# PHANEROZOIC HISTORY OF THE CENTRAL MIDCONTINENT UNITED STATES

by

Bill J. Bunker, Brian J. Witzke, W. Lynn Watney,

and Greg A. Ludvigson

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TABLE OF CONTENTS


| | PAGE NO. |
|---|---|
| Introduction | 1 |
| Precambrian Basement Framework | 1 |
| Sauk Sequence | 3 |
| Cambrian | 3 |
| Lower Ordovician | 6 |
| Sub-Tippecanoe Erosional Surface | 7 |
| Tippecanoe Sequence | 7 |
| Middle and Upper Ordovician | 7 |
| Silurian | 12 |
| Pre-Kaskaskia Erosional Episode | 14 |
| Kaskaskia Sequence | 15 |
| Devonian | 15 |
| Mississippian | 19 |
| Pre-Absaroka Erosion Cycle | 21 |
| Absaroka Sequence | 22 |
| Pennsylvanian | 22 |
| Permian | 26 |
| Sub-Zuni Erosional Surface | 28 |
| Zuni Sequence | 28 |
| Jurassic | 28 |
| Cretaceous | 29 |
| Sub-Cenozoic Erosional Surface and Structure | 32 |
| Cenozoic Nonmarine Deposition | 32 |
| Phanerozoic Igneous Activity | 35 |
| Concluding Remarks | 36 |
| Acknowledgements | 39 |
| References | 43 |

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## Introduction

The region of the central midcontinent has commonly been termed the "stable interior" of the North American continent. The magnitudes of Phanerozoic crustal deformation in the cratonic interior certainly are very small compared to those known from active continental margins, and the rates of deformation have been generally slower (Schwab, 1976). Nevertheless, the Phanerozoic sedimentary record in the central midcontinent region is replete with evidences of tectonic activity of surprising diversity and pattern. The central midcontinent, as defined for this report, includes Iowa, Kansas, southeastern South Dakota, Nebraska (excluding the panhandle), southern Minnesota, and Missouri north of 37°N latitude.

The Phanerozoic stratigraphic record in the central midcontinent region of North America is divided into six major depositional sequences, each bounded by major interregional unconformities (Sloss, 1963). The structural and stratigraphic development of this region is evaluated utilizing a series of isopach and paleogeologic maps constructed within the general framework of Sloss' (1963) cratonic sequences (text fig. 1).

Text Figure #1 near here

## Precambrian Basement Framework

Phanerozoic sedimentary rocks in the central midcontinent region are underlain by Archaean and Proterozoic igneous, sedimentary, and metamorphic rocks. The Midcontinent Rift System (MRS), which bisects the midcontinent, is one of several prominent structural features evident in the Precambrian basement complex of this region (Pl. 3, fig. 1). Prominent gravity and magnetic anomalies and drillhole data document extension of the MRS southwestward from Lake Superior beneath the Paleozoic cover into northeastern Kansas (King and Zietz, 1971; Van Schmus and Hinze, 1985). Basalts, related mafic intrusions, and thick sedimentary rock sequences characterize this Keweenawan rift system. Offsets of the MRS near the Nebraska-Kansas and Iowa-Minnesota borders have been interpreted as possible transform faults (Chase and Gilmer, 1973) associated with development of the MRS. The central area of the MRS was uplifted during the Late Proterozoic, dramatically reorganizing the structure and creating a complex fault-bounded horst system along its axis (Craddock, 1972; Anderson and Black, 1982). Phanerozoic faulting and flexuring along the southern margin of the central horst area attest to continued structural activity along Precambrian basement structures associated with the MRS.

The Chadron and Cambridge arches of Nebraska and the Central Kansas Uplift (Pl. 3, fig. 1) are part of a north-northwest trending Precambrian structural high (Black Hills-Central Kansas Uplift, Muehlberger et al., 1967) along the western margin of the study area. This basement feature appears to have remained structurally positive with respect to adjacent areas throughout much of the Phanerozoic. The central area of this feature (i.e. Chadron and Cambridge arches) cuts across a portion of the north-northeast trending Transcontinental Arch (Pl. 3, fig. 2) , a broad midcontinent Phanerozoic structural feature.

The Sioux Ridge (Pl. 3, fig. 1), a prominent Precambrian paleotopographic feature, cuts diagonally across the crest of the Transcontinental Arch. The ridge forms an east-west trending feature occupied by a broad synclinal fold of Proterozoic Sioux Quartzite, which was more resistant to erosion than the flanking older Precambrian basement units (Baldwin, 1949; Bunker, 1981). Phanerozoic rock units have onlapped and overstepped the ridge repeatedly, only to be erosionally stripped back during periods of emergence.

The area between the Sioux Ridge and the Black Hills-Central Kansas Uplift served as an intermittent seaway connection (Nebraska Sag, Adler et al., 1971; Pl. 3, fig. 3) between the Williston Basin and the central midcontinent during various intervals in the Paleozoic. At times, seas appear to have migrated around the northern flank of the Sioux Ridge connecting with the eastern Iowa area.

## Sauk Sequence

Sauk Sequence rocks were deposited in the central midcontinent during the Cambrian and Early Ordovician (text fig. 1).

Cambrian. Sauk deposition was initiated over most of the area during the Late Cambrian, although thick basal Sauk sandstone sequences in portions of Illinois and Iowa probably include older Cambrian strata. The basal Sauk sandstone interval, assigned to the Mt. Simon Sandstone, reaches a thickness in excess of 750 m in northeastern Illinois and ranges from 150 to 450 m across most of eastern and central Iowa. The Mt. Simon thins abruptly against the southeastern margin of the central horst of the MRS in Iowa. Across western Iowa, Missouri, Nebraska, and Kansas, the basal Sauk sandstone sequence (variably assigned to the Lamotte, Reagan, or Mt. Simon Ss) is markedly thinner (10-100 m) and is locally absent over topographic highs on the Precambrian surface. In general, regional thickness patterns of the basal Sauk sandstone interval "appear to be unrelated to that of overlying" Sauk strata (Howe et al., 1972, p. 51).

The Precambrian surface had significant relief prior to burial by Sauk rocks: up to 450 m in the Ozark-St. Francois Mountains area of Missouri (Chenoweth, 1968), up to 500 m across the MRS in central Iowa, and knobs with up to 200 m of relief in Kansas (especially along 38°N). Most of the Precambrian surface in the central midcontinent was buried during the Sauk II interval (Palmer, 1981), although some topographic and structural features remained emergent until later Sauk deposition. Structural patterns developed during deposition of the post-Mt. Simon Sauk interval are reflected on the regional isopach map (Pl. 3, fig. 2). In general, the Sauk Sequence thickens southeastward across the study area toward the present-day Illinois Basin and Ozark Uplift area. Northward from the region of maximum Sauk subsidence in the Illinois and "Ozark basin" (Lee, 1943, 1956) areas, the Hollandale Embayment represents an axis of Sauk thickening which trends across eastern Iowa into southern Minnesota. Broad positive structural elements reflected on the Sauk isopach map include the Southeast Nebraska Arch, Transcontinental Arch, and Wisconsin Dome (with its southward extending arch). A broad Precambrian upland area, "ancestral to the central Kansas uplift" (Chenoweth, 1968, p. 1683), occupied the central part of Kansas during the Cambrian. As suggested by Keroher and Kirby (1948), this positive structural feature may not have been buried by Sauk deposits until the Early Ordovician.

The Sauk Sequence in the central midcontinent is characterized by a series of depositional cycles (Ostrom, 1970). The first major cycle spread marine and marginal marine deposits across most of the study area during the Dresbachian. Following deposition of the basal Cambrian sandstone, a series of broad marine facies became established in the area by the middle to late Dresbachian: 1) predominantly sandstone in eastern Minnesota and Wisconsin (Eau Claire Fm), 2) mixed facies of siltstone, shale, sandstone, and minor carbonate across eastern Iowa and northeastern Missouri (Eau Claire Fm), and 3) carbonate-dominated facies with some shale and siltstone across central and western Iowa and much of Missouri (Bonneterre Fm). The Wisconsin Dome area and/or nearby regions on the Canadian Shield were the primary clastic source terranes. Potential sources of detrital materials include Keweenawan sediments (especially sandstones) and Precambrian granitic and other igneous/metamorphic rocks. The broad exposed crystalline terrane on the Transcontinental Arch apparently supplied comparatively little clastic material to the adjacent seaway during Sauk deposition.

Keroher and Kirby (1948), Lochman-Balk (1971), and Chenoweth (1968) correlated supposed late Dresbachian carbonate strata (Bonneterre) across eastern Kansas, and suggested that "Franconian and early Trempealeauan" strata are "absent over most" of Kansas (Chenoweth, 1968, p. 1676). However, the discovery of Franconian fossils in the basal Cambrian sandstone of southwestern Missouri indicates that "the Bonneterre Formation is not present" in the area (Kurtz et al., 1975, p. 19). Instead, the basal Cambrian sandstone-carbonate succession in eastern Kansas may represent a sequence of Franconian sediments that lapped northwestward onto the margins of the ancestral Central Kansas Uplift. However, Dresbachian strata are present in western Kansas (Chenoweth, 1968). Basal Sauk relations are not known with certainty in Nebraska, although Dresbachian units present in western Iowa have been tentatively correlated into eastern Nebraska (Carlson, 1969). The late Dresbachian was marked by a significant regressive event, and a disconformity (Sauk II/Sauk III boundary; Palmer, 1981) apparently formed at the top of the Dresbachian interval over large portions of the central midcontinent.

In a general sense, younger Sauk depositional cycles resemble the Dresbachian pattern, although carbonate-dominated facies are more widespread during the Trempealeauan and Canadian. The Franconian-Trempealeauan cycle was initiated with deposition of a basal sandstone interval in Wisconsin, northern Illinois, Minnesota, and eastern Iowa (Ironton Ss, Wonewoc Fm) and eastern Kansas (Lamotte or Reagan Ss). Several broad facies tracts characterize subsequent Franconian deposition: 1) primarily glauconitic sandstones in Wisconsin and adjacent areas of Minnesota, Iowa, and Illinois (Lone Rock Fm, Franconia Fm); 2) a mixed facies belt, primarily characterized by siltstone, shale, and dolomite, across much of

Iowa and Missouri (Davis Fm); and 3) carbonate-dominated facies in southwestern Iowa, eastern Nebraska, western Missouri, and Kansas (Davis Fm, lower "Arbuckle Gp"). Carbonate-dominated facies expanded across much of Missouri and Iowa during the late Franconian and earliest Trempealeauan (Derby-Doerun Fms).

Most of the central midcontinent area was covered by a carbonate facies during the Trempealeauan (St. Lawrence Fm, Potosi Fm). The late Trempealeauan and earliest Canadian generally marked a period of significant marine offlap during which sandstone units prograded off the Wisconsin Dome area across much of Minnesota, Iowa, and northeastern Missouri (Jordan Ss, Momence Ss). Coeval carbonate and sandy carbonate facies (Eminence Fm) are present across western Iowa, eastern Nebraska, and much of Missouri, extending westward to the edge of the ancestral Central Kansas Uplift (Keroher and Kirby, 1948). As reported by many workers, maximum regression, generally coincident with the Cambrian-Ordovician boundary, was apparently marked by development of a disconformity over portions of the central midcontinent.

Lower Ordovician. A widespread sandstone and sandy carbonate interval probably represents the basal unit of the succeeding Lower Ordovician depositonal cycle across much of the central midcontinent (upper Jordan and/or basal Oneota Fm in eastern Iowa, Minnesota, Wisconsin; Gunter Ss in Missouri, western Iowa, eastern Nebraska, and northeastern Kansas). Relatively pure carbonate deposition dominated the remainder of the cycle across most of the study area (Oneota Fm in Minnesota, Wisconsin, Iowa, Illinois; Gasconade Fm in Nebraska, Kansas, Missouri). These deposits apparently onlapped Precambrian granites in south-central Kansas (Keroher and Kirby, 1948). The final regressive phase of this cycle was marked by development of an unconformity over portions of the midcontinent, especially in the Wisconsin Dome area (Ostrom, 1970) and eastern Kansas (Keroher and Kirby, 1948). The succeeding cycle was initiated with widespread deposition of a basal sandstone and/or sandy carbonate sequence (New Richmond Ss in Wisconsin, Iowa, Minnesota, Illinois; Roubidoux Fm in Missouri, Nebraska, and Kansas). Roubidoux sediments buried the Precambrian upland surface in central Kansas (ibid.). Subsequent deposition was dominated by carbonates, although deposition of sandy carbonate and minor sandstone is noteworthy (Shakopee Fm in Wisconsin, Minnesota, Iowa, Illinois; Jefferson City-Cotter Fms in Missouri, Kansas). Later Sauk carbonate and sandy carbonate deposition is documented in southeastern Missouri (Powell and Smithville Fms), although equivalent units are absent over most of the central midcontinent due to non-deposition (?) and/or extensive pre-Tippecanoe erosional stripping.

## Sub-Tippecanoe Erosional Surface

A prolonged period of erosion, including the Whiterockian and portions of the Chazyan and late Canadian, separated deposition of the Sauk Sequence from the overlying Tippecanoe Sequence over most of the central midcontinent (Witzke, 1980). The vast sheet of Sauk rocks, primarily dolomite, that was deposited over the area was eroded marginally and around structurally positive features (Wisconsin Arch, Southeast Nebraska Arch). The exposed carbonates were subjected to karstification and valley formation to varying degrees. Prominent karst sinkholes and valleys, up to 200 m deep, are best developed in Kansas (Merriam and Atkinson, 1956), northern Illinois (Buschbach, 1964), northern and western Missouri, eastern Iowa, and Wisconsin. The youngest Sauk stratigraphic units are preserved in the structural depression coinciding with the southern Illinois and "Ozark basin" area. Sauk strata were erosionally stripped from the crest of the Southeast Nebraska Arch, where Precambrian crystalline and clastic rocks form the sub-Tippecanoe surface.

## Tippecanoe Sequence

Middle and Upper Ordovician. In general, the initial Whiterockian phases of

Tippecanoe deposition (text fig. 1) were restricted to regions of maximum late Sauk subsidence. Whiterockian sandy carbonates and sandstones (Everton Fm) were deposited on the eroded Sauk surface in southeastern Missouri and southern Illinois. Whiterockian strata also occur as far north as the Oklahoma-Kansas border area (Oil Creek Fm of Simpson Gp). However, Whiterockian strata were not deposited over the remainder of the central midcontinent, where erosion remained the dominant process.

As Middle Ordovician seas onlapped into the central midcontinent area during the Chazyan, the underlying erosion surface was buried beneath a time-transgressive sheet of St. Peter Sandstone (Dapples, 1955). Sporadically distributed sections of exceptionally thick (greater than 200 m) St. Peter Sandstone represent clastic-filled karst features and valleys on the pre-Tippecanoe erosion surface (Witzke, 1980). The great purity and maturity of the St. Peter quartz arenites over much of the midcontinent suggest that a substantial portion of the St. Peter sand was derived from earlier generation Sauk and Keweenawan quartz sandstones. The St. Peter shoreline spread onto the margins of the Transcontinental Arch and across most or all of the Southeast Nebraska Arch, apparently by the late Chazyan or early Blackriveran. In those areas (i.e., Nebraska, northwestern Iowa, and southeastern Minnesota), the St. Peter Sandstone is locally argillaceous and silty with interbedded fossiliferous brown and green shales (ibid.). The St. Peter includes shales and oolitic ironstones across portions of northern Kansas (Leatherock, 1945) and southeastern Nebraska. It extends northwestward from north-central Nebraska (Carlson, 1969) to join with basal Winnipeg clastics in South Dakota. These Middle Ordovician deposits trend directly across the Transcontinental Arch paralleling the southern margin of the Sioux Ridge along the Nebraska Sag (Pl. 3, fig. 3).

An extensive sandstone body, probably of Blackriveran age, that trends across northern Illinois, southeastern Iowa, and northern Missouri is termed the Starved Rock Sandstone (Fraser, 1976). The thin Glenwood Shale unit interfingers with the Starved Rock Sandstone on its northern margin and trends across Iowa, Minnesota, and Wisconsin. Contemporaneous carbonate and evaporite facies (Joachim Fm) are noted south of the Starved Rock Sandstone body in Illinois and eastern Missouri.

Marine carbonate sediments were deposited across the eastern portion of the central midcontinent following St. Peter-Glenwood deposition (Plattin Ls, Platteville Fm). Correlative strata in the western and northern portions of the study area include significant quantities of terrigenous clastic material, commonly green or brown shales and varying quantities of sandstone, reflecting proximity to source terranes along the Transcontinental Arch and in portions of Kansas (Leatherock, 1945; Sloan, 1972; Witzke, 1980). The overlying Decorah Formation undergoes significant facies variations in the central midcontinent: 1) the Decorah in northwestern Iowa and Minnesota is primarily a shale unit with scattered limestone interbeds; 2) the Decorah in eastern Iowa and Missouri is primarily a carbonate unit with some shale; 3) Decorah or upper Simpson strata in portions of southwestern Iowa, Nebraska, and Kansas include carbonates, shales, and sandstones. The northwestward increase in Decorah shale thicknesses in Iowa and Minnesota identifies the Transcontinental Arch as the source area (Witzke, 1980). Decorah sedimentation was succeeded by "Trentonian" carbonate deposition across the central midcontinent (Galena Gp, Kimmswick Ls, "Viola" Fm). The Decorah-Galena boundary is a diachronous facies transition in Iowa and Minnesota, and the upper Decorah in the region bordering the Transcontinental Arch is a contemporaneous facies to lower Galena carbonates in areas away from the arch (ibid.).

