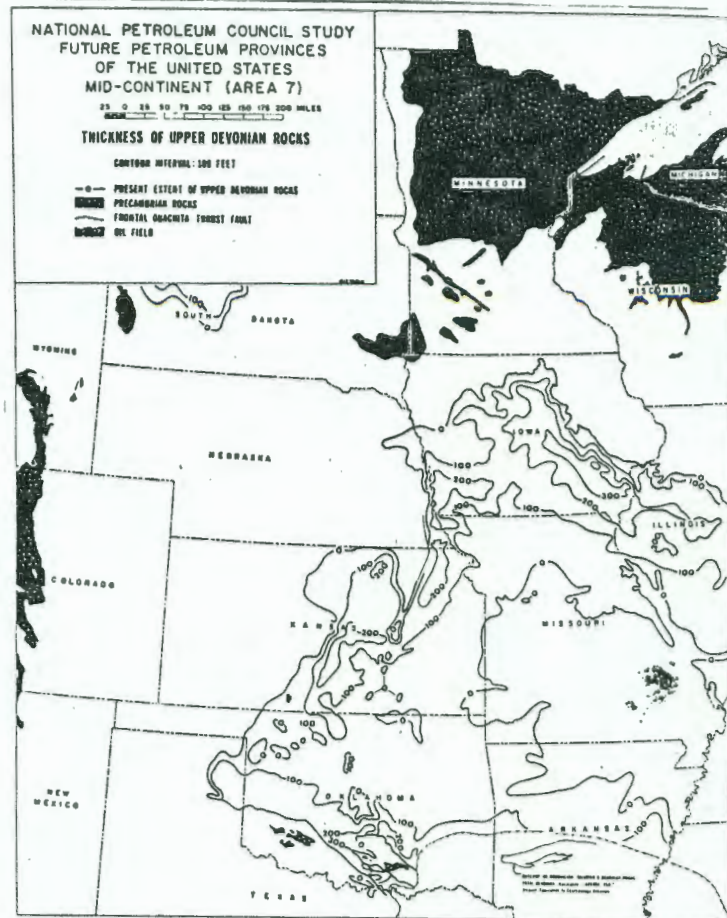
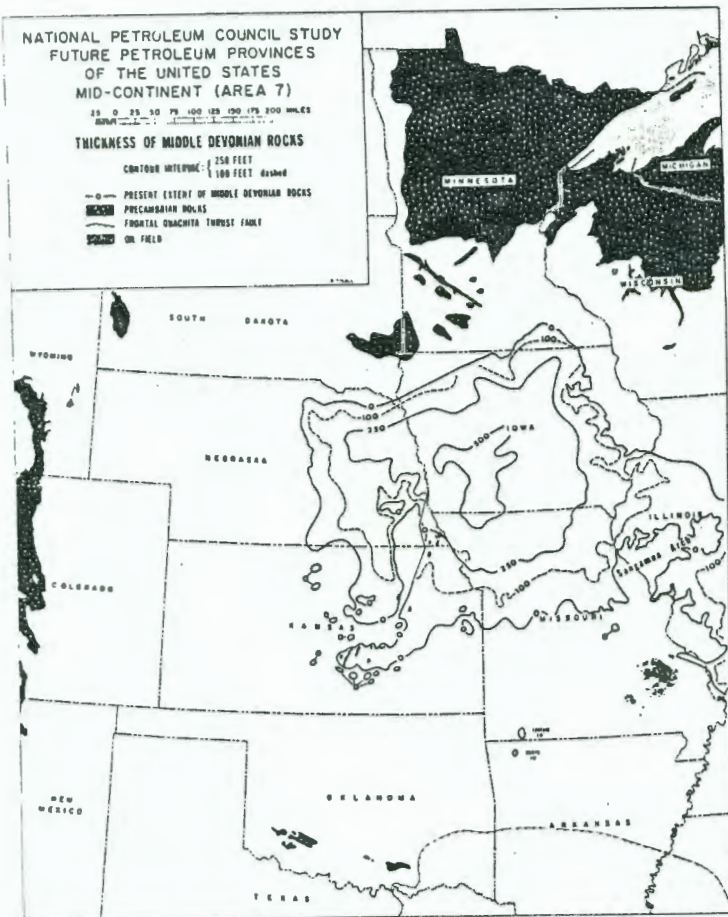


FIG. 3—Thickness (isopachs) and extent of Lower and middle Mississippian rocks in the Mid-Continent (after Adler et al, 1971, Fig. 14). These rocks originally extended throughout the Mid-Continent, thus their absence from various areas is the result of removal following deposition. The patterns show our interpretation of times when Lower and middle Mississippian rocks were removed from positive features in the Mid-Continent. Stratigraphic relationships in Mississippi embayment establish the pre-Upper Cretaceous existence of the Ozark dome-Pascola arch. However, the Ozark dome was also uplifted in post-Mississippian, pre-Pennsylvanian time (McCracken, 1971).

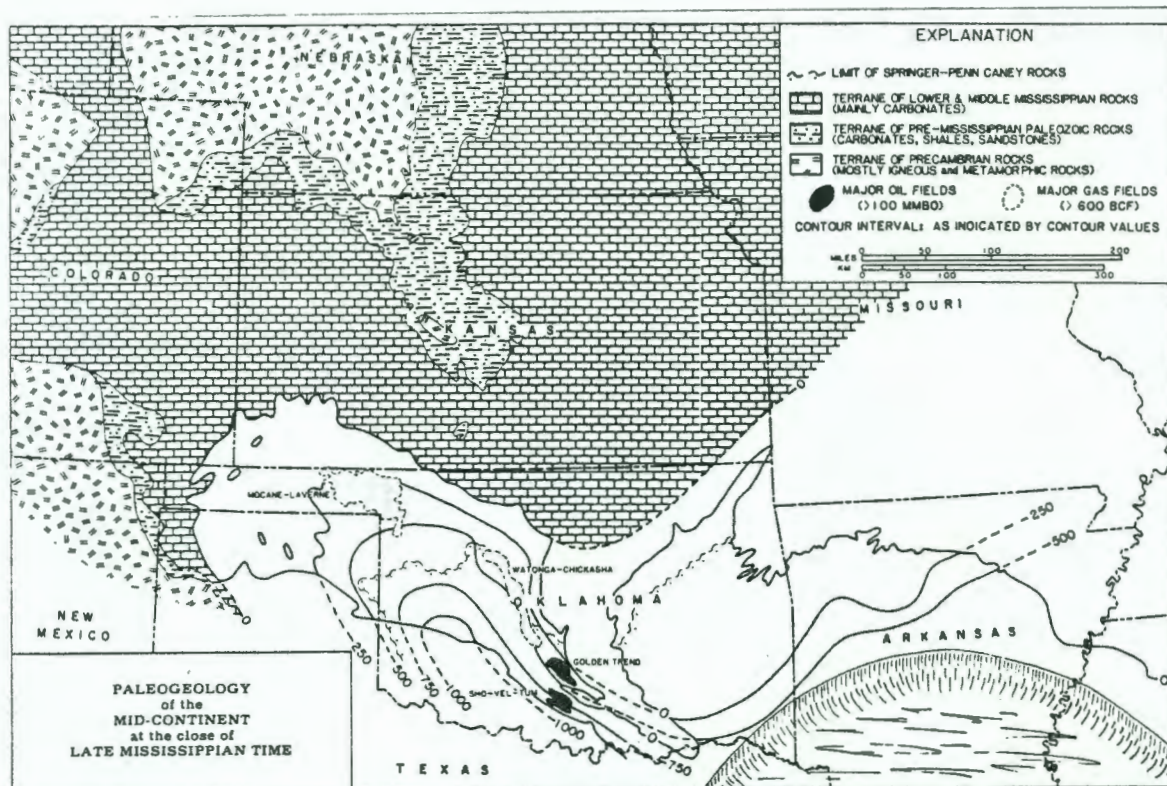
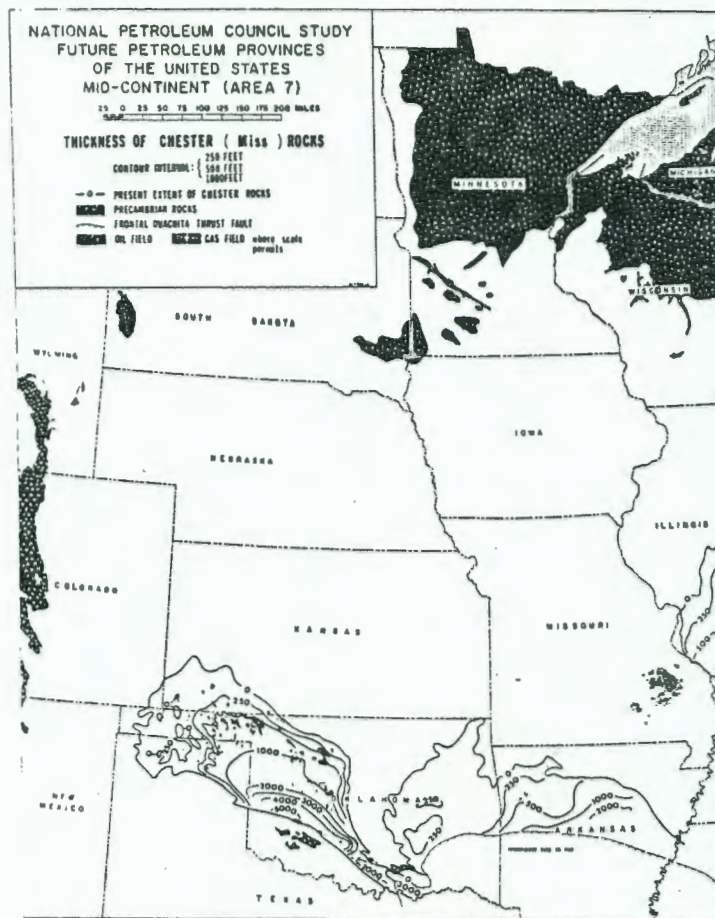
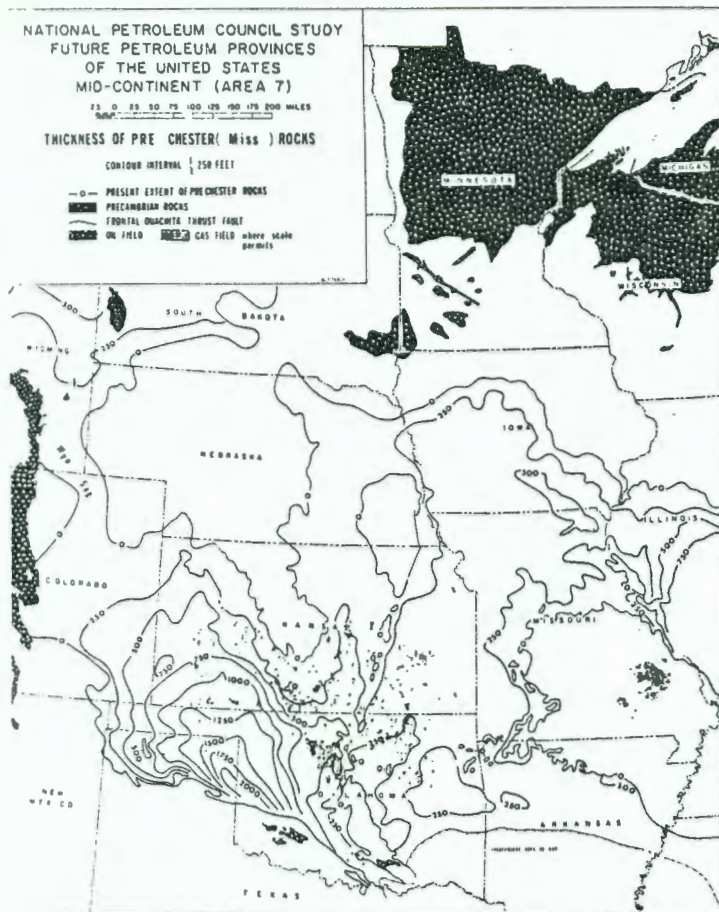


FIG. 4.—Paleogeology of the Mid-Continent at the close of the Late Mississippian, and isopachs of Upper Mississippian rocks. On the northeastern and northwestern margins of the Anadarko basin the limits of Upper Mississippian rocks are the result of post-Mississippian, pre-Morrowan erosion. However, on the northwestern flank of the Arkoma basin and along the Seminole arch the limits of Upper Mississippian rocks are the result of post-Morrowan, pre-Atokan erosion. Although the Ozark dome came into existence at the end of the Late Mississippian, the rocks exposed on the feature cannot be indicated owing to lack of data. The youngest Upper Mississippian rocks are the Springer-Penn Caney sediments.