Continued marine transgression during the late Middle and early Late Ordovician inundated vast areas of the midcontinent. "Viola" carbonates overstepped the Simpson edge in northwestern Kansas (Cole, 1975) and portions of the ancestral Central Kansas Uplift. Large areas of the Transcontinental Arch also were submerged, reducing clastic influx to the epeiric sea and allowing Galena carbonate sedimentation to become more prevalent. Ross (1976, p. 91) termed this "the greatest inundation in North American history." Galena-"Viola" carbonate strata are generally characterized by skeletal wackestones/packstones and/or fossiliferous dolomites containing varying quantities of chert. For the most part, complex dolomite and limestone facies patterns do not parallel depositional patterns but are secondary diagenetic features (Witzke, 1983a).

A general reorganization of Sauk structural patterns occurred during the Middle Ordovician. The southward thickening of Platteville/Plattin strata in Illinois and eastern Missouri resembles Sauk isopach trends, although the northward trending axis of Sauk thickening (Hollandale Embayment) was disrupted by Middle and Late Ordovician uplift of a broad arch trending north from the Ozark region across northern Missouri and southeastern Iowa (Pl. 3, fig. 3) termed the Northeast Missouri Arch (Bunker, 1981). However, the northern extension of the Hollandale Embayment in northeastern Iowa and southern Minnesota remained an area of increased subsidence during the Middle Ordovician, where the thickest sequences of Galena Group strata in the central midcontinent are preserved (Witzke, 1983a). Positive structural elements, the Transcontinental and Wisconsin arches, flanked the embayment. Middle Ordovician strata thin southwestward across Iowa approaching the area of the Southeast Nebraska Arch. Pronounced upwarping of the Ozark Uplift during deposition of the Galena/Kimmswick sequence resulted in erosional beveling of these carbonate strata around the uplift prior to Maquoketa deposition (Templeton and Willman, 1963). The emergence of the Ozark Uplift during Tippecanoe deposition marked the destruction of the older Sauk "Ozark basin." Tippecanoe development of the Chautauqua and Northeast Missouri arches was generally coincident with that of the Ozark Uplift. "Viola" strata thin toward the Chautauqua Arch in Kansas. Numerous bentonites in the Middle Ordovician sequence of Minnesota, Iowa, Illinois, and Missouri (Kolata, 1983) originated from volcanic sources associated with the newly emerging Taconic Mountains, presaging Upper Ordovician influx of Taconic-derived clastics into the midcontinent.

Carbonate depositional patterns became disrupted during the middle and late Cincinnatian, and Maquoketa shales spread across the central midcontinent area. Lower Maquoketa shale facies in eastern Iowa and Illinois are primarily brown organic-rich shales with interbedded carbonates and phosphorites. This shale facies is replaced to the west and northwest by carbonate-dominated facies. Maquoketa shale-dominated facies progressively overstep Maquoketa carbonate-dominated facies westward in Iowa (Witzke, 1983a). The "Viola" carbonate sequence in Kansas and adjacent areas is not an exact chronostratigraphic equivalent of the Iowa-Illinois Galena Group carbonate sequence but includes younger strata (ibid.; Adler et al., 1971). The westward spread of shale facies over carbonate facies during Maquoketa deposition in the midcontinent probably represents the distal progradation of clastic sediment from Taconic sources. However, additional clastic sources within the central midcontinent significantly modified this general picture; sand and mud were shed off areas on the Ozark Uplift and Transcontinental Arch (Witzke, 1980).

Structural patterns developed during or after Maquoketa deposition resemble those of the Middle Ordovician, although new features are evident. In particular, the area of the Southeast Nebraska Arch subsided during Maquoketa deposition as evidenced by southwestward thickening of Maquoketa strata in Iowa toward the former arch. The initiation of increased subsidence in the vicinity of the

Southeast Nebraska Arch and in eastern Iowa during the late Middle and Late Ordovician marked the early development of the North Kansas and East-Central Iowa basins.

The youngest Ordovician deposits in the midcontinent occur at the top of the Maquoketa interval. Uppermost Ordovician sediments in Iowa include red silty shales with scattered oolitic ironstones, whereas skeletal and oolitic limestones are present in Missouri. An erosional unconformity, with up to 50 m of relief in eastern Iowa, separates Ordovician and Silurian strata over the midcontinent area, which probably developed during a major glacial eustatic drop in sea level (Sheehan, 1978).

Silurian. Outside of the Illinois Basin area, Silurian strata in the central midcontinent are restricted to the East-Central Iowa and North Kansas basins and the structural sag that connects these two regions (Pl. 3, fig. 4). Silurian carbonate deposition undoubtedly extended far beyond the present-day Silurian edge across much or all of the Transcontinental (Chronic et al., 1969; Colville and Sheehan, 1983) and Chautauqua arches. However Silurian strata were removed over vast areas of the midcontinent during a prolonged period of pre-Kaskaskia nondeposition and erosion which lasted some 40 million years.

The initial transgression of Silurian seas into the midcontinent proceeded from the Illinois area into eastern Iowa, where shaly carbonates were deposited in topographic depressions on the Maquoketa Shale surface during the early Llandoverian. However, Silurian deposition across central Iowa and the North Kansas Basin area did not begin until the middle to late Llandoverian (Carlson and Boucot, 1967; Witzke, 1981), and late Llandoverian strata overlie the Ordovician surface in eastern Missouri (Thompson and Satterfield, 1975). Subsequent Llandoverian-early Wenlockian marine carbonate depositional patterns and biofacies distributions across the midcontinent area were strongly influenced by relative changes in sea level (Johnson, 1980; Witzke, 1983b). Level-bottom marine carbonate environments were locally modified in eastern Iowa during portions of the late Llandoverian and Wenlockian as carbonate mound facies (bioherms) developed on the sea bottom (Witzke, 1983b). Carbonate mound complexes achieved dimensions up to 2.5 km in diameter in Iowa.

A profound change in carbonate depositional patterns occurred during the middle to late Wenlockian in the East-Central Iowa Basin area, as open-marine carbonate environments were replaced by restricted-marine subtidal laminated carbonate environments (Philcox, 1972; Witzke, 1983b). Open-marine epeiric circulation patterns became disrupted as the Late Silurian marine offlap proceeded, creating conditions of increased salinity within the basin. Late Wenlockian-Ludlovian carbonate mound facies containing abundant low-diversity invertebrate faunas interfinger with laminated carbonate facies in eastern Iowa (Witzke, 1983b).

Silurian stratigraphy in the North Kansas Basin area is poorly known, although lithologic and biostratigraphic similarities with eastern Iowa provide the most consistent comparisons. Ireland (1967) proposed a correlation of the North Kansas Basin Silurian section with the Silurian section in Oklahoma, although his correlations are inconsistent with the brachiopod biostratigraphy established in Nebraska (Carlson and Boucot, 1967; Witzke, 1981). The Chautauqua Arch apparently served as an effective barrier separating Silurian carbonate environments in the North Kansas Basin area from Silurian carbonate/clastic environments in Oklahoma. Close similarities between the Silurian sequences in the North Kansas and East-Central Iowa basins suggest that similar structural and depositional conditions existed in both basins. Maximum thicknesses of Silurian rocks in the central areas of both basins are similar (150 m; Pl. 3, fig. 4), and thickening of individual Silurian rock units towards the center of each basin is documented

(Ireland, 1967; Witzke, 1981, 1983b). The absence of Silurian strata in the central midcontinent across the Transcontinental Arch, ancestral Central Kansas Uplift, Northeast Missouri Arch, Chautauqua Arch, and Ozark Uplift suggests that these features were probably positive structural elements during Silurian deposition as well as the subsequent pre-Middle Devonian erosional episode.

## Pre-Kaskaskia Erosional Episode

Prior to the initial Kaskaskia transgression into the central midcontinent, an extensive period of erosion ensued during which several hundred meters of Tippecanoe, Sauk, and Precambrian rocks were stripped from portions of the continental interior. The pre-Kaskaskia paleogeologic map (Pl. 3, fig. 5) reflects the pattern of basins and arches that had developed prior to Kaskaskia deposition. Because of extensive sub-Kaskaskia erosional stripping, Silurian rocks were preserved only in areas of maximum structural subsidence. The general distribution of Silurian rocks (Pl. 3, fig. 4) depicts a northeast to southwest trending synclinal trough across the central midcontinent coincident in part to the southeastern margin of the MRS. This depressed area, as discussed previously, has been subdivided into the North Kansas and the East-Central Iowa basins. Other prominent structural features evident on the pre-Kaskaskia paleogeologic map (Pl. 3, fig. 5) include the Ozark Uplift, Northeast Missouri Arch, Chautauqua Arch, ancestral Central Kansas Uplift, and Transcontinental Arch.

Pre-Kaskaskia paleotopographic relief developed from differential erosional characteristics of truncated pre-Kaskaskia strata, in particular between Silurian carbonates and Upper Ordovician shales. Erosional escarpments of low relief (10-30 m) developed along the pre-Kaskaskia erosional margins of the Silurian, and probably served as effective barriers to open-marine circulation in the initial transgressing Kaskaskia seas (Bunker et al., 1983, 1985).

## Kaskaskia Sequence

The Kaskaskia Sequence (text fig. 1) in the central midcontinent region includes strata ranging in age from Middle Devonian (Late Eifelian: Hilpman, 1969; Klapper and Barrick, 1983; Bunker et al., 1985) to late Middle Mississippian (Meramecian). The structural framework influencing early Kaskaskia deposition in this region was largely inherited, with some variations, from that which developed during the late Tippecanoe.

Devonian. Collinson and James (1969) considered the Middle Devonian rocks of eastern Iowa and northwestern Illinois to be the southeasternmost transgressive deposits of a vast seaway that extended northwestward into western Canada. Recent biostratigraphic (Klapper and Barrick, 1983) and lithostratigraphic (Bunker et al., 1983, 1985; Witzke and Bunker, 1984) interpretations of the Middle Devonian rocks in north-central Iowa and south-central Minnesota indicate that open-marine carbonate environments (Spillville Fm) characterized this region during the Late Eifelian. These Eifelian units are physically separated from correlative restricted-marine carbonate units (Otis Fm) in the East-Central Iowa Basin area (Bunker et al., 1983, 1985) by a paleoescarpment of Silurian carbonate strata in the northern part of the East-Central Iowa Basin. Upper Eifelian rocks are absent elsewhere across central Iowa, although probable upper Eifelian strata are present in the North Kansas Basin area (Hilpman, 1969). In general, southward transgressing seas expanded into the central midcontinent area during the Late Eifelian and reoccupied the two major Tippecanoe basinal areas. However, there was apparently no direct Late Eifelian seaway connection between the North Kansas and East-Central Iowa basins across central Iowa. The Nebraska Sag probably served as a seaway connection between the Williston and the North Kansas basins during the Middle Devonian onlap. Seaway connections may have been established around the northern flank of the Sioux Ridge with the East-Central

Iowa and Williston basins. Biogeographic similarities between basal Middle Devonian rocks in northeastern Iowa and eastern Wisconsin (Klapper and Barrick, 1983) suggest that seaway connections with the Michigan Basin were also probably established across the area of the Wisconsin Arch. However, extensive post-Devonian erosion has removed Devonian strata from the Transcontinental and Wisconsin arches, obscuring physical relationships.

Successive expansion of the Middle Devonian seaway, into the central mid-continent region, is recorded by a series of trangressive-regressive depositional cycles (Witzke and Bunker, 1984; Witzke et al., 1985), which are similar in timing to those noted in Manitoba (Norris et al., 1982),and complementary to those noted across Euramerica (Johnson et al., 1985). The first cycle, as noted, spread Late Eifelian carbonate (Spillville-Otis Fms) environments across portions of the East-Central Iowa and North Kansas basins. The upper regressive part of this cycle (Wapsipinicon Fm) is characterized by an extensive carbonate and gypsum-anhydrite evaporite sequence (Dorheim and Campbell, 1958; Sendlein, 1964, 1968, 1972) which is preserved in the subsurface of south-central and south-eastern Iowa. Brecciated carbonates, textures primarily developed by evaporite solution collapse, characterize this interval in the outcrop area of eastern and northeastern Iowa (Norton, 1920; Bunker et al., 1983, 1985).

Late Givetian-Early Frasnian (Cedar Valley-Shell Rock Fms) cyclic sedimentation in the central midcontinent region is similarly characterized by fossiliferous dolomitic intervals at the base of each cycle, recording deposition in open-marine carbonate shelf environments during each successive transgressive phase. Laminated, intraclastic, and brecciated carbonates in the upper part of each cycle record deposition in shallow, restricted subtidal and tidal flat settings during each regressive phase (Witzke and Bunker, 1984). Evaporites (gypsum-anhydrite) laterally equivalent to each of the regressive phases are present in the subsurface of central Iowa. The lower Cedar Valley Formation represents a widespread transgression (Taghanic Onlap, Johnson, 1970; Klapper and Johnson, 1980) which marked the end of provincialism among brachiopods, corals, and trilobites across the North American continent. The Sangamon Arch in central Illinois, which initially developed during the Middle Devonian (Whiting and Stevenson, 1965), together with the Ozark Uplift and the Chautauqua Arch, formed the southern margin of the merging North Kansas and East-Central Iowa basins. Cedar Valley carbonate deposition along the southern margin of the developing Iowa Basin was influenced by the influx of Ozark-derived clastics (Hoing Sandstone) across central and northern Missouri and portions of southern Iowa (Fraunfelter, 1967; Schumacher, 1976).

Prior to the Late Frasnian transgression across the central midcontinent, a period of erosion and karst development occurred over much of the area. Sinkholes and caverns developed in the Middle Devonian and Silurian carbonates, and stratigraphic leaks of Upper Devonian shale (Independence Shale of eastern Iowa, Urban, 1972; Klapper, 1975) filled these karst features. Lee (1956, p. 65) described a pre-Chattanooga valley (McPherson Valley) with paleotopographic relief of more than 60 m in south-central Kansas, as well as the presence of several Middle Devonian outliers along the western margin of the North Kansas Basin. However, marine and restricted-marine carbonates and evaporites were deposited in central Iowa (Iowa Basin) coincident with erosion in areas to the southeast and west.

Significant changes in structural and depositional patterns occurred prior to and/or during the Late Devonian (Late Frasnian-Famennian) transgression into the central midcontinent. While earlier Middle Devonian marine incursions appear to have spread from northern and eastern seaways, the Late Devonian transgression apparently came from a seaway to the southeast. The Upper Devonian in this region can be grouped into three broad northeasterly trending megafacies. The southeasternmost facies (New Albany Shale Group, Cluff et al., 1981) consists predominantly of gray and black to brownish black organic-rich shales. The New Albany Shale Group grades laterally to the northwest into gray shales which in turn grade to and are interbedded with carbonates and green shales (Yellow Spring Group, Dorheim et al., 1969). Biostratigraphic investigations of Devonian carbonates in the central midcontinent have also revealed that strata previously classified as Middle Devonian (Collinson, 1967; Adler et al., 1971) are, in part, a Late Devonian carbonate lithosome (Klug and Tynan, 1981; Klug, 1982) as earlier suggested by Carlson (1963, p. 35). The northwesternmost megafacies is a sparsely fossiliferous carbonate-dominated interval, with abundant solution collapse(?) breccias, which progressively onlapped and overstepped truncated Tippecanoe rocks along the southeastern flank of the Transcontinental Arch. Laminated brown shales, containing a probable Givetian-Frasnian freshwater fish fauna, overlie Cambrian and Precambrian rocks near the Sioux Ridge in northwest Iowa (note outlier on Pl. 3, fig. 6).

The total Devonian isopach map (Pl. 3, fig. 6) does not reflect the individual histories of the separate Middle and Late Devonian structural and depositional regimes. However, the isopach map does suggest a merging of the North Kansas and East-Central Iowa basins into one depositional basin located in central Iowa (i.e., the Iowa Basin), sometime during the late Middle to Late Devonian. The axis of this northeasterly trending elongated basinal feature occupies a position coincident to the southeastern margin of the MRS suggesting probable structural influence on both Middle and Upper Devonian sedimentation. Structural movements along the northwest-southeast trending Lincoln Fold System in northeastern Missouri and southeastern Iowa locally influenced Devonian depositional and erosional patterns (McQueen et al., 1961) in this area.

Mississippian. Following a regressive offlap at the end of the Devonian, Mississippian marine environments transgressed across a region of low erosional relief. The basal sequence of Mississippian rocks (Kinderhookian Series) in the midcontinent is dominated by marine carbonate deposits, although significant quantities of Kinderhookian shale and siltstone occur in southeastern Iowa and northeastern Missouri. Mississippian onlap along the flanks of the Transcontinental Arch and the Cambridge Arch-Central Kansas Uplift has been described for the northern and western parts of the study area (Carlson, 1963, 1979; Goebel and Stewart, 1979). Intermittent seaway connections with the Williston Basin area were probably established through the area of the Nebraska Sag. Similar onlap is also noted around the flanks of the Ozark Uplift (Thompson, 1979) indicating that this area remained a positive structural feature during the Mississippian.