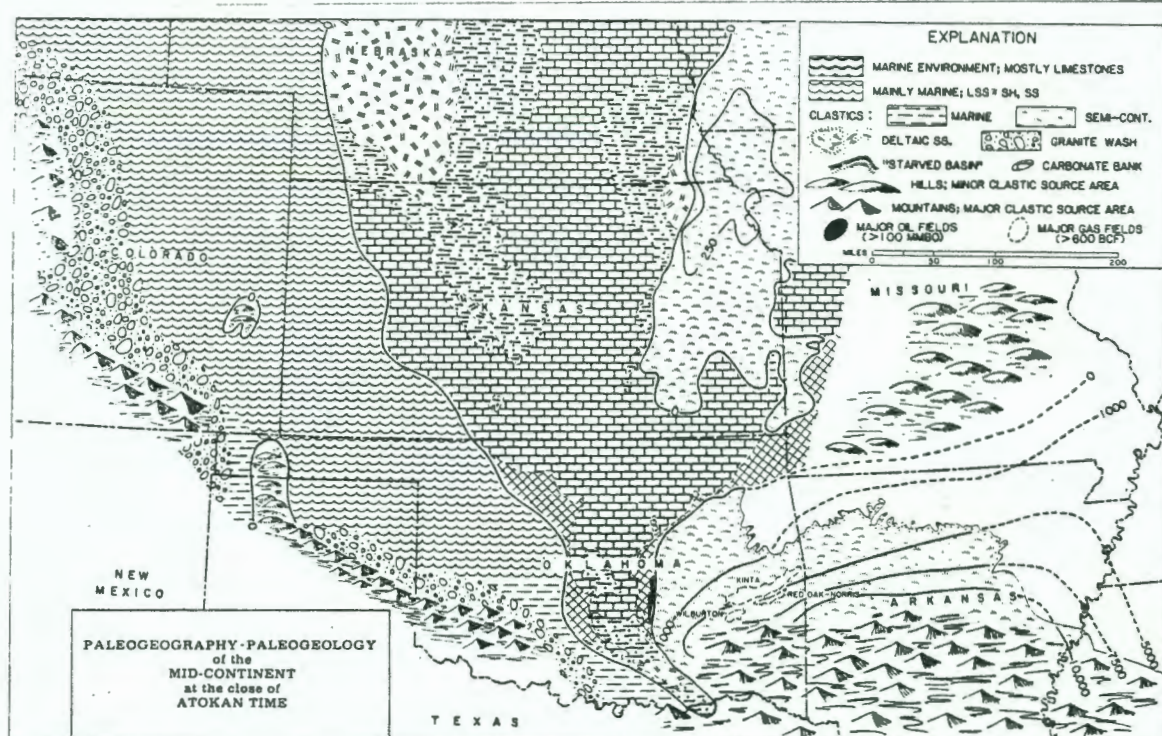
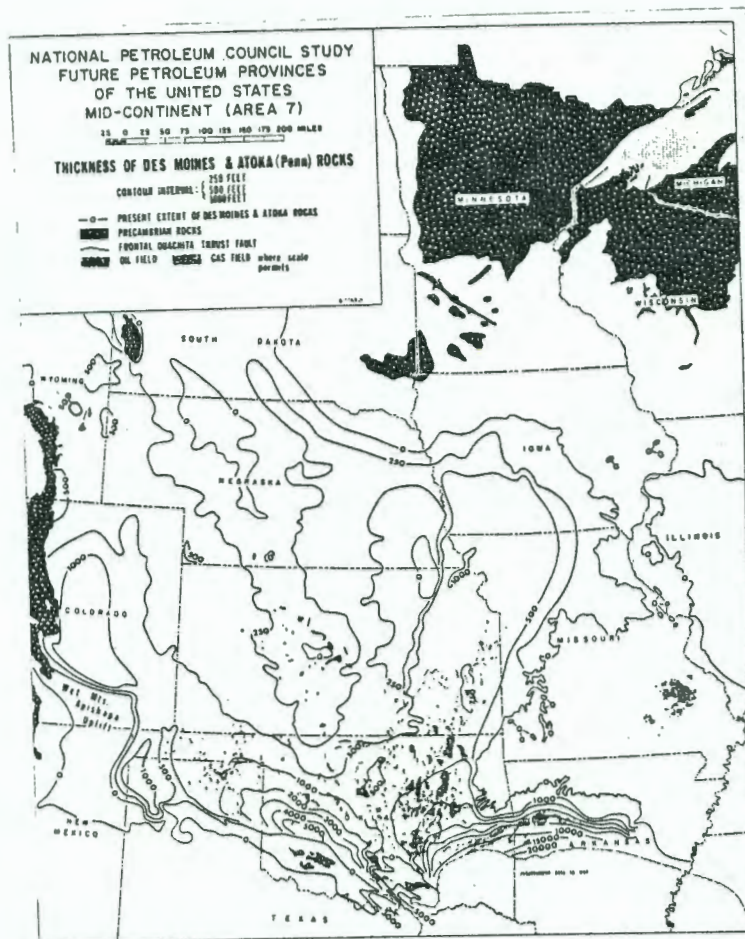


FIG. 6—Paleogeography and paleogeology of the Mid-Continent at the close of the Atokan, and isopachs of Atokan rocks in Arkoma basin. The patterns indicative of pre-Pennsylvanian terranes are shown or explained in Figures 4 and 5. On the eastern flank of the Seminole arch which was not covered by Atokan rocks, the terrane of Morrowan rocks is shown in black. The late Morrowan, early Atokan Ouachita orogeny brought the Ouachita foldbelt, the Amarillo-Wichita, Apishapa, Front Range, and Nemaha uplifts into existence. We postulate that the Ozark uplift was also positive at this time.

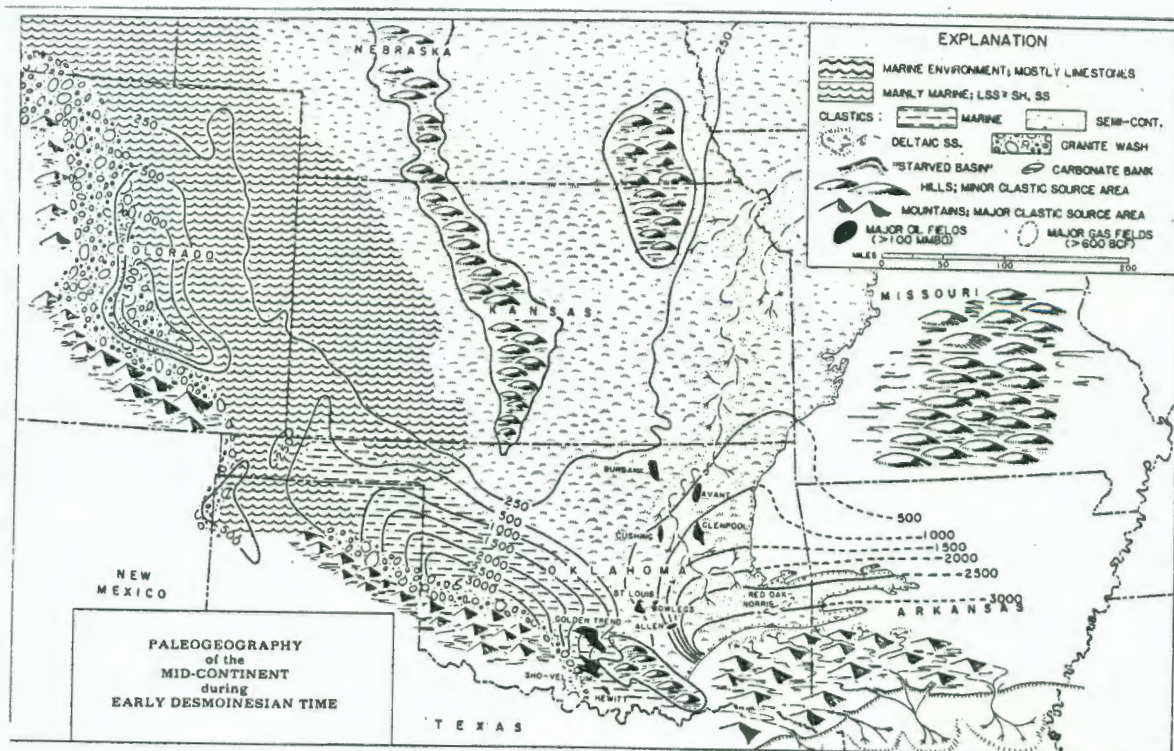


FIG. 7—Paleogeography of the Mid-Continent during the early Desmoinesian, and isopachs of lower Desmoinesian rocks, includes Atokan in Anadarko basin. East of the Nemaha uplift the fluvial-deltaic system of the Bartlesville sandstone is shown. This interpretation is based on the work of Weirich (1953) and Visser and others (1971). During early Desmoinesian time the principal source of sediments lay to the northeast, and sediments were transported into the Mid-Continent by a succession of fluvial-deltaic systems, of which the Bartlesville is typical and is the most important economically. Giant oil accumulations in the Bartlesville Sandstone are the Avant, Cushing, and Glenpool fields.

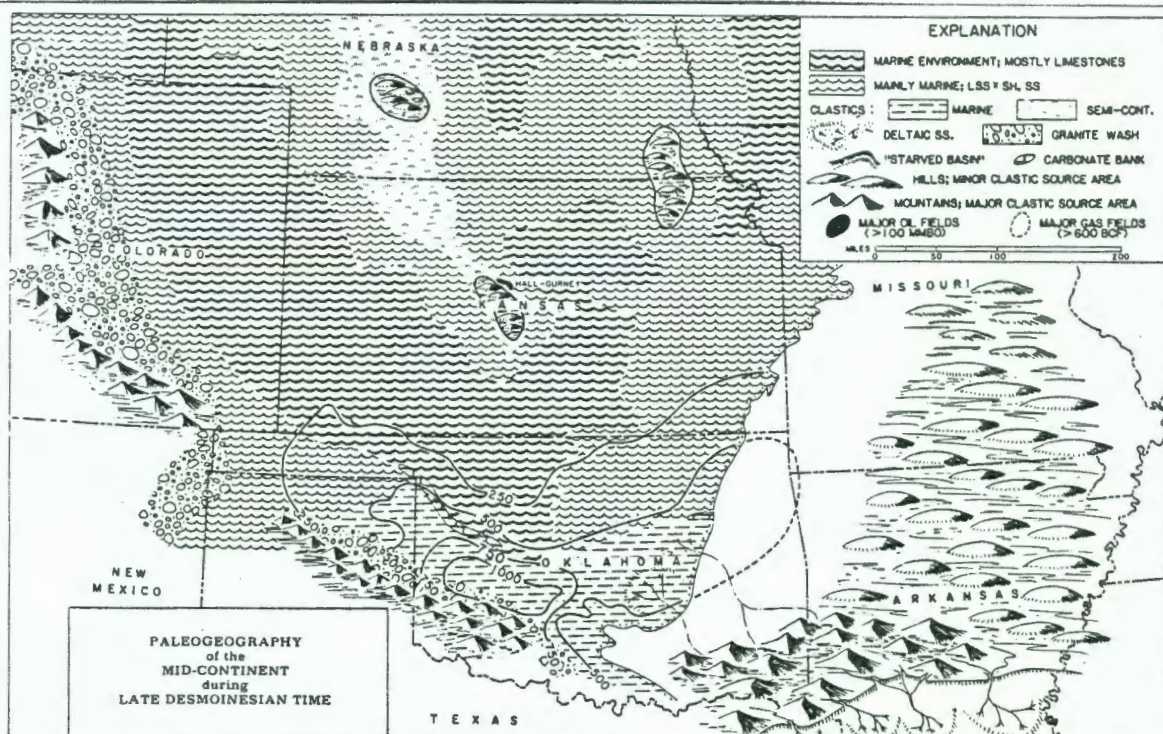


FIG. 8—Paleogeography of the Mid-Continent during the late Desmoinesian, and isopachs of upper Desmoinesian rocks. In the late Desmoinesian time, the Ouachita foldbelt became the principal source of clastics in the southern Mid-Continent (Krumme, 1981). Marine transgression had inundated all but the topographically highest areas of the Central Kansas and Nemaha uplifts.