The Mississippian is typically subdivided into four widely recognized series--the Kinderhookian, Osagian, Meramecian, and Chesterian. Many problems involving time-stratigraphic relationships, vertical and lateral facies variations, and the extent of regional and local unconformities have precluded meaningful synthesis of the Mississippian System across the entire central midcontinent area. For example, disconformable relationships between Kinderhookian and Osagean strata in southeastern Iowa attest to late Kinderhookian uplift and erosion. Whether this unconformity is of local or regional significance is not well established. Laudon (1937) used this disconformity in southeastern Iowa to explain the apparent transgressive overlap of crinoid zones within the Burlington Limestone (Osagean). Lithostratigraphic relationships (Harris and Parker, 1964) also suggest that successively younger members of the Burlington progressively overlie younger units of the "Kinderhookian Series" north and west from southeastern Iowa. Parker (1973), however, suggested that a facies relationship may exist between the lower Burlington and portions of the Hampton (formerly considered "Kinderhookian") in central Iowa. Recent biostratigraphic investigations (Glenister and Sixt, 1982; Baxter and Brenkle, 1983) have now assigned portions of the Hampton and Gilmore City formations in central Iowa to the Early Osagean.

Osagean rocks were deposited during a major transgressive episode in the midcontinent. Shallow seas with normal salinities and a diverse assemblage of benthic invertebrates characterized most of this interval. The Central Kansas Uplift was overlapped and the Hugoton Embayment of southwestern Kansas actively subsided (Goebel and Stewart, 1979), connecting southward into the Anadarko Basin.

Meramecian strata in the central midcontinent include carbonates, evaporites, shales, and sandstones deposited in various open-marine and restricted-marine environments during several transgressive-regressive cycles. A major regressive interval during the Meramecian resulted in the development of an erosion surface within the western Kansas sequence (ibid.). Restriction of the Meramecian sea in south-central Iowa permitted development of a gypsum-anhydrite evaporite sequence (Carlson, 1979). Chesterian rocks are generally absent from the region, being restricted to the southern basins. Eroded Chesterian rocks occur within the Hugoton Embayment, and it seems probable that Chesterian deposition may have extended across other portions of the central midcontinent. However, pre-Absaroka erosion has removed any evidence of Chesterian rocks across most of the area.

The present thickness of Mississippian rocks in the midcontinent (Pl. 3, fig. 7) reflects extensive pre-Absaroka uplift and erosion, especially along the trend of the Nemaha Uplift. Nevertheless, the isopach map outlines several areas of increased Mississippian subsidence. 1) The Hugoton Embayment of western Kansas contains the thickest sequence of Mississippian strata in the central midcontinent. However, because of unresolved stratigraphic problems, the thickness patterns shown include some Upper Devonian strata (Hilpman, 1969; Goebel and Stewart, 1979). 2) Mississippian thickening in northeast Kansas and adjacent Missouri reflects development of a shallow basin which Lee (1946) termed the Ancestral Forest City Basin. 3) The thick Mississippian section in western Iowa is informally included in the "Massena basin." This basin coincides with the western extent of the Late Devonian Iowa Basin. 4) A synclinal depression in northeastern Missouri and southern Iowa is also apparent on the Mississippian isopach map, and is informally termed the "Appanoose trough." This trough is a major structural low associated with the Lincoln Fold System (Pl. 3, Fig. 9), indicating active development of Lincoln Fold structures during the Mississippian. Meramecian evaporites are preserved within this feature.

## Pre-Absaroka Erosion Cycle

The pre-Absaroka unconformity reflects a profound change in the tectonic framework of the central midcontinent. Renewed uplift of older positive features, and erosional stripping of uplifted strata led to the development of a geologically complex land surface. Early to Middle Pennsylvanian sediments onlapped and overstepped the erosionally beveled edges of Kaskaskia through Sauk units, and rest on Precambrian basement rocks along the crest of some pre-Absaroka uplifts. The pre-Absaroka paleogeologic map illustrates this complex erosion surface (Pl. 3, fig. 8).

The Nemaha Uplift, a reactivation of the older (Sauk) Southeast Nebraska Arch, is apparent at the center of the map (Pl. 3, fig. 8). Regional beveling removed Kaskaskia and Tippecanoe strata, exposing Precambrian crystalline rocks along the crest of the uplift. Uplift and erosional beveling is also noted along the trend of the Cambridge Arch-Central Kansas Uplift. Lower Tippecanoe and upper Kaskaskia rocks are preserved along the axis of the Nebraska Sag. In east-central Iowa and northwestern Illinois, uplift of the Savanna-Sabula Anticlinal System (Pl. 3, fig. 9) and faulting along the Plum River Fault Zone (Pl. 3, fig. 8) is indicated by regional beveling of Kaskaskia and upper Tippecanoe rocks along the crest of the anticline (Bunker et al., 1985). The East-Central Iowa Basin, developed during Tippecanoe-lower Kaskaskia deposition, had been uplifted and erosionally beveled to the northeast prior to Absaroka deposition. Continued presence of the Ozark Uplift is indicated by erosional stripping of Kaskaskia and Tippecanoe strata, so that Pennsylvanian rocks of the region rest upon Lower Ordovician strata.

## Absaroka Sequence

The Absaroka Sequence (text fig. 1) in the central midcontinent consists primarily of strata ranging in age from Middle Pennsylvanian to Late Permian. Triassic strata are present only along the extreme western margin of the study area. Late Chesterian rocks are restricted to the Illinois and Anadarko basins, but possible stratigraphic leaks have been noted within karstified Kaskaskia rocks in the central midcontinent (Urban, 1971, 1972; Goebel and Stewart, 1979).

Pennsylvanian. Lower Pennsylvanian (Morrowan) rocks in the study area are known from the Hugoton Embayment of southwestern Kansas and the Illinois Basin. Nonmarine Morrowan strata have also been identified in east-central Iowa and northern Illinois (Kosanke et al., 1960; Fitzgerald, 1977) along the southern flank of the Savanna-Sabula Anticlinal System and the crest of the Mississippi River Arch (Bunker et al., 1985). Basal Pennsylvanian strata in the central area of the Forest City Basin have not been dated, and possible Morrowan strata may be included (Wanless, 1975, p. 99).

Middle Pennsylvanian (Atokan-Desmoinesian) strata (Cherokee and Marmaton Gps) cover much of the central midcontinent, but are absent across structural highs along the trend of the Cambridge Arch-Central Kansas Uplift and Nemaha Uplift (Pl. 3, fig. 9). Lower and Middle Pennsylvanian strata are dominated by nonmarine clastic deposits, although marine shale and limestone units occur within the sequence. Clastic sediments of the Cherokee Group are primarily shales and mudstones with locally abundant sandstone and siltstone units. Coal seams, locally thick enough to be of economic interest, occur within the Cherokee Group, especially in the eastern part of the study area. Lower Cherokee strata in the central portion of the Forest City Basin are dominated by black and gray shale with minor sandstone. However, the upper Cherokee includes beds of coarse-grained arkosic sandstone, possibly derived from Precambrian granites on the crest of the Nemaha Uplift during the late Middle Pennsylvanian (Lee, 1943, 1956). In the Salina Basin, Cherokee strata are dominated by shale and sandstone; coal beds, although present, are less significant than in the basins to the east. Gray silty shales are interstratified with red shale beds, in particular along the flanks of the Central Kansas Uplift (Lee, 1956). Compared to the lower Cherokee, upper Cherokee and Marmaton strata show increasing evidence of marine deposition across the midcontinent, including prominent cyclic marine shale-limestone units.

Much of subsequent Absaroka Sequence deposition was characterized by cyclic patterns (cyclothems) of marine and nonmarine sedimentation, apparently in response to eustatic sea level fluctuations in the midcontinent. Eustatic fluctuations may relate to the waxing and waning of Gondwanan glaciers during the Late Mississippian through Middle Permian (Crowell, 1978; Heckel, 1980). The ideal-

Text Figure #2 near here

ized "Kansas cyclothem " (text fig. 2), which characterizes many Upper Pennsylvanian cyclic units in the midcontinent, includes four basic components (Heckel, 1977): 1) a thin basal transgressive limestone; 2) a phosphatic black fissile offshore marine shale (maximum transgression); 3) a thick regressive limestone;

and 4) a sandy nearshore and nonmarine shale locally with sandstone and coal (maximum regression). However, not all cyclothems contain the four basic components. In some cyclothems the basal transgressive limestone is extremely thin to absent and the black marine shale interval directly overlies coal beds or nearshore shale facies ("Illinois cyclothem;" Heckel, 1980). The lack of the black marine shale in some cycles suggests that the magnitudes of eustatic sea level fluctuations varied. Regional facies variations are noted within individual cyclothems, including carbonate mound and oolite shoal facies (Heckel and Cocke, 1969; Watney, 1980). Regional examination of the Kansas City Group in western Kansas indicates that the entire shelf was exposed repeatedly during late regression in each cycle (Watney, 1984). The configuration of the shelf during deposition of these cycles was controlled by continued though subtle uplift of the Central Kansas Uplift and its extension to the south, the Pratt Anticline. Subtle flexures along the platform were sometimes loci for the formation of ooid shoals, when waves and currents were focused on these areas during the late regressive phases of some cycles (ibid.).

Middle Pennsylvanian faulting along the Humboldt Fault Zone (Pl. 3, fig. 1), apparently contemporaneous with the Ouachita-Marathon Orogeny (Kluth and Coney, 1981), gave rise to the Nemaha Uplift, in part a reactivation of the older (Sauk) Southeast Nebraska Arch. The Nemaha Uplift bisected the region of the late Tippecanoe North Kansas Basin and cut off the southwestern extension of the mid-Kaskaskia Iowa Basin. Up to 320 m of pre-Missourian Pennsylvanian rocks accumulated in the structural depression east of the Humboldt Fault Zone (Pl. 3, fig. 9). This area constitutes the Forest City Basin as defined by Lee (1943, 1946). Maximum differential subsidence of the Forest City Basin was essentially contemporaneous with the rising Nemaha Uplift. The Nemaha Uplift forms the eastern margins of two basins created during this period of increased structural activity: 1) the Salina Basin of north-central Kansas and south-central Nebraska, and 2) the Sedgwick Basin, a structural depression in south-central Kansas that plunges southward to join the Anadarko Basin of Oklahoma. West of the Central Kansas Uplift, the Hugoton Embayment continued to be a region of increased subsidence during the Pennsylvanian.

Eastward thinning of Middle Pennsylvanian strata from the Forest City Basin toward a broad outcrop area in northeastern Missouri indicates the presence of a broad northward trending arch, apparently the Absaroka expression of the older pre-Kaskaskia Northeast Missouri Arch (Pl. 3, fig. 5). The Mississippi River Arch (Howell, 1935) and the Lincoln Fold System (McQueen et al., 1961) occur along the present day structural crest of this broad feature. The Lincoln Fold, active during the Mississippian, continued as a prominent structural feature during the Middle Pennsylvanian (Searight and Searight, 1961). The Mississippi River Arch, which developed during the Middle Pennsylvanian, apparently formed concurrently with maximum subsidence of the Forest City Basin (Bunker et al., 1985). Pennsylvanian clastic source areas included four general regions: 1) the Ancestral Rocky Mountains to the west, 2) the Marathon-Ouachita Mountains to the south, 3) Canadian Shield sources to the north, and 4) alluvial-deltaic sediments that prograded into the midcontinent from Appalachian sources.

Differential basinal subsidence of the Forest City and Salina basins decreased during the Late Pennsylvanian. The Nemaha Uplift and Central Kansas Uplift continued to stand in mild positive relief until overlapped by the Kansas City Group (post-Hertha; Lee, 1943, 1946, 1956). Although prominent Middle Pennsylvanian structural features continued to influence Late Pennsylvanian deposition, the Late Pennsylvanian was marked by more subdued structural patterns in the eastern and central portions of the study area. In contrast with Lower and Middle Pennsylvanian units, the widespread lateral continuity of members within the Upper Pennsylvanian cyclothems reflects relative structural stability across much of the midcontinent.

Permian. Permian strata occur across much of Kansas and Nebraska, but are generally absent in the study area east of the Missouri River. Permian strata thicken to the west and southwest in the central midcontinent, reaching thicknesses in excess of 1000 m in portions of southwestern Kansas (Peterson, 1980). Lower Permian (Wolfcampian) strata (Admire, Council Grove, Chase Gps) include a series of limestone/shale cyclothemic units similar to those noted in the Upper Pennsylvanian (Mudge and Yochelson, 1962). Gypsum units also occur within the Wolfcampian sequence (Burchett, 1970). Younger Permian strata (Leonardian, Guadalupian), included in the Sumner Group, Nippewalla Group, and Whitehorse Formation in Kansas, are characterized by a thick sequence of shale/sandstone redbeds and evaporites (gypsum, anhydrite, and halite) with some carbonate units. More than 400 m of evaporitic deposits occur within the redbed sequence in portions of southwestern Kansas (Merriam, 1963).

Permian structural patterns in the midcontinent strongly influenced Permian deposition. Early Permian subsidence in the Salina Basin and Hugoton Embayment areas generally resembled Pennsylvanian patterns. Structural reorganization of these patterns occurred during the Leonardian-Guadalupian as "arching of the Central Kansas uplift ceased" and "the areas of the Salina basin and Central Kansas uplift began to be tilted as a whole toward the southwest into the Hugoton embayment" (Lee, 1956, p. 157). In addition, a south-plunging anticline in western Kansas, the Oakley Anticline, developed at that time within the Hugoton Embayment area (Merriam, 1963). The Hugoton Embayment area merged with the Anadarko Basin to the south and extended westward to the Las Animas Arch, which extended northeastward from the Apishipa Uplift in southeastern Colorado into southwestern Nebraska (Rascoe, 1978). This arch had a pronounced effect on sedimentation during the Lower Permian, controlling carbonate and evaporite deposition on its flanks. Farther west the relatively shallow Denver Basin spread to the eastern flanks of the Ancestral Rocky Mountain source areas in Colorado. Although the youngest strata included in the Absaroka Sequence across most of the central midcontinent are Guadalupian in age, Triassic strata (Dockum Gp) are known in a small area of southwestern Kansas. Deposition of the non-marine Dockum Group was largely controlled by structural settings inherited from relict Late Paleozoic basins (McGowen et al., 1983).

## Sub-Zuni Erosional Surface

Upper Jurassic and Cretaceous strata overlie the sub-Zuni erosional surface in the central midcontinent. The Paleozoic sequence is progressively beveled beneath Zuni rocks across northwestern Iowa and northeastern Nebraska in the direction of the Sioux Ridge (Pl. 3, fig. 10), where up to 100 m of relief is developed across strike-oriented Cretaceous valleys (Witzke et al., 1983). Jurassic strata overlie Permian rocks in western Kansas and central Nebraska, although Jurassic strata truncate the Pennsylvanian sequence and rest directly on Precambrian basement rocks in eastern South Dakota (Pl. 3, fig. 10). Cretaceous strata overstep the eroded Jurassic edge and overlie the Precambrian surface across eastern South Dakota and western Minnesota. Cretaceous outliers in eastern Minnesota, Iowa, and Wisconsin rest on progressively older Paleozoic units in the direction of the Wisconsin Dome. In general, the sub-Zuni erosional surface reflects the position of positive structural and topographic features: 1) Wisconsin Dome, 2) Transcontinental Arch (and the included Sioux Ridge), and 3) an upland area of Precambrian rocks in western Minnesota and eastern South Dakota.

## Zuni Sequence

Jurassic. Zuni deposition in the central midcontinent was initiated during the Late Jurassic, generally coincident with the eastward encroachment of the "Sundance Sea." The maximum eastward extent of this epeiric sea is not known, and much of the preserved Jurassic sequence in Kansas, Nebraska, and central South Dakota is apparently of nonmarine origin. Except for structurally-preserved outliers in north-central Iowa (Ft. Dodge Gypsum), Jurassic strata in the central midcontinent occur entirely in the subsurface. Few stratigraphic studies have been undertaken on these strata, and correlations remain uncertain. Nevertheless, the Jurassic of Nebraska-Kansas, which reaches thicknesses in excess of 60 m, shares its closest similarities with the upper Sundance-Morrison interval of Wyoming (Condra and Reed, 1943; Merriam, 1955, 1963). The Kansas Jurassic consists primarily of sandy shale, commonly containing anhydrite and cherty beds in the lower part and limestone beds in the upper part (ibid.). Sandstones also occur within the Jurassic interval across Kansas, Nebraska, and South Dakota; sandstone beds are more abundant to the east in Kansas (ibid.). As suggested by Brenner (1983), "cratonic siliciclastic sources may have continued supplying nearshore settings along the eastern margin of the epeiric sea as they shifted eastward during the Oxfordian." As such, Jurassic sediments in the central midcontinent probably were deposited as a complex series of nonmarine fluvial and nearshore marine facies. The abundance of anhydrite in the lower part of this interval suggests that tidal flat or nearshore restricted-marine settings were associated with Late Jurassic transgression along the eastern margin of the seaway.

The economic Ft. Dodge Gypsum of Iowa overlies Mississippian and Middle Pennsylvanian strata, and is preserved within a structural depression overlying the Northern Boundary Fault of the MRS. These Jurassic strata occur over 450 km east of the present Jurassic edge. The Ft. Dodge Gyspum contains Late Jurassic palynomorphs (Cross, 1966), and may have been deposited in a "marginal marine basin" (Bard, 1982). A possible late Jurassic redbed and dolomite interval with minor gypsum ("Hallock redbeds") also occurs east of the Jurassic edge in northwestern Minnesota (Mossler, 1978). These occurrences suggest that considerable erosional stripping of Jurassic strata occurred prior to burial of the Jurassic edge beneath Cretaceous sediments.

Cretaceous. Cretaceous strata in the central midcontinent were deposited along the eastern margin area of the north-south trending Western Interior Seaway. Cretaceous sedimentation in this area was controlled by several factors including: 1) "the rise and fall of sea level, and hence base level in fluvial systems, during five major transgressive-regressive cycles;" 2) relative rates of terrigenous clastic influx from eastern and western source areas; and 3) the distribution of structural and paleotopographic features, most notably the Transcontinental Arch, Sioux Ridge, Precambrian uplands of Minnesota, and Wisconsin Dome (Witzke et al., 1983). Cretaceous deposition in the central midcontinent area was apparently initiated during transgression of the Albian Kiowa-Skull Creek marine cycle. Albian marine shale facies (Kiowa, Skull Creek Sh) spread eastward into central Nebraska and Kansas and eastern South Dakota. Correlative nearshore and nonmarine sandstone deposits are known in Kansas and eastern South Dakota, and a portion of the lower Dakota fluvial sandstone sequence in eastern Nebraska and western Iowa may have aggraded as base levels rose during the Kiowa-Skull Creek cycle (ibid.). Eastern-derived terrigenous clastic sediments prograded westward across the central midcontinent area during the regressive phase of this marine cycle.

Marine shale facies (Graneros Sh) and offshore pelagic carbonate facies (Greenhorn Fm) spread eastward across the central midcontinent, progressively displacing nearshore and nonmarine facies (Dakota Fm) during the Cenomanian. This marked the initial transgressive phase of the Greenhorn cycle. Nonmarine and marine deposition was initiated across the Precambrian upland surface in western Minnesota during the Cenomanian, although prominent topographic highs, especially the Sioux Ridge, remained emergent through much or all of the Greenhorn cycle. By the Turonian, deposition of Greenhorn carbonates had spread across the western half of the central midcontinent, "reflecting a significant decrease in eastern clastic influx in the offshore areas as shorelines spread eastward to the Wisconsin dome area" (Witzke et al., 1983, p. 241). Westward progradation of eastern-derived mud and sand (Carlile Sh) during the middle Turonian, followed by marine offlap and subaerial erosion, marked the regressive phase of the Greenhorn cycle. However, a Precambrian granite knob in western Minnesota and eastern South Dakota was buried by lower Carlile strata, suggesting that sea level continued to rise during the early phases of Carlile deposition (Shurr, 1981).

Following a period of late Turonian-early Coniacian erosion, marine carbonate and chalky shale deposition expanded across the western half of the central midcontinent during the Niobrara marine cycle (late Coniacian-Santonian). Eastern source areas supplied clastic material to the nearshore facies of the lower Niobrara Formation, including clastic-dominated facies in western Minnesota and silty-sandy chalk facies in northeast Nebraska and the Sioux Ridge area (Witzke et al., 1983). A unique sequence of clastic rocks overlain by biogenic siliceous strata (Split Rock Creek Fm) is restricted to paleovalleys incised into the flanks of the Sioux Ridge, and correlates, in part, to the Niobrara Formation (Ludvigson et al., 1981; Witzke et al., 1983; Hammond and Ludvigson, 1985). The low rate of eastern clastic influx coupled with limited dispersal of western-derived clastics from Cordilleran sources across the axis of the Transcontinental Arch (Rice and Shurr, 1983), permitted widespread development of pelagic carbonate-dominated facies across much of Nebraska, Kansas, and southeastern South Dakota. The Niobrara becomes progressively more shaly northwestward from the arch.

The Pierre Shale of Campanian-Maastrichtian age was deposited disconformably above Niobrara rocks in the central midcontinent, and reaches thicknesses up to 400 m along the western edge of the study area. Members within the Pierre thin eastward to their erosional margin. In general, Pierre clastics were derived from western sources associated with the rising Sevier Orogenic Belt, , although influx of minor quantities of eastern-derived clastics influenced depositional patterns along the eastern margin of the Western Interior Seaway (Witzke et al., 1983). At times when influx of western clastics was reduced, shaly chalk and chalky shale Pierre facies developed in the eastern portion of the seaway. Lower Pierre strata, including widespread black shale facies, were deposited during the Claggett marine cycle. An erosional unconformity was developed around the Sioux Ridge following Clagget deposition (ibid.). The bulk of Pierre strata was deposited during the succeeding Bearpaw marine cycle. The Cretaceous seaway withdrew from the continental interior during the regressive phase of this cycle.

Zuni deposition in the central midcontinent occurred within two major structural regimes: 1) a broad, relatively stable eastern platform, and 2) a broad "hinge" zone area east of the rapidly subsiding basins in the western portion of the Western Interior (Kauffman, 1977). Zuni stratigraphic units thicken westward in the area, reflecting subsidence rates in the midcontinent. Numerous bentonites in the Zuni sequence originated from western volcanic sources. In the east, minor structural movements along the Transcontinental Arch and Nemaha Uplift probably influenced Cretaceous deposition (Witzke et al., 1983). Farther west, upwarping along the crest of the Chadron Arch-Cambridge Arch was initiated during or immediately following latest Cretaceous Pierre deposition (Fuenning, 1942; Merriam, 1963). Zuni structural patterns in the midcontinent were modified by later "Laramide" epeirogenic movements.

## Sub-Cenozoic Erosional Surface and Structure

The central midcontinent Cretaceous sequence is beveled to the south and east beneath Tertiary strata (Pl. 3, fig. 11). Uplift along the trend of the Cambridge Arch-Chadron Arch was probably a latest Cretaceous-early Tertiary event; up to 400 m of Cretaceous strata were apparently removed from the crest of the Chadron Arch prior to burial by Oligocene sediments (Pl. 3, fig. 12). As reflected on Cretaceous structure (Fuenning, 1942; Merriam, 1963; Carlson and Reed, 1969) and isopach (Pl. 3, fig. 12) maps, the Cambridge Arch-Chadron Arch trend marks the western margin of a shallow basin that occupies the general area of the Salina Basin and Nebraska Sag (Kennedy Basin). It was apparently during the Tertiary that other broad "Laramide" epeirogenic features developed, including: 1) broad upwarping along the trend of the Nemaha Uplift (Bunker, 1981), and 2) upwarping along the Las Animas Arch in western Kansas and adjacent Colorado, which separated the Western Kansas Basin from the Denver-Julesburg Basin.

## Cenozoic Nonmarine Deposition

At the onset of Tertiary deposition, the western portion of the central midcontinent was an eastward sloping plain receiving sediments from volcaniclastic material from western sources and epiclastic sediments from the rising Rocky Mountains and Black Hills. This contrasts with the westward dipping regional structural patterns in the Cretaceous. Oligocene bentonitic mudstones, siltstones, and channel sandstones (White River Gp) are preserved as far east as north-central Nebraska, and represent the oldest Tertiary deposits in the western portion of the central midcontinent. However, erosional remnants of Lower Eocene strata are known from northeastern Nebraska (M.R. Voorhies, 1984, pers. comm.). Uppermost Oligocene/ Lower Miocene siltstones and sandstones, and volcaniclastic material (Arikaree Gp) extend eastward into north-central Nebraska and adjacent South Dakota, and overlie an eroded surface on the White River Group (Swinehart et al., 1985).

Significant erosional downcutting of Arikaree and White River strata preceded deposition of the Ogallala Group (ibid.). The Ogallala consists primarily of sand, gravel, and silt with beds of limestone and ash. The Ogallala oversteps the Arikaree/White River edge and unconformably overlies Cretaceous strata across Kansas and eastern and southern Nebraska. Although many workers considered the Ogallala to be primarily Pliocene in age, fission-track dating of intercalated volcanic ashes indicates that much of the Ogallala is of Miocene age (Boellstorff, 1978a). The Ogallala apparently includes some Pliocene strata in the western portion of the central midcontinent, but a more complete Pliocene record is preserved in eastern and central Nebraska (ibid.). The Ogallala is capped by a persistent hard pisolitic limestone over much of its extent (Swinford et al., 1958). This limestone is actually a form of caliche, but was formerly termed the "algal limestone" (Elias, 1931). Significant erosional downcutting of Ogallala strata, in places incised up to 150 m, preceded Late Pliocene-Pleistocene deposition over much of the western portion of the central midcontinent (Swinehart et al., 1985). Blancan (Late Pliocene) sediments filled some of these valleys, but the deposits were subsequently dissected by later Quaternary drainages.

In general, the Pleistocene sequence in the central midcontinent region includes a complex series of glacial tills, fluvial sands and gravels, paleosols, and lacustrine and aeolian deposits. Numerous Pleistocene erosional events further complicate the stratigraphy. Fission-track dating of volcanic ashes in the sequence helps bracket glacial episodes in the midcontinent (Boellstorff, 1978a, b). Two or more glacial tills are present beneath a 2.2 million year old (m.y.) ash in western Iowa and eastern Nebraska, and represent the oldest Cenozoic glacial deposits known in the U.S. Additional till units occur between 0.7 and 1.2 m.y. ashes and above a 0.6 m.y. ash (ibid.). These glacial deposits extend across much of Illinois, Iowa, eastern Nebraska, northern Missouri, eastern South Dakota, and northeastern Kansas; their distribution approximates the southern limits of Pleistocene continental glaciation in North America.

Although the classic two-part "Nebraskan" and "Kansan" glacial stage terminology was originally proposed in the area containing this till sequence, new stratigraphic investigations indicate that up to seven or more separate glacial advances are represented in the sequence (ibid.; Hallberg and Boellstorff, 1978). The included glacial till units and associated deposits (paleosols, aeolian/alluvial sediments) are now informally lumped together in the "pre-Illinoian" stage. Eroded "pre-Illinoian" strata are covered by Illinoian and Wisconsinan glacial and associated deposits across much of the central and northern portions of the central midcontinent. Wisconsinan loess deposits are especially well developed along the Missouri River Valley. The Pleistocene sequence reaches thicknesses in excess of 100 m in portions of western Iowa and eastern Nebraska. West of the limits of glacial deposits in South Dakota, Kansas, and Nebraska, Pleistocene alluvial and aeolian deposits are found in terraces of incised drainage systems. Widespread Wisconsinan and Holocene aeolian deposits (loess, sand dunes) mantle the terraces and upland bedrock surfaces (Reed and Dreeszen, 1965).

Quaternary depositional and erosional processes have shaped the modern landscape in the central midcontinent. Although the area remains one of relative tectonic stability, limited seismic data indicate that the midcontinent is certainly not quiescent. Late Cenozoic Laramide-related epeirogenic movements probably account for the general eastward tilt of Ogallala strata across the Great Plains (Merriam, 1963, p. 197). Erosional processes and human activities continue to modify the modern midcontinent landscape.

## Phanerozoic Igneous Activity

While the Phanerozoic rock record in the central midcontinent is almost completely comprised of cratonic sedimentary sequences, a suite of alkalic to ultramafic igneous rocks is known in the region from a set of widely scattered dikes, sills, plugs, and diatremes. Isotopic age investigations and field relationships of these rocks show that they were explosively emplaced during several Phanerozoic episodes (Zartman, 1977). Within the study area, Upper Cambrian pyroclastic rocks record explosive submarine volcanism at several localities in southeast Missouri (Wagner and Kisvarsanyi, 1969; Snyder and Gerdemann, 1965; Kisvarsanyi and Hebrank, 1982). In addition, a swarm of Devonian kimberlite and carbonatite diatremes intrude Cambrian strata in the Avon area of southeast Missouri (Kidwell, 1947; Zartman et al., 1967). These Phanerozoic igneous rocks are located close to 38° N latitude, where an east-west trending axis of recurrent Phanerozoic tectonic activity in eastern and central North America has been described (Snyder and Gerdemann, 1965; Zartman, 1977).

Early Cretaceous kimberlite diatremes intrude Permian strata along the crest of the Nemaha Uplift in northeast Kansas (Brookins, 1970; Brookins and Naeser, 1971). The Elk Creek Carbonatite (Treves et al., 1972a, b; Brookins et al., 1975) intrudes Upper Pennsylvanian strata along the crest of the Nemaha Uplift in southeast Nebraska (R. R. Burchett, 1983, personal comm.). Late Cretaceous peridotite dikes intruding Upper Pennsylvanian strata are known along 38° N latitude in southeast Kansas (Knight and Landes, 1932, Zartman et al., 1967; Franks et al., 1971).

In addition to the known areas of explosive igneous activity in the central midcontinent region, a group of cryptoexplosion structures of possible explosive igneous or extraterrestrial impact origin occur within the study area. These include the Crooked Creek (post-Early Ordovician; Hendricks, 1954; Snyder and Gerdeman, 1965) and Decaturville (post-Silurian; Snyder and Gerdemann, 1965; McCracken, 1971, p. 23) structures located along 38° N latitude in southern Missouri, the Manson Anomaly (latest Cretaceous or Tertiary; Hoppin and Dryden, 1958; Witzke et al., 1983) in northwest Iowa, and the Rock Elm structure (post-Early Ordovician; Cordua, 1985) in southwest Wisconsin.

## Concluding Remarks

The modern structural geology of the central midcontinent, as portrayed on three structural cross sections (Pl. 3), reflects a complex Phanerozoic history. Changing patterns of differential crustal movements characterized the region. In comparison to some cratonic basin areas that displayed relatively long-term patterns of unidirectional subsidence (e.g., Michigan and Williston basins), basinal development in the central midcontinent region was a more transitory phenomenon. Areas of maximum basinal subsidence shifted within the region during the Phanerozoic, and reversals in vertical crustal movements through time are apparent at specific localities. The tectonic processes responsible for these complex patterns are poorly understood. The general correspondence of many Phanerozoic structures to Precambrian basement features, such as noted along the MRS in Iowa, suggests that midcontinent Phanerozoic tectonism may be, in part, a reactivation of earlier structures by deep seated crustal processes.

Text Figure #3 near here

The Phanerozoic burial histories of three different portions of the Forest City Basin-Nemaha Uplift region are depicted in text figure 3. These subsidence curves were constructed by following the general guidelines discussed by Siever (1983), although no attempt was made to estimate the rates or magnitudes of compactional thinning during the accumulation of the strata. We have, however, made an attempt to estimate the magnitudes of erosional exhumation that occurred during extended periods of emergence and/or uplift. The gross timing of depositional and erosional episodes of all three areas were generally similar, but differences in the original depositional thicknesses, chronologies and magnitudes of post-depositional erosion, and resulting preserved thicknesses illustrate the influence of differential vertical crustal movements on the Phanerozoic stratigraphy of this region.

The Forest City Basin was a relatively short-lived asymmetric fault-bounded sedimentary basin that subsided in synchrony with the ascension of the Nemaha Uplift along the mutually bounding Humboldt Fault Zone during Absaroka Sequence deposition (text fig. 3, A and B). Earlier and subsequent Phanerozoic sedimentation in the area occurred in short-lived depositional basins whose structural geometries were strikingly dissimilar. The resulting superimposition of several discordant structural, depositional, and erosional patterns in the area obviates simple classification of Phanerozoic structural elements in the central midcontinent. Text figure 3 shows that the center of the Forest City Basin (text fig. 3, A; Absaroka Sequence), the crest of the Nemaha Uplift (text fig. 3, B; Tippecanoe Sequence, North Kansas Basin), and the eastern margin of the Forest City Basin in central Iowa (text fig. 3, C; Sauk Sequence; Kaskaskia Sequence, Iowa Basin) each have been the locus of maximum subsidence during different Paleozoic intervals. Subsequent Mesozoic and Cenozoic sedimentation in the region was controlled by tectonic and depositional regimes which were grossly dissimilar to the preceding Paleozoic history.

Paleogeographic syntheses of various Phanerozoic intervals in North America indicate that intraplate tectonism can be grossly correlated with episodes of orogenesis along the continental margins. High angle faulting along the Humboldt

Fault Zone apparently was contemporaneous with high angle block-faulting in the Ancestral Rockies of the western Cordillera, and has been related to collisional tectonics in the Ouachita-Marathon thrust belt (Kluth and Coney, 1981). Likewise, the development of the north-south trending Mesozoic foreland basins of North America have been placed in a larger plate tectonic context (Brenner, 1983; Weimer, 1983). Bevelling of Cretaceous rocks by Cenozoic strata along the Chadron Arch and the western flank of the Nemaha Uplift indicates tectonic activity that was roughly contemporaneous with the development of similarly-oriented, but larger-scale Laramide uplifts to the west. These regional relationships indicate that potential exists for integrating the Pennsylvanian-Cenozoic history of the central midcontinent region into a larger continent-wide tectonic synthesis. The relationships between earlier Paleozoic structural patterns in the central midcontinent and coeval crustal deformation along the continental margins are more obscure, however.

The Phanerozoic crustal dynamics of the central midcontinent region present some of the most intriguing challenges to those interested in mechanically modelling intraplate tectonism. It is still unclear to us which structures and deformational episodes would be best explained in terms of isostatic crust-mantle interactions vs. deviatoric stresses in the shallow crust. For example, does the emplacement of Early Cretaceous kimberlites along the axis of the Nemaha Uplift (Brookins and Naeser, 1971) indicate an extensional stress regime or anomalous heat flow during Mesozoic reactivation of the structure (Witzke et al., 1983, p. 228)? How can the multiple reversals in the direction of vertical crustal movement which characterized much of this region be explained? Finally, can the magnitudes of relative vertical crustal movements in the midcontinent be filtered from the stratigraphic record to deduce the magnitudes of Phanerozoic eustatic sea level changes? Sleep, Nunn, and Chou (1980, p. 31) have used the mean elevation to the Dakota Formation-Graneros Shale contact from 90 well logs in northwest Iowa to deduce the magnitude of eustatic sea level change since the mid-Cenomanian. Structure contouring of the overlying Turonian Greenhorn Limestone (Bunker, 1981, p. 16), however, shows that the Cretaceous rocks of the region have experienced relative vertical displacements of greater than 250 m. We are unable to discern any stable "benchmark" in the region to which other areas might be compared, and so find no reason to suppose that any part of the central midcontinent has remained at a constant elevation relative to other areas for the last 100 million years.