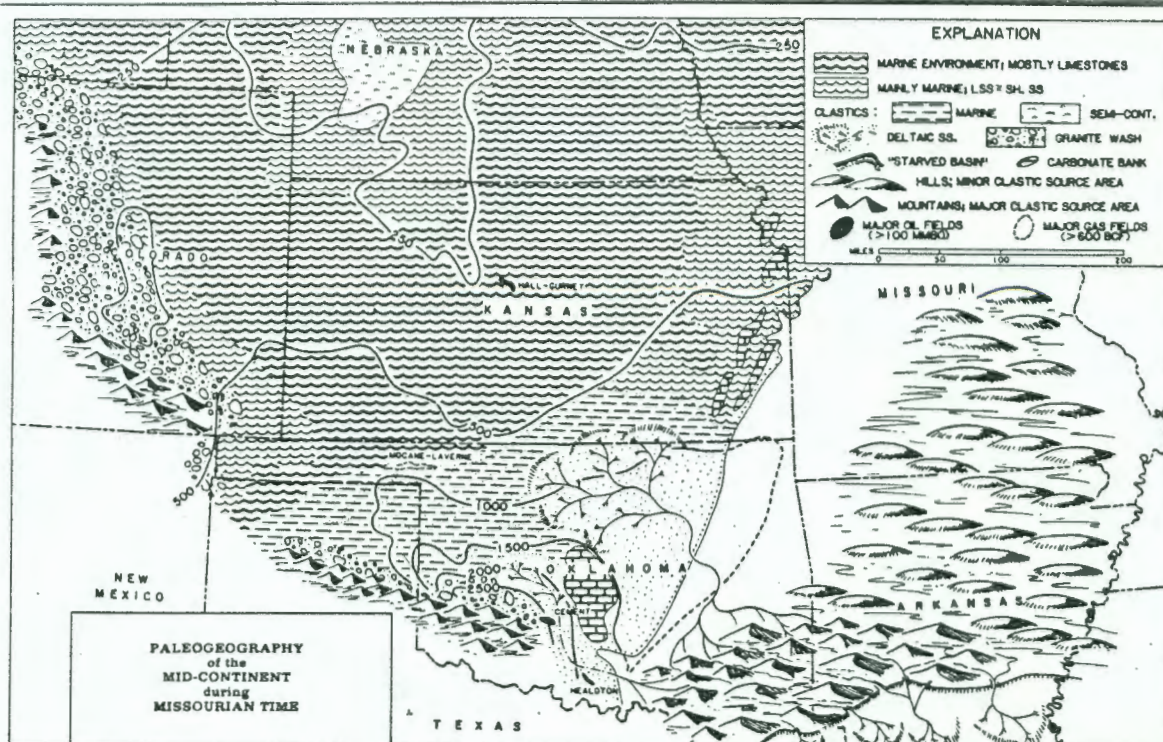


FIG. 9—Paleogeography of the Mid-Continent during the Missourian, and isopachs of Missourian rocks. Carbonate banks of Missourian age are present in eastern Kansas (Heckel, 1977). The extent of the Tonkawa sandstone in the Anadarko basin is shown; we interpret a fluvial-deltaic facies of this formation which is bordered on the north and west by a marine facies. The updip edge of the Tonkawa Sandstone is productive in the Mocane-Laverne field. To the south the extent of the delta-front Medrano Sandstone is indicated. The Medrano Sandstone is the major reservoir in the Cement field (Hermann, 1961). Marine transgression inundated the highest areas of the Central Kansas and Nemaha uplifts in Missourian time.

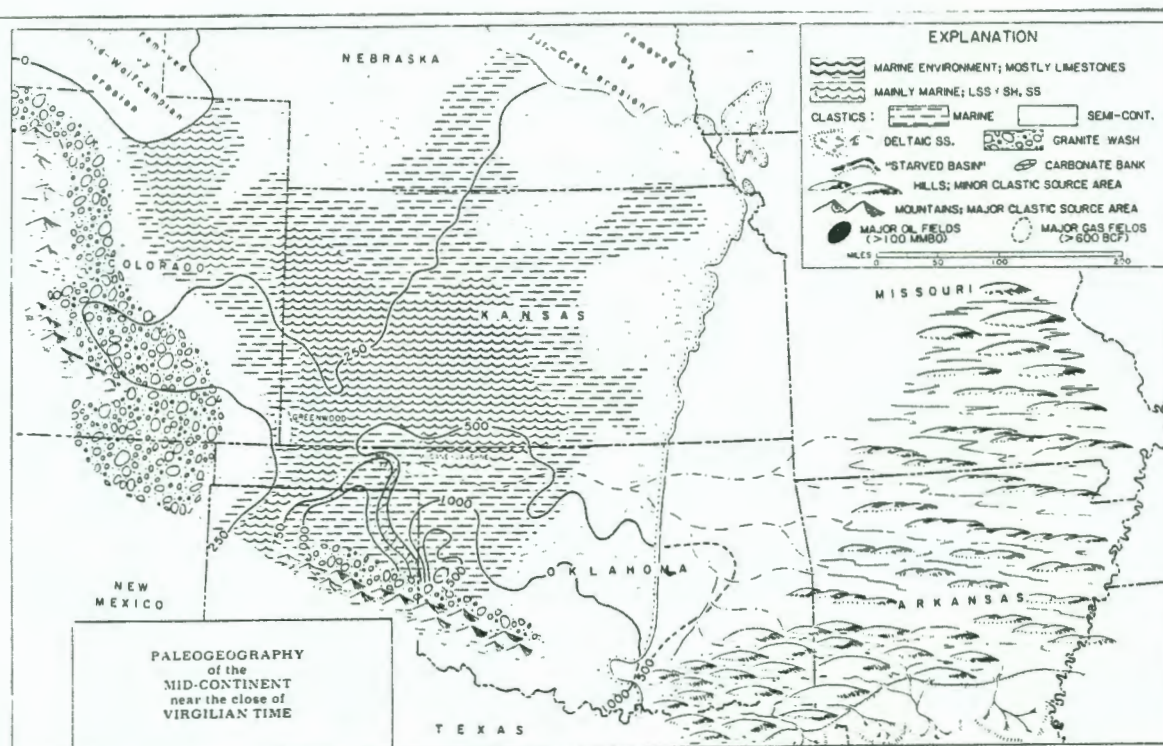


FIG. 10—Paleogeography of the Mid-Continent near the close of the Virgilian, and isopachs of Virgilian rocks. Regressive semi-continental clastics encroached on the Mid-Continent from the east and north. The "starved" Anadarko basin occupied the Texas and Oklahoma Panhandles (Rascoe, 1978). The Laverne-Hoover Sandstone is a reservoir in the Mocane-Laverne gas field. The Ouachita foldbelt had become greatly reduced in topographic elevation near the close of Virgilian time.