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Plate 3 Figure Captions

**Figure 1.** Structural configuration of the Precambrian surface in the central midcontinent. Contour interval is 300 m; dashed where Cambrian clastic rocks (Mt. Simon-Lamotte-Reagan) overlie Precambrian clastics and position of contact is uncertain. M-Manson Anomaly, a cryptoexplosion structure. HFZ-Humboldt Fault Zone. Modified from Thwaites, 1957; Bradbury and Atherton, 1965; Carlson, 1966; Kisvarsanyi, 1975; Cole, 1976; Bunker, 1982.

**Figure 2.** Sauk isopach map (excludes Mt. Simon Sandstone). Contour interval is 50 m. Δ-Sauk rocks absent, paleotopographic highs of Precambrian rocks directly overlain by younger strata. Modified from Merriam, 1963; Koenig, 1967; Carlson, 1970; Buschbach, 1975; Willman and Buschbach, 1975; Cole, 1975; Bunker, 1982.

**Figure 3.** Tippecanoe isopach map (excludes St. Peter Ss-lower Simpson sand). Contour interval is 50 m. Modified from Merriam, 1963; Carlson, 1970; Willman and Atherton, 1975; Willman and Buschbach, 1975; Cole, 1975; Bunker, 1982.

**Figure 4.** Silurian isopach map. Contour interval is 50 m. PRFZ-Plum River Fault Zone. After Witzke, 1981.

**Figure 5.** Pre-Kaskaskia paleogeologic map. Modified from Merriam, 1963; Carlson, 1963, 1970; Miller, 1971, Bunker, 1982.

**Figure 6.** Total Devonian isopach map. Contour interval is 50 m. PRFZ-Plum River Fault Zone. Modified, in part, from Collinson, 1967; Hilpman, 1967; Carlson, 1970.

**Figure 7.** Total Mississippian isopach map (includes undifferentiated Upper Devonian rocks in the Hugoton Embayment area). Contour interval is 50 m. AFCB-"Ancestral" Forest City Basin (Lee, 1946); MB-"Massena basin;" AT-"Appanoose trough." Modified from Carlson, 1970; Horick and Steinhilber, 1973; Craig and Conner, 1979.

**Figure 8.** Pre-Absaroka paleogeologic map. PRFZ-Plum River Fault Zone. Modified from Carlson, 1963; Merriam, 1963; Willman and others, 1967; Bunker 1982; Bunker et al., 1985.

**Figure 9.** Lower and Middle Pennsylvanian isopach map. Basal Upper Pennsylvanian rocks (Pleasanton Gp) are included. Contour interval is 50 m. FCB-Forest City Basin; SB-Salina Basin; NU-Nemaha Uplift. SKB-Sedgwick Basin. HE-Hugoton Embayment. Modified from McKee and Crosby, 1975; Bunker, 1982; Burchett, 1982.

**Figure 10.** Pre-Cretaceous paleogeologic map. Modified from Andrews, 1958; Carlson, 1963; Merriam, 1963; Willman and Frye, 1975; Bunker, 1981; Burchett, 1982; Munter et al., 1983.

**Figure 11.** Sub-Tertiary and present-day outcrop distribution of Cretaceous stratigraphic units. M-Manson Anomaly, a cryptoexplosion structure. Modified from Fuenning, 1942; Merriam, 1963; Burchett, 1969; Willman and Frye, 1975; DeGraw, 1971; Bunker, 1981; Munter et al., 1983.

**Figure 12.** Total Cretaceous isopach map. Contour interval is 150 m. M-Manson Anomaly, a cryptoexplosion structure. Modified from Fuenning, 1942; Gries, 1954; Meriam, 1963; Willman and Frye, 1975; DeGraw, 1971; Munter et al., 1983.

Text Figure Captions

Figure 1. Generalized correlation diagram of Phanerozoic stratigraphic units in the central midcontinent. Largely adapted from GSA COSUNA correlation charts.

Figure 2. Generalized Upper Pennsylvanian "Kansas cyclothem." Modified from Heckel, 1977, 1980.

Figure 3. Phanerozoic subsidence curves in the region of the Forest City Basin. A. Center of Forest City Basin at tri-state border of Nebraska, Kansas, and Missouri. B. Crest of Nemaha Uplift in southern Pawnee County, Nebraska. C. Eastern margin of Forest City Basin, in northwest Madison County, Iowa. Based on published data in Carlson, 1970; Burchett, 1982; Bunker, 1982; and Witzke et al., 1983.

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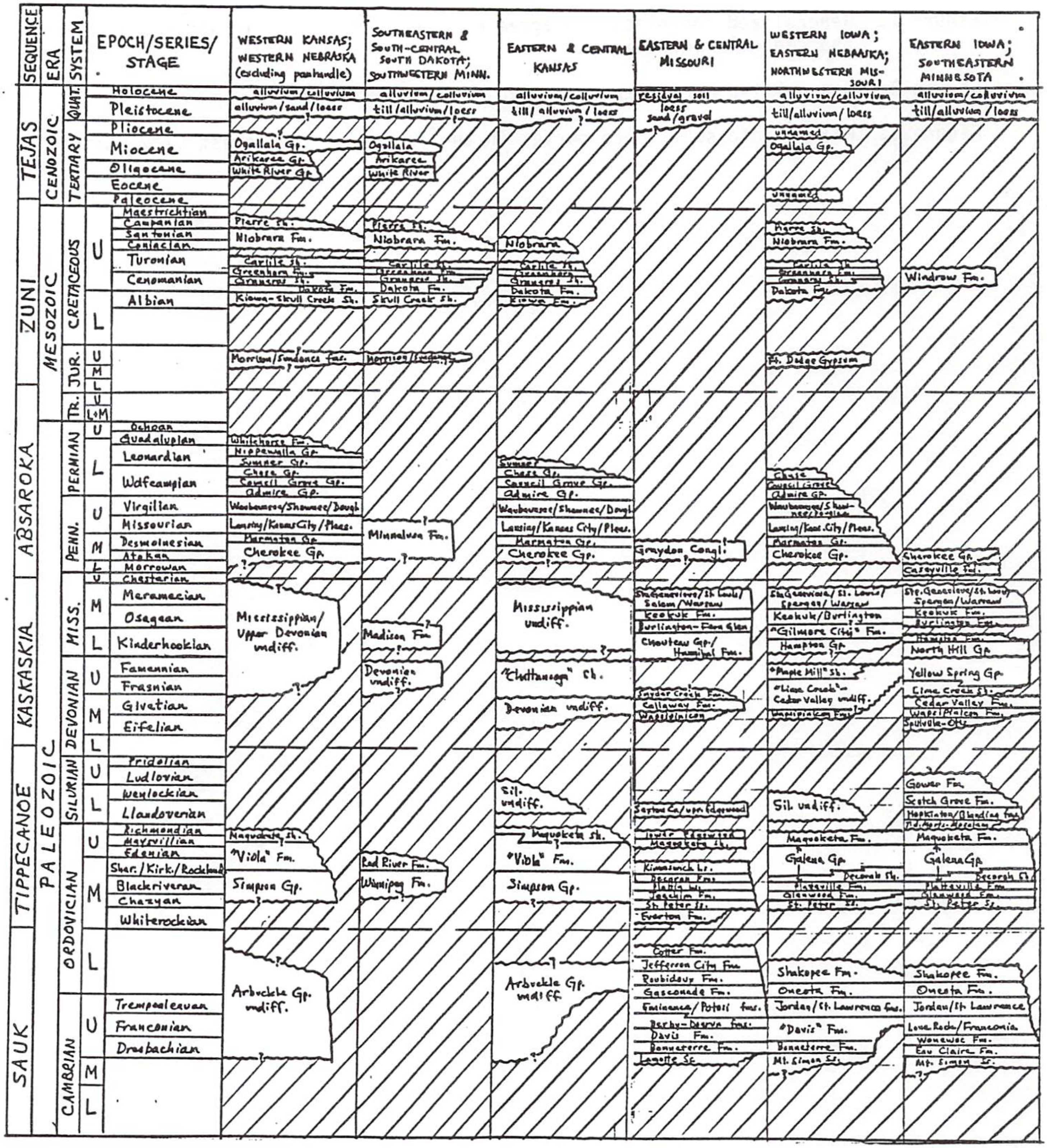
Text Figure Captions

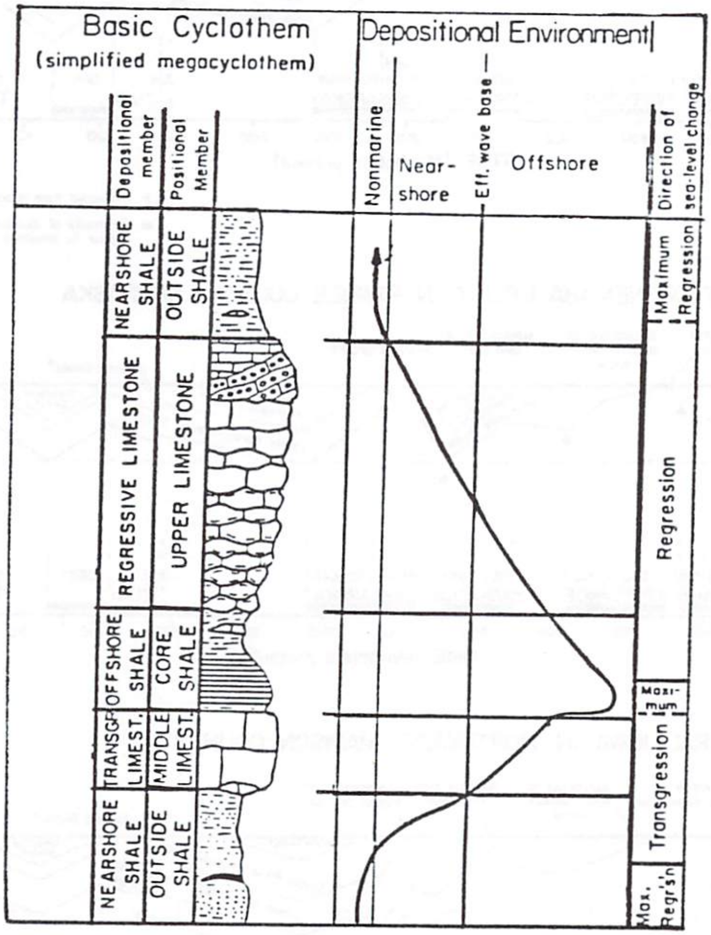
Figure 1. Generalized correlation diagram of Phanerozoic stratigraphic units in the central midcontinent.

Figure 2. Generalized Upper Pennsylvanian "Kansas cyclothem."

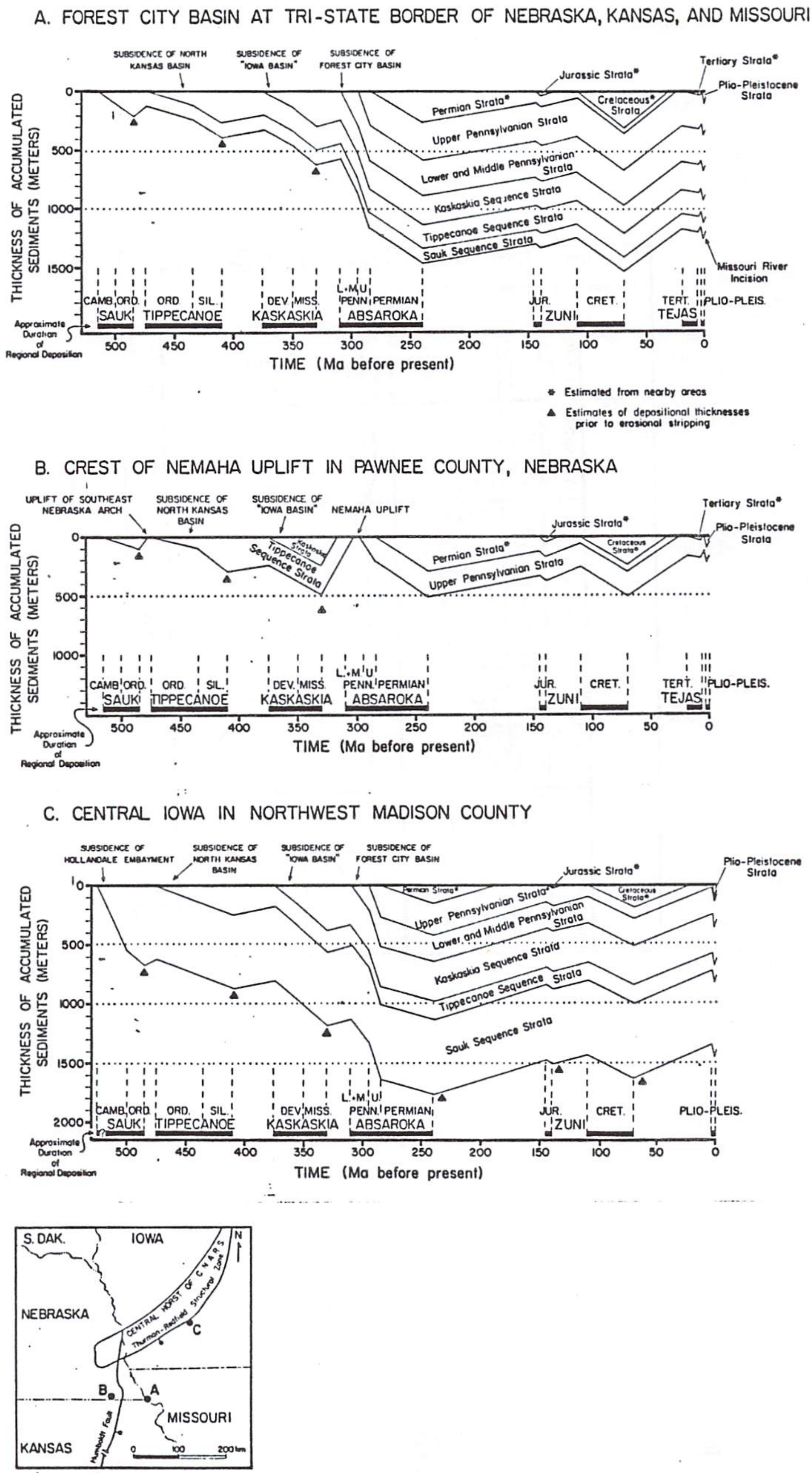
Figure 3. Phanerozoic subsidence curves in the region of the Forest City Basin.




TEXT FIGURE 1




TEXT, FIGURE 2




TEXT FIGURE 3

# KEY

## MAPS

- Present day outcrop area. Covered in part across the northeast 3/4 of the study area by Pleistocene glacial deposits.
- Tertiary. Line denotes present known eastern extent.

K — Cretaceous
- Area of pre-Cretaceous erosion and overlap
- $K_u$ Undifferentiated
- $K_d$-$K_b$ Dakota Fm.-Baylis Fm.
- $K_w$ Windrow Fm.
- $K_B$ Benton Group (includes Graneros-Greenhorn-Carlile Fms.)
- $K_n$ Niobrara Fm.
- $K_p$ Pierre Fm.

J — Jurassic
- Area of pre-Jurassic erosion and overlap

P — Permian

IP — Pennsylvanian
- Area of pre-Pennsylvanian erosion and overlap

M — Mississippian
- Area of pre-Mississippian erosion and overlap

D — Devonian
- Area of pre-Devonian erosion and overlap

S — Silurian

U&MO — Upper and Middle Ordovician

LO — Lower Ordovician

Є — Cambrian

PЄ — Precambrian undifferentiated
- Sioux Quartzite
- Keweenawan intrusive and extrusive rocks
- Keweenawan sedimentary rocks

## CROSS-SECTIONS

Precambrian

- Clastic rocks (sandstone, siltstone, shale)
- Mafic igneous rocks (basalt, gabbro)
- Quartzite (minor argillite/phyllite)
- Igneous & Metamorphic rocks undifferentiated (mostly granitic)

Plate 3 Figure Captions (For Table of Contents)


Figure 1. Structural configuration of the Precambrian surface in the central midcontinent.

Figure 2. Sauk isopach map.

Figure 3. Tippecanoe isopach map.

Figure 4. Silurian isopach map.

Figure 5. Pre-Kaskaskia paleogeologic map.

Figure 6. Total Devonian isopach map.

Figure 7. Total Mississippian isopach map

Figure 8. Pre-Absaroka paleogeologic map.

Figure 9. Lower and Middle Pennsylvanian isopach map.

Figure 10. Pre-Cretaceous paleogeologic map.

Figure 11. Sub-Tertiary and present-day outcrop distribution of Cretaceous stratigraphic units.

Figure 12. Total Cretaceous isopach map.

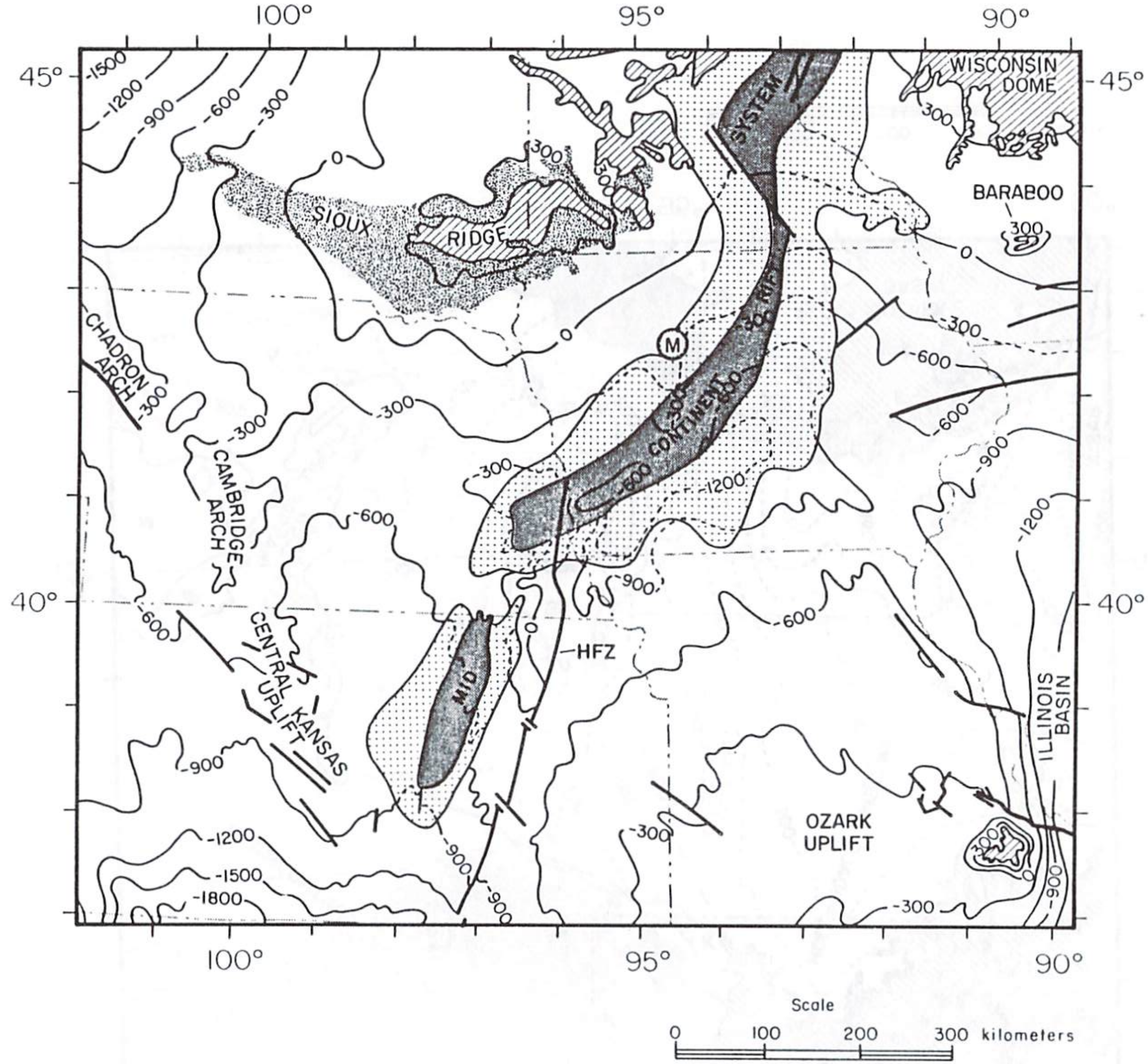
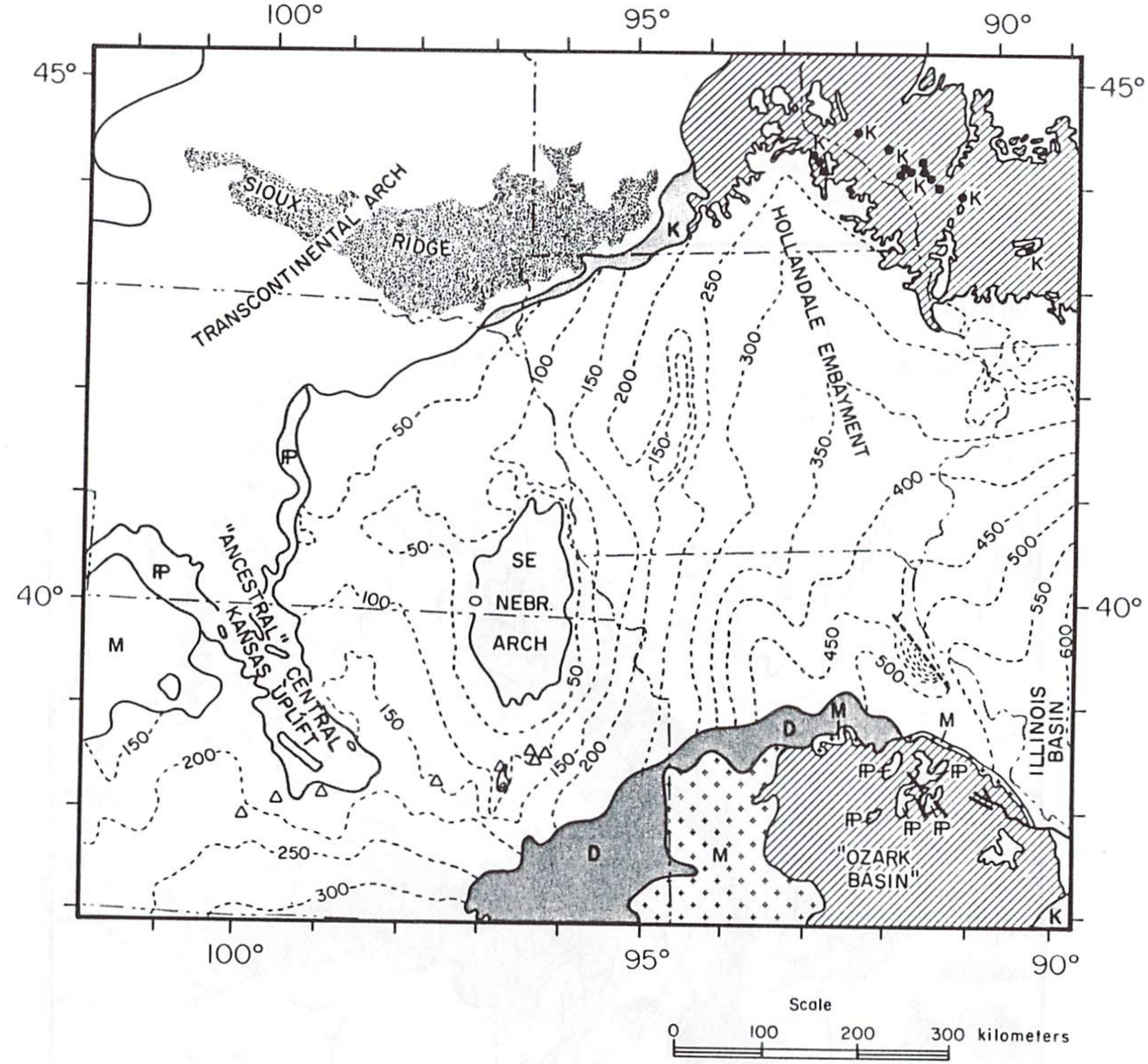



Plate 2, Figure 1



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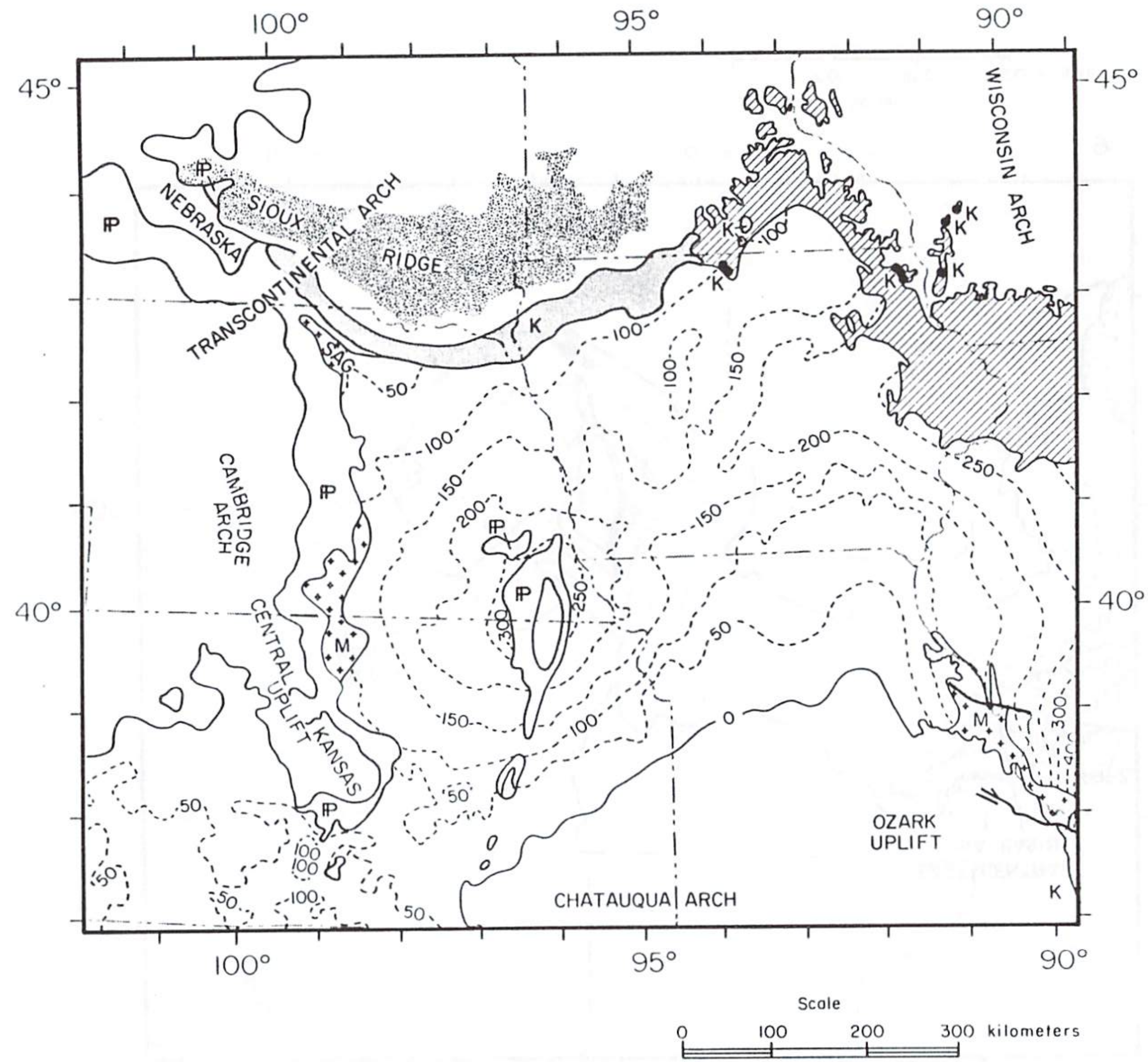
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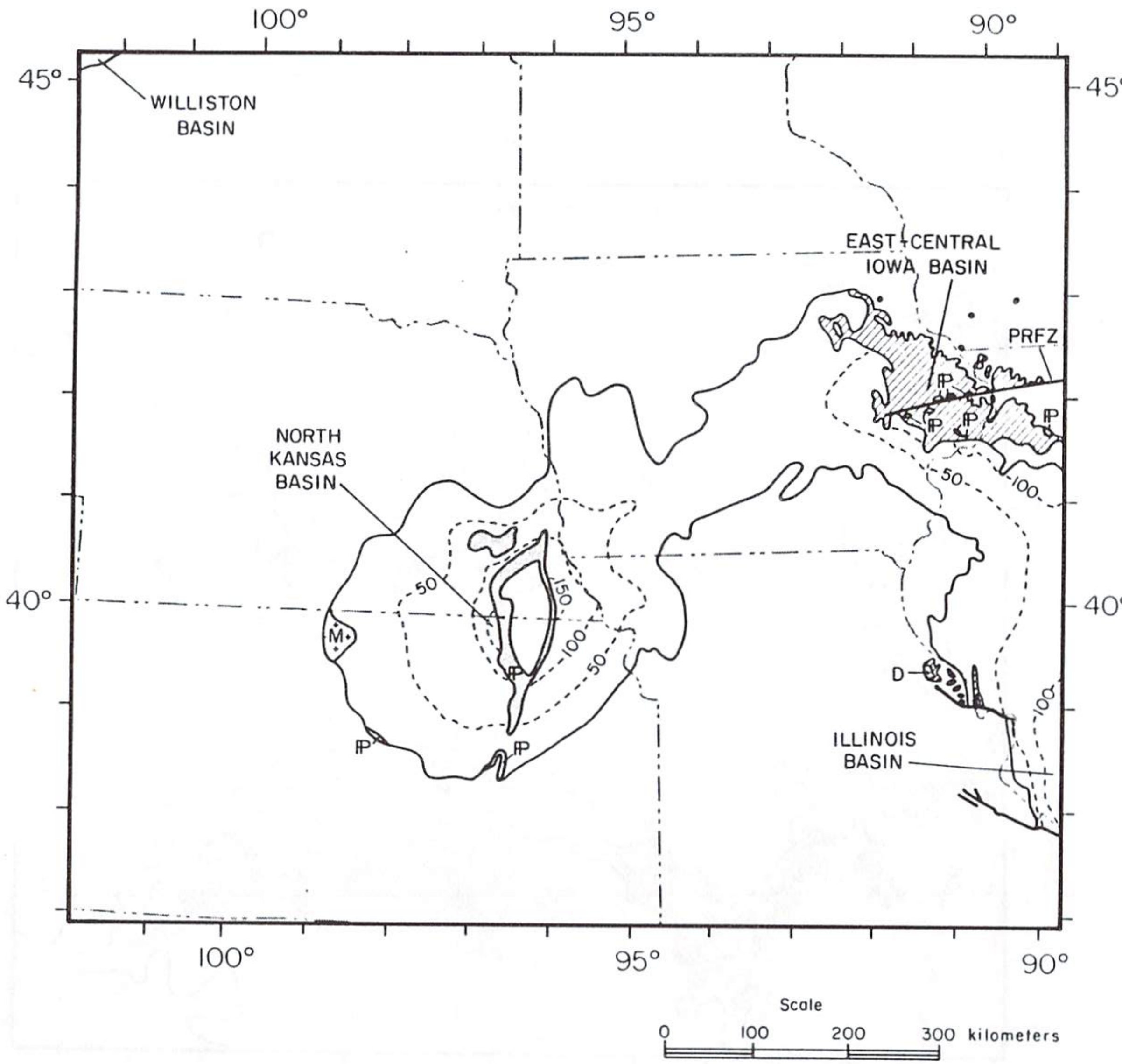
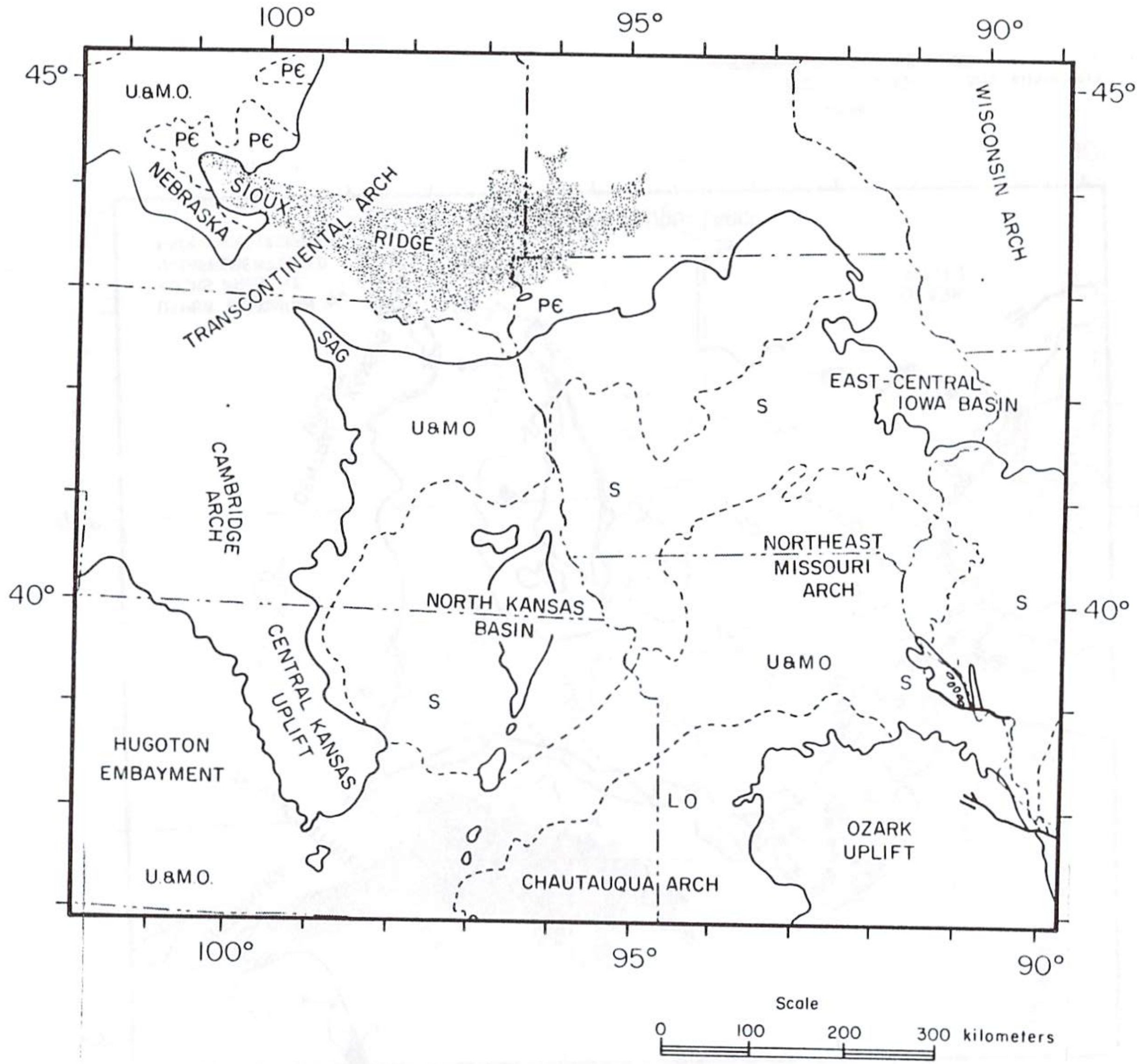