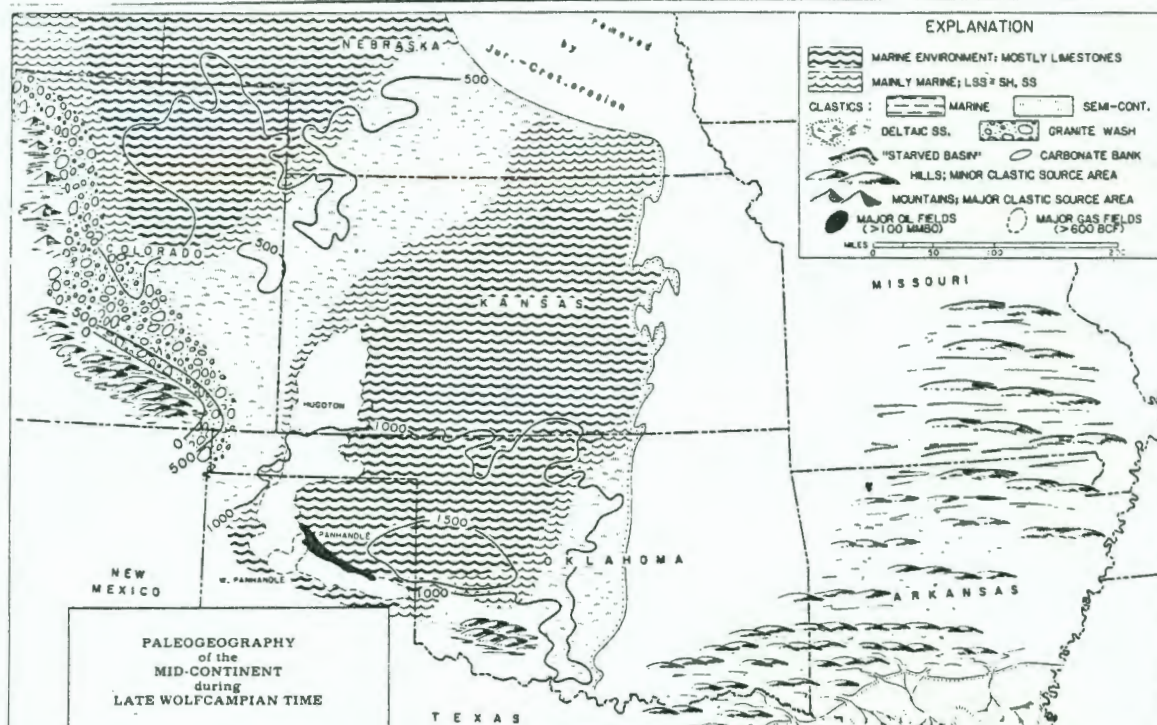
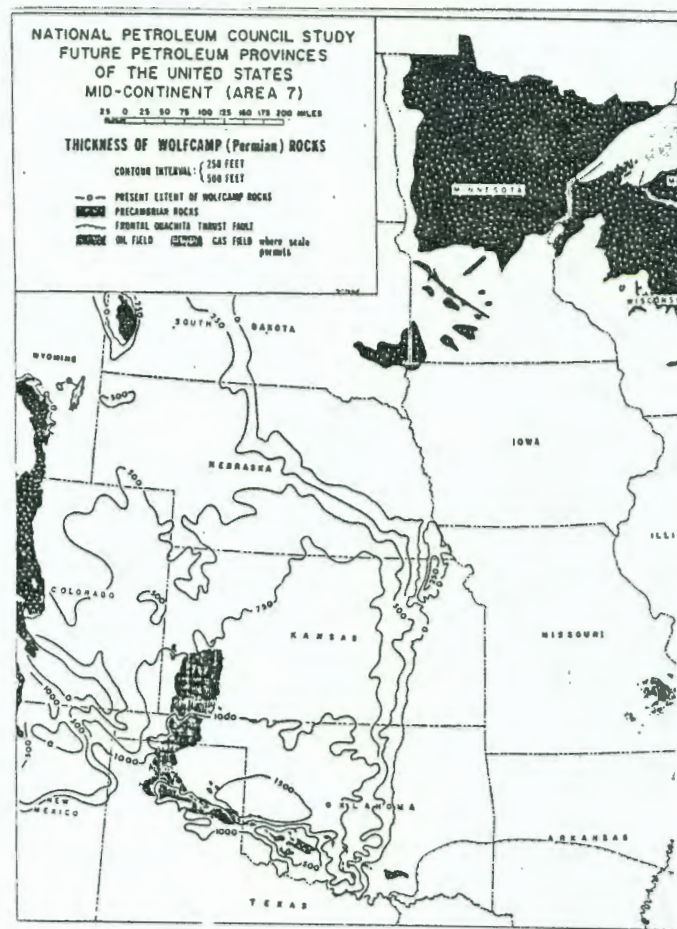
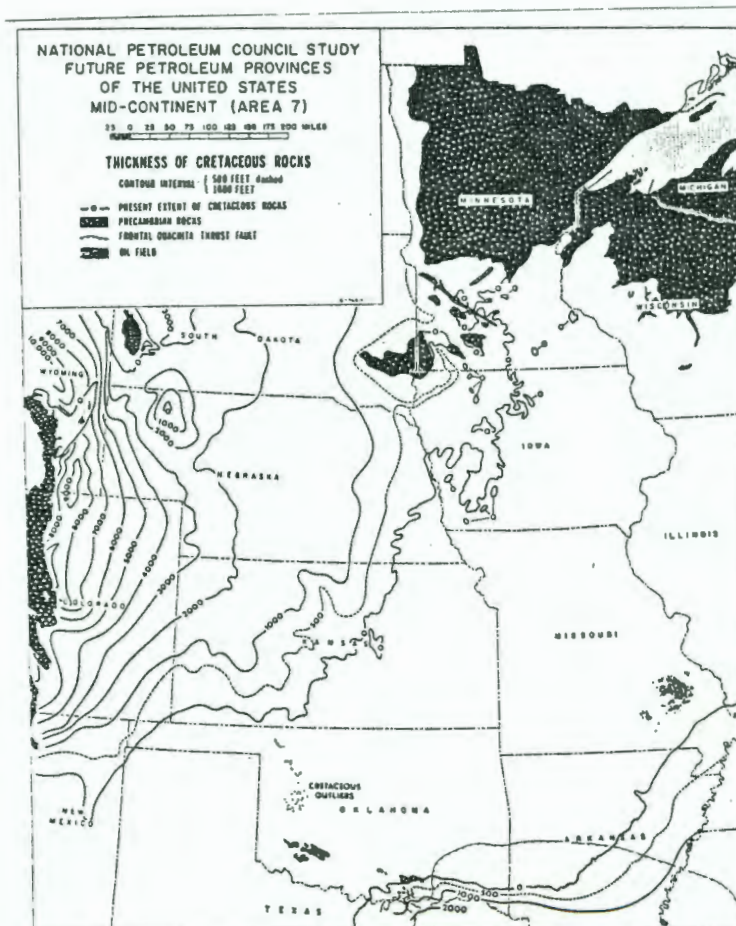
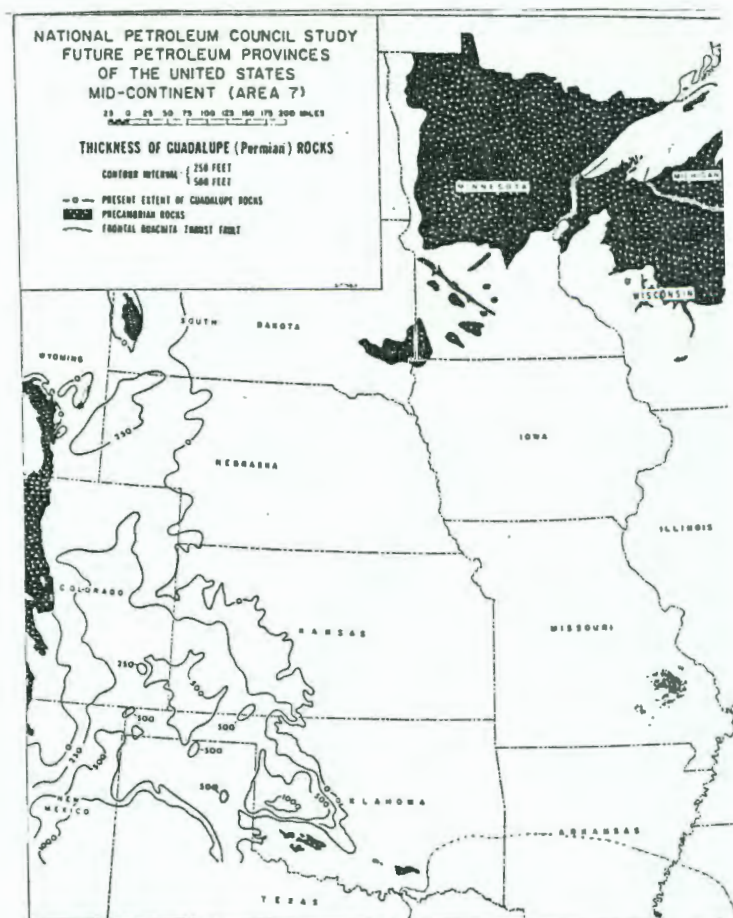
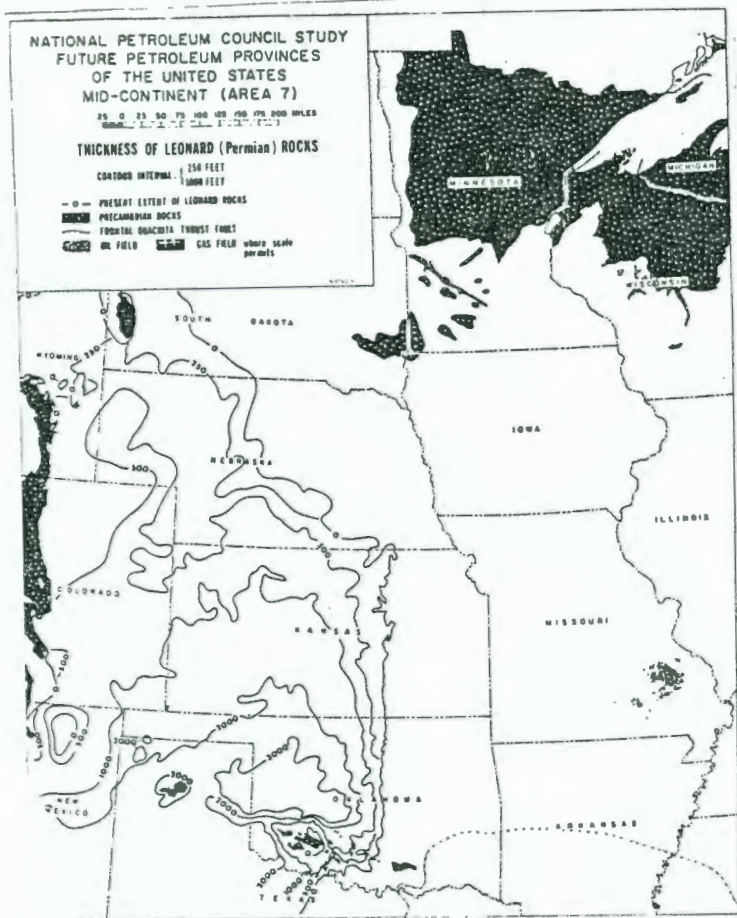