Plate 3, Figure 4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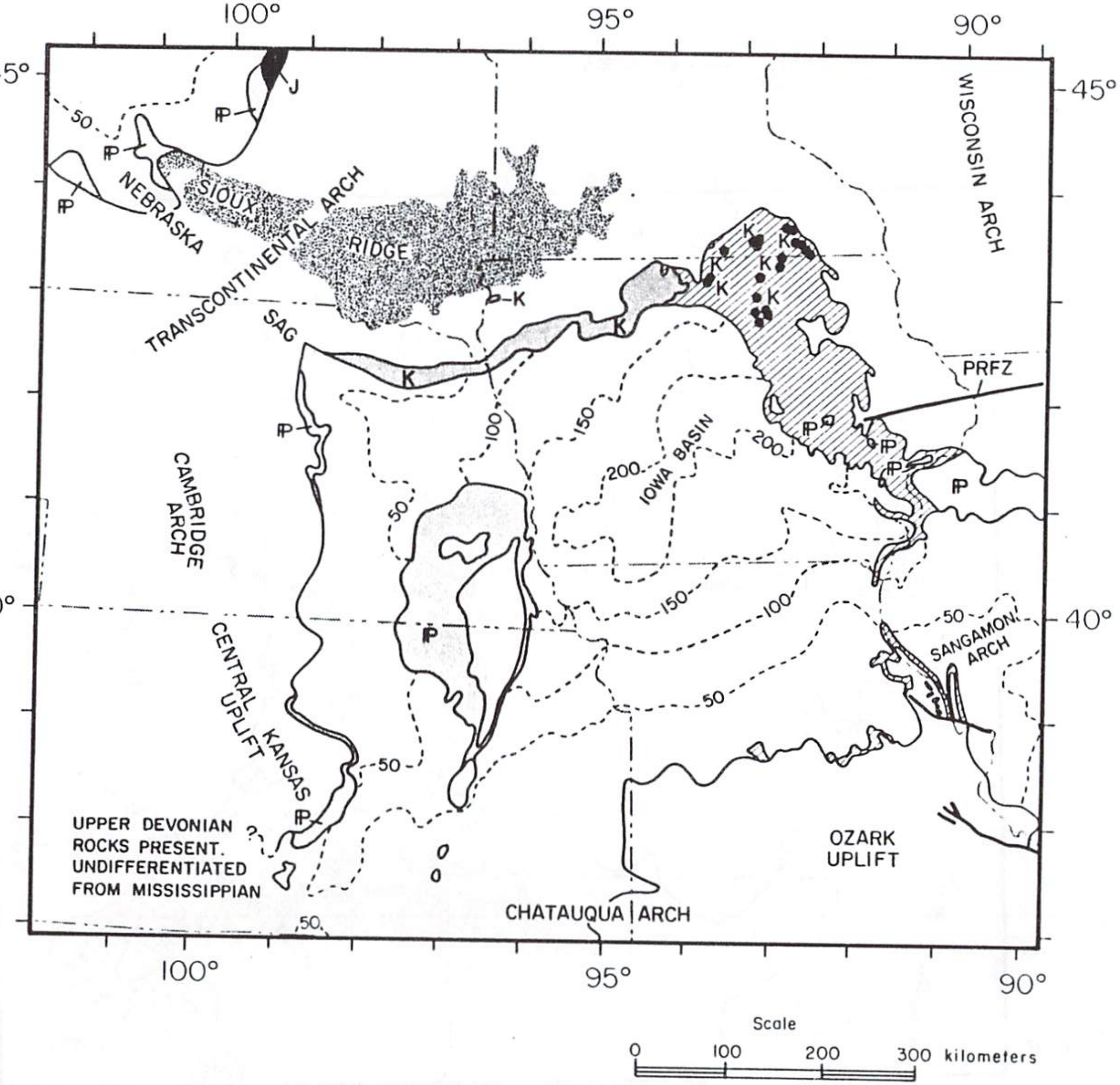

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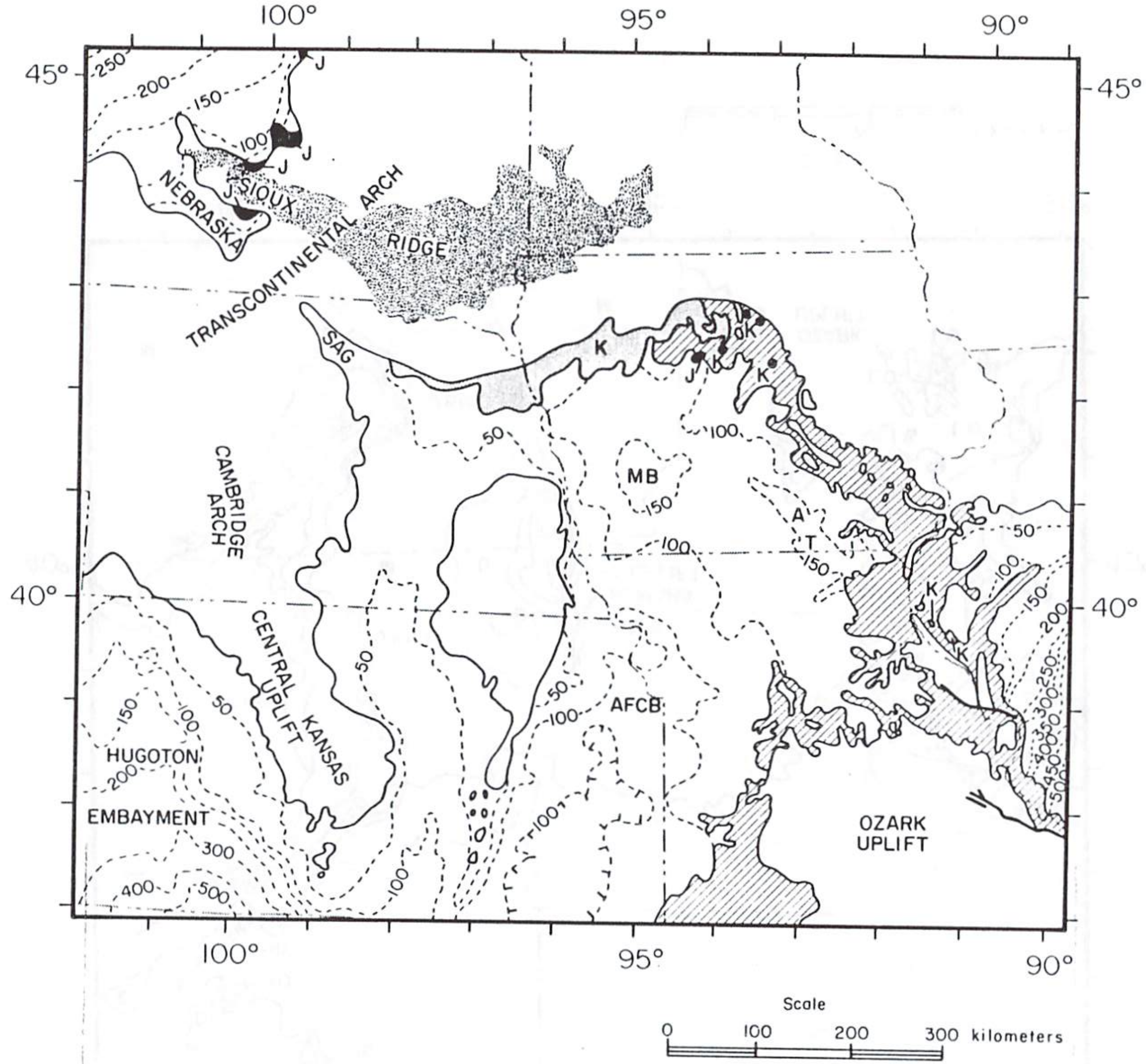
Plate



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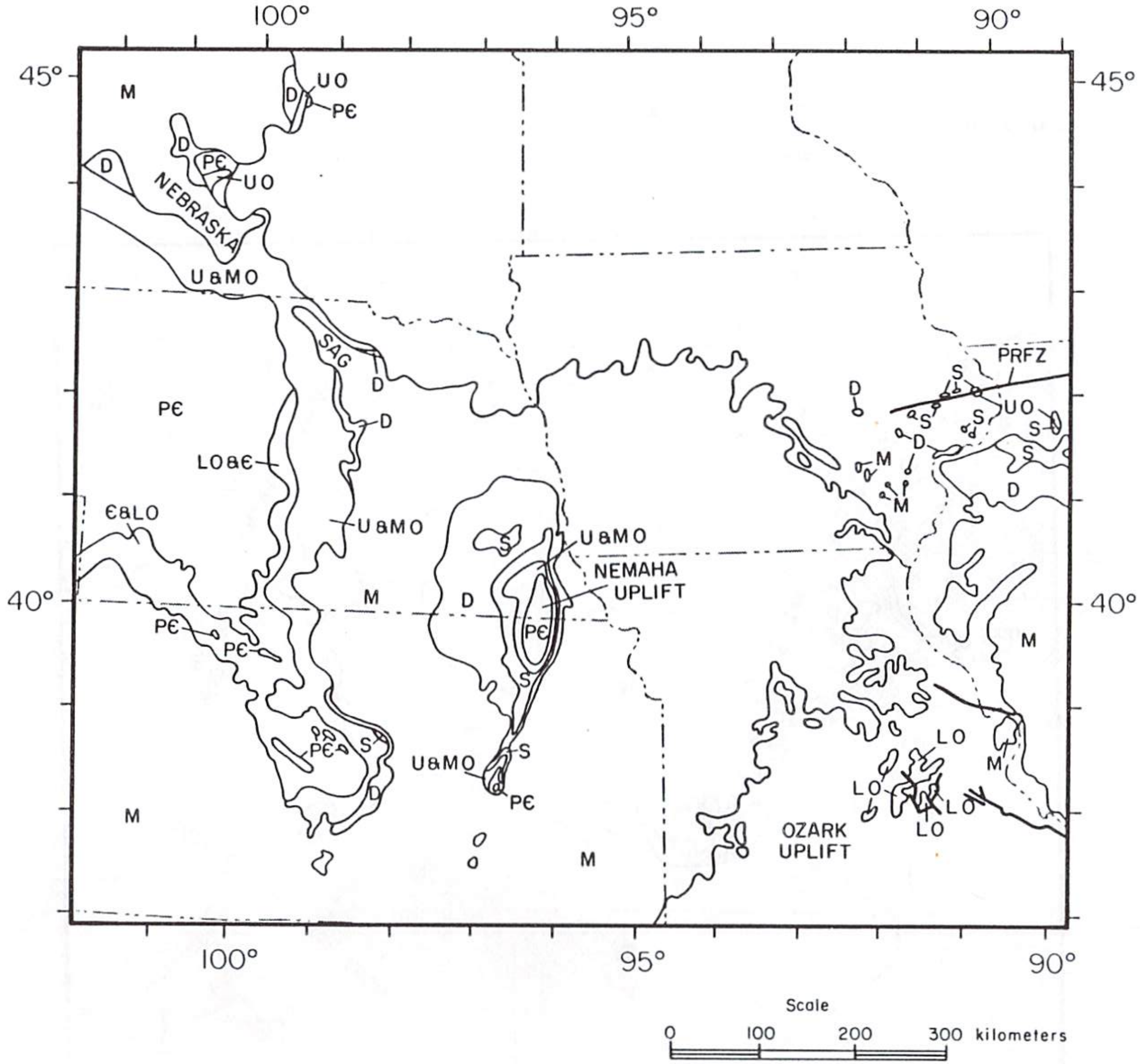