FIG. 11—Paleogeography of the Mid-Continent during the late Wolfcampian, and isopachs of Wolfcampian rocks. The Anadarko "basin" was covered by shelf carbonates of late Wolfcampian age. These carbonates grade upland into semi-continental clastics to the west, and this facies change forms the trap for the giant Hugoton gas field (Pippin, 1970). The oil and gas accumulations in the Panhandle field are associated with the Amarillo uplift. "W. Panhandle" outlines the accumulation in the Red Cave sandstone of Leonardian age.



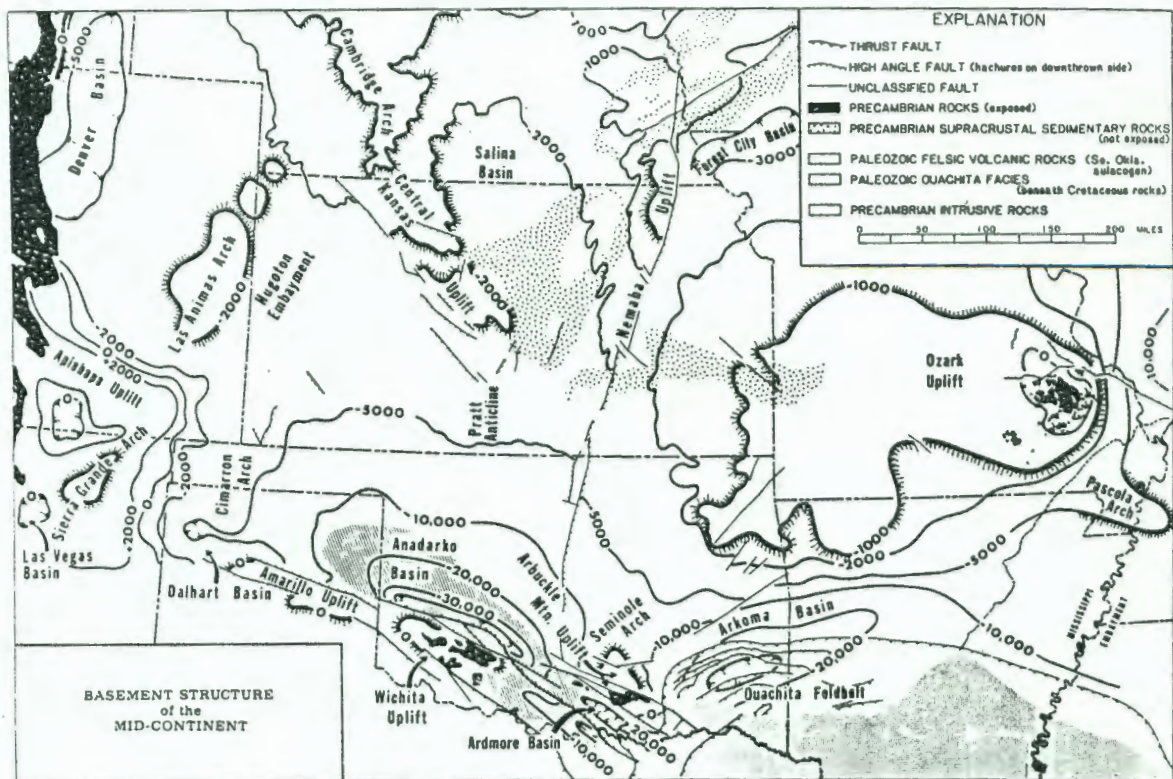


FIG. 1—Basement structure of the Mid-Continent (after Adler et al, 1971, Fig. 3).

**NATIONAL PETROLEUM COUNCIL STUDY
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MID-CONTINENT (AREA 7)**

THICKNESS OF CAMBRIAN & LOWER ORDOVICIAN ROCKS

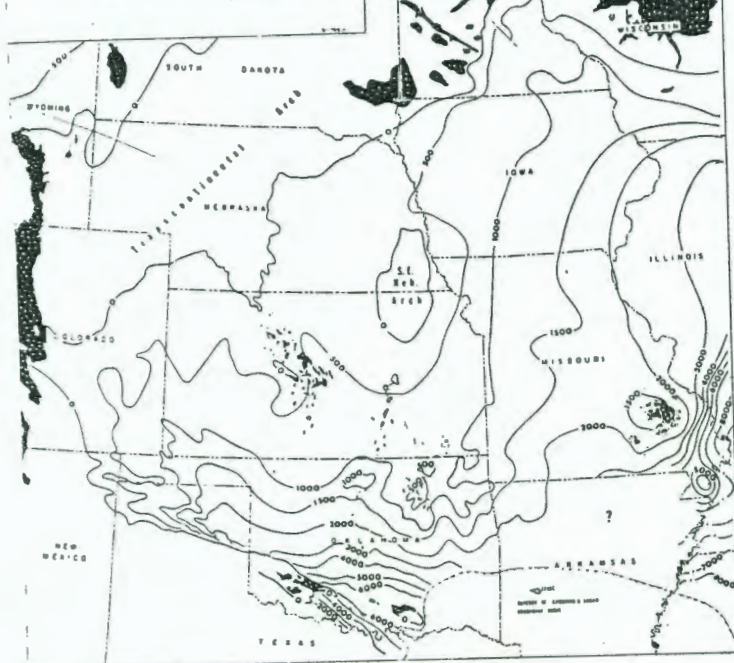
CONTOUR INTERVAL: 500 FEET
1000 FEET

— 0 — PRESENT EXTENT OF LOWER MIDDLE ORDOVICIAN ROCKS

PRECAMBRIAN ROCKS

FRONTAL QUACHITA THRUST FAULT

OIL FIELD GAS FIELD where scale permits



**NATIONAL PETROLEUM COUNCIL STUDY
FUTURE PETROLEUM PROVINCES
OF THE UNITED STATES
MID-CONTINENT (AREA 7)**

THICKNESS OF LOWER MIDDLE ORDOVICIAN ROCKS

CONTOUR INTERVAL: 100 FEET dashed
500 FEET

— 0 — PRESENT EXTENT OF LOWER MIDDLE ORDOVICIAN ROCKS

PRECAMBRIAN ROCKS

FRONTAL QUACHITA THRUST FAULT

OIL FIELD GAS FIELD where scale permits