Plate 3 Figure 8

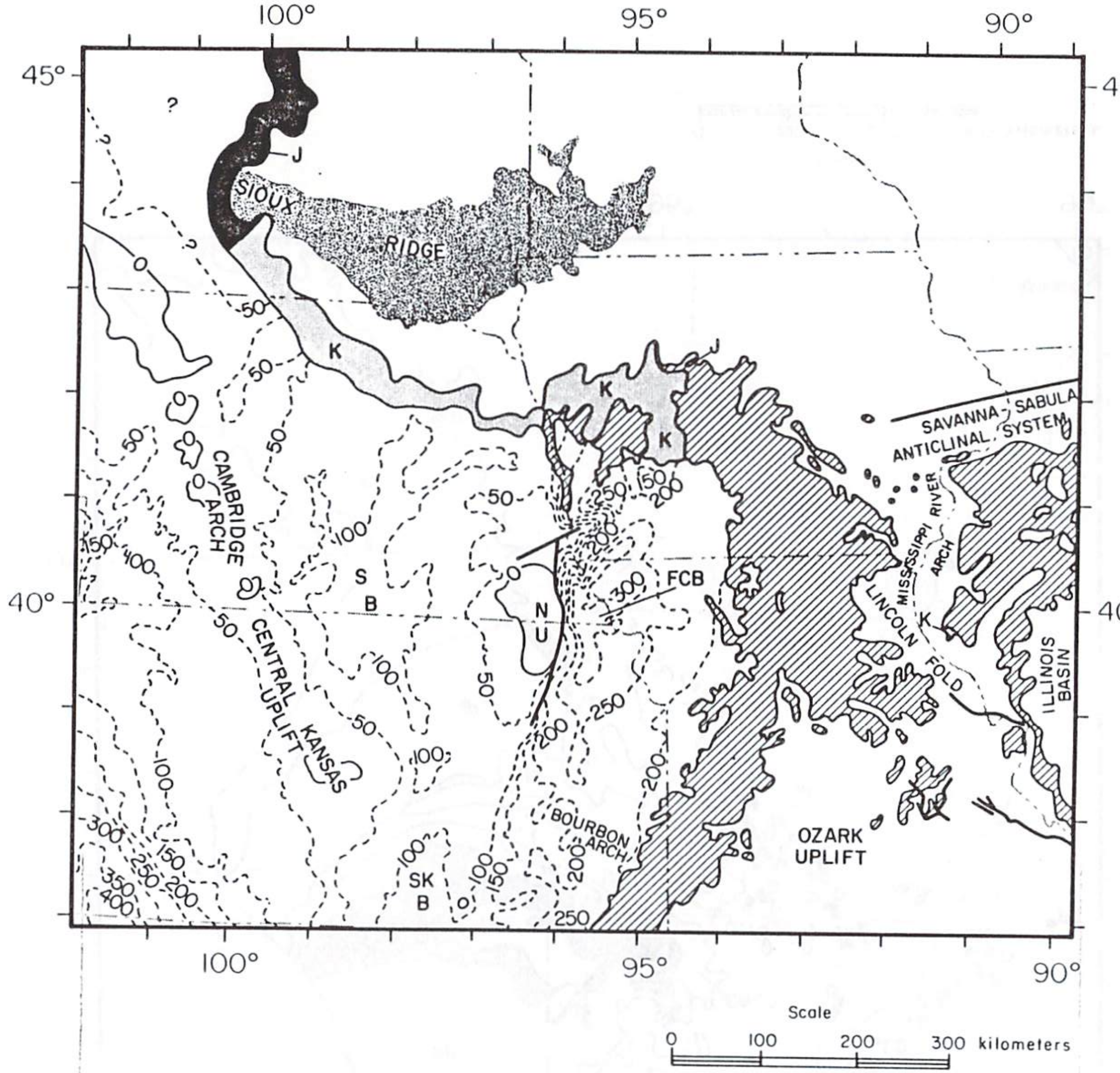



Plate [illegible] Figure 9

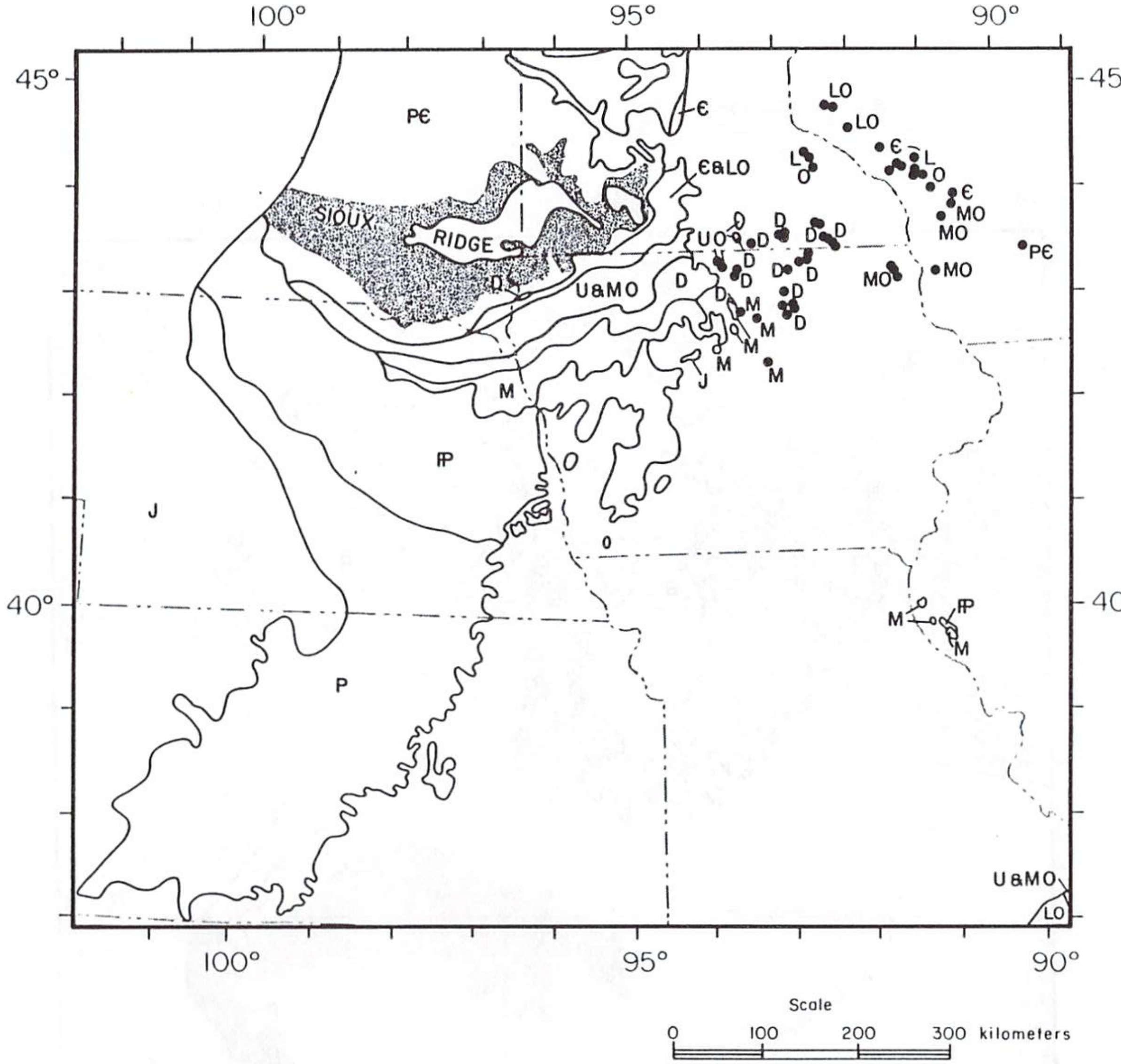



Plate 3, Figure 10

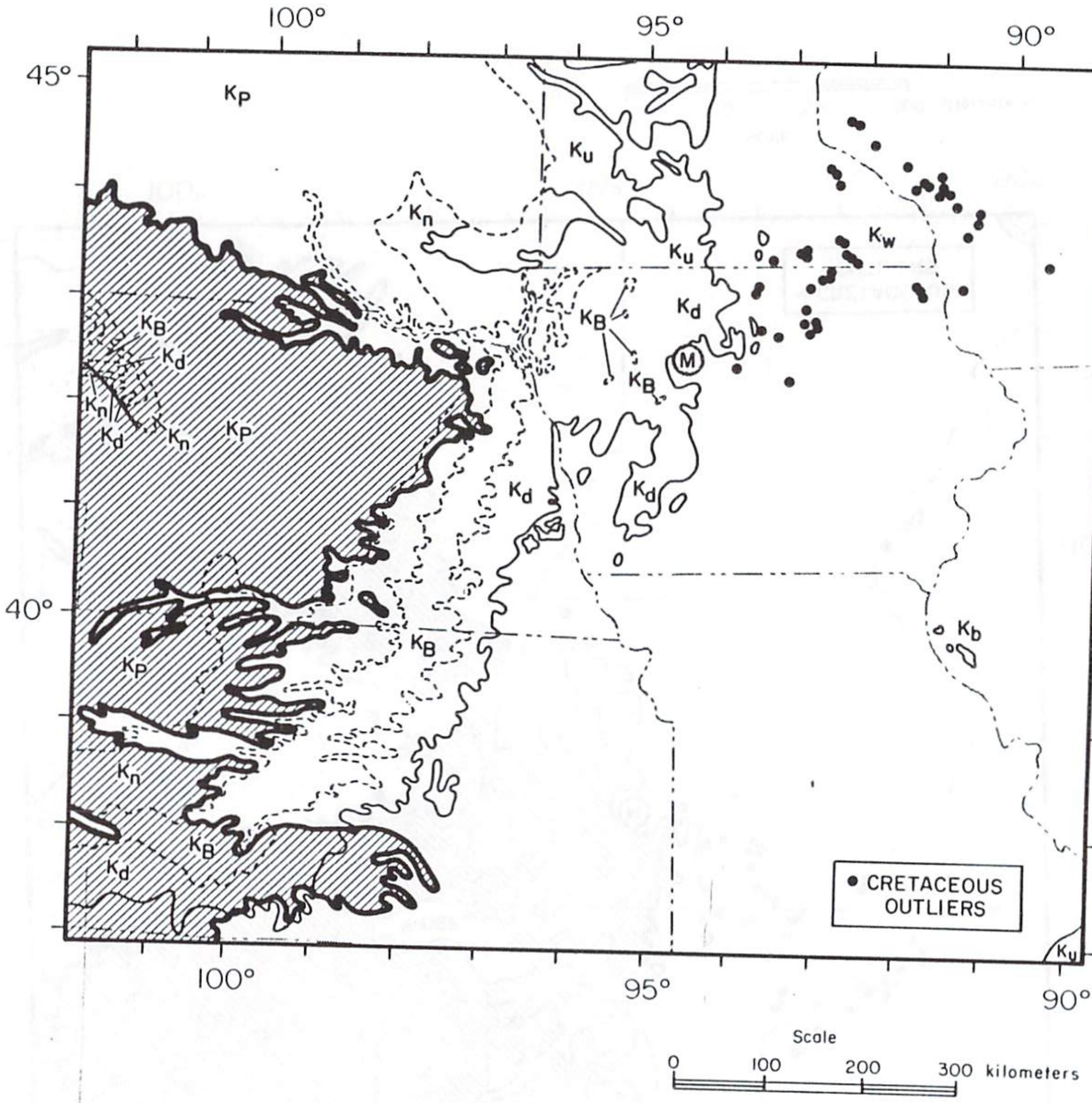



Plate 3 Figure 4

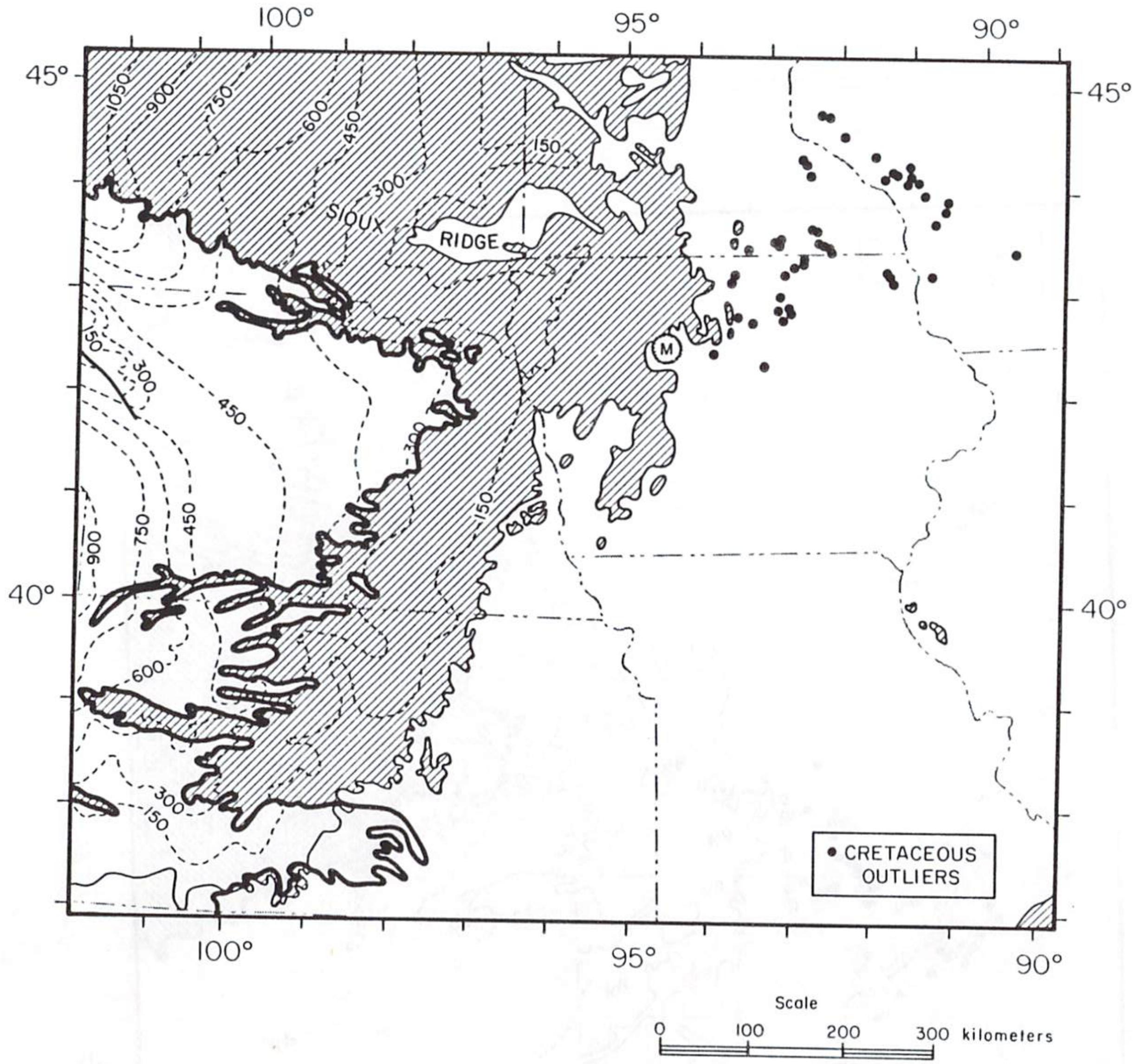
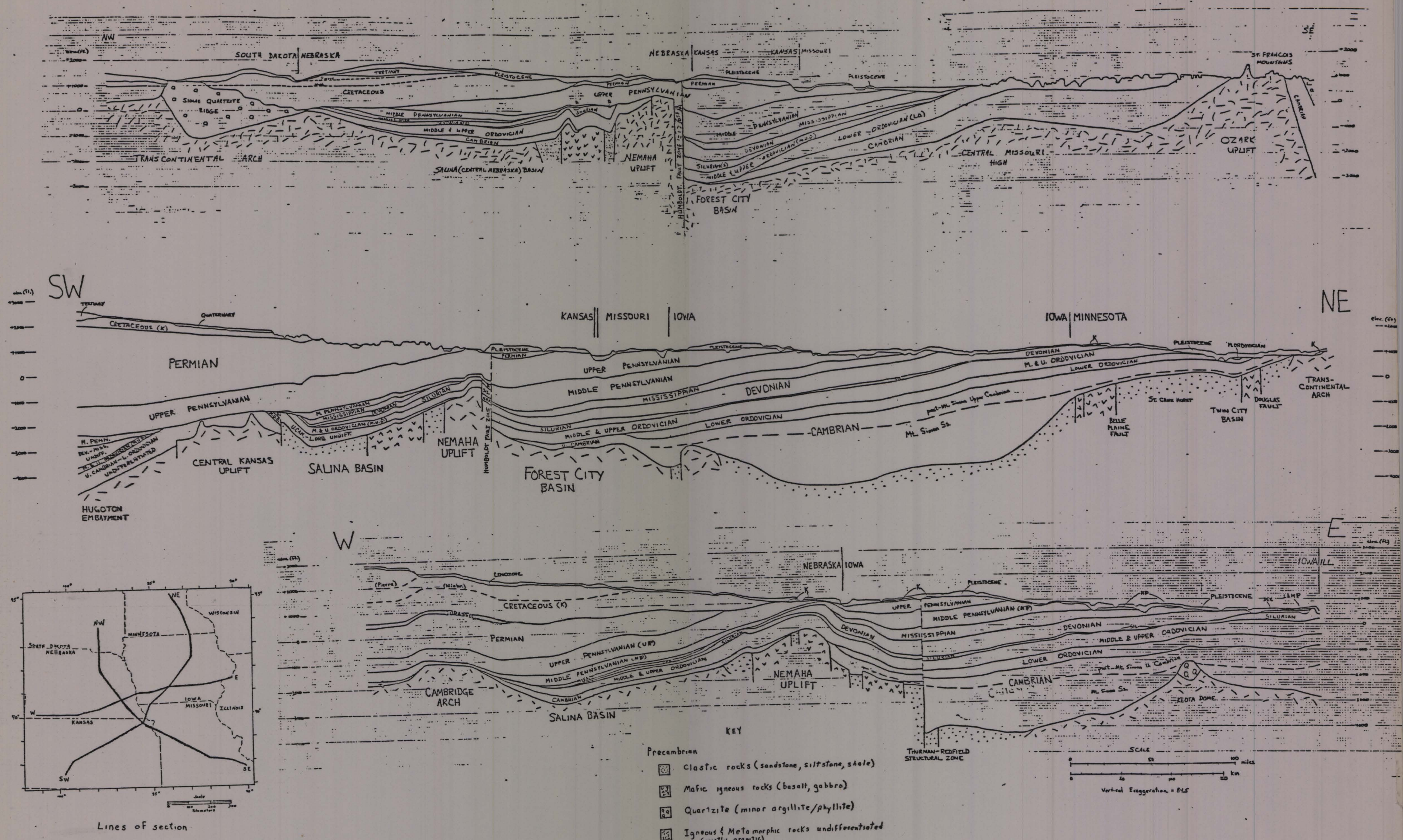



Plate 3, Figure 12


NW
SE
SOUTH DAKOTA
NEBRASKA
KANSAS
MISSOURI
TERTIARY
PLEISTOCENE
CRETACEOUS
PERMIAN
UPPER PENNSYLVANIAN
MIDDLE PENNSYLVANIAN
MIDDLE & UPPER ORDOVICIAN
CAMBRIAN
MISSISSIPPIAN
DEVONIAN
LOWER ORDOVICIAN (LO)
SIOUX QUARTZITE RIDGE
TRANSCONTINENTAL ARCH
SALINA (CENTRAL NEBRASKA) BASIN
NEMAHA UPLIFT
HUMBOLDT FAULT ZONE
FOREST CITY BASIN
CENTRAL MISSOURI HIGH
OZARK UPLIFT
ST. FRANCOIS MOUNTAINS
SW
NE
TERTIARY
QUATERNARY
CRETACEOUS (K)
IOWA
MINNESOTA
PERMIAN
UPPER PENNSYLVANIAN
MIDDLE PENNSYLVANIAN
MISSISSIPPIAN
DEVONIAN
SILURIAN
MIDDLE & UPPER ORDOVICIAN
LOWER ORDOVICIAN
M. & U. ORDOVICIAN
CAMBRIAN
Mt. Simon Ss.
post-Mt. Simon Upper Cambrian
M. PENN.
CENTRAL KANSAS UPLIFT
SALINA BASIN
NEMAHA UPLIFT
HUMBOLDT FAULT ZONE
FOREST CITY BASIN
HUGOTON EMBAYMENT
BELLE PLAINE FAULT
St. Croix Horst
TWIN CITY BASIN
DOUGLAS FAULT
TRANS-CONTINENTAL ARCH
W
E
NEBRASKA
IOWA
ILL
CENOZOIC
CRETACEOUS (K)
JURASSIC
PERMIAN
UPPER PENNSYLVANIAN (UP)
MIDDLE PENNSYLVANIAN (MP)
MIDDLE & UPPER ORDOVICIAN
DEVONIAN
MISSISSIPPIAN
SILURIAN
LOWER ORDOVICIAN
CAMBRIAN
Mt. Simon Ss.
post-Mt. Simon U. Cambrian
PLEISTOCENE
CAMBRIDGE ARCH
SALINA BASIN
NEMAHA UPLIFT
THURMAN-REDFIELD STRUCTURAL ZONE
KEOTA DOME
SCALE
miles
km
Vertical Exaggeration = 845
MINNESOTA
WISCONSIN
SOUTH DAKOTA
NEBRASKA
IOWA
MISSOURI
ILLINOIS
KANSAS
Lines of section
KEY
Precambrian
Clastic rocks (sandstone, siltstone, shale)
Mafic igneous rocks (basalt, gabbro)
Quartzite (minor argillite/phyllite)
Igneous & Metamorphic rocks undifferentiated (mostly granitic)