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CRETACEOUS STRATIGRAPHY AND SEDIMENTATION
IN NORTHWEST IOWA, NORTHEAST NEBRASKA, & SOUTHEAST SOUTH DAKOTA

a field guide with research papers for the meeting of the North-Central Section of the Geological Society of America

by R.L. Brenner, R.F. Bretz, B.J. Bunker, D.L. Iles, G.A. Ludvigson, R.M. McKay, D.L. Whitley, and B.J. Witzke *with additional papers by* W.A. Cobban, E.M. Merrewether, R.L Ravn, and G.W. Shurr

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with additional papers
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The stratigraphic nomenclature and classification used in portions of this report do not necessarily conform to the current formal usage of the Iowa Geological Survey.

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Cover Photo: Field Trip Stop 3: West wall of Ballou Quarry showing lower mudrock section overlain by coaly-shale and cross-stratified sandstone. Geologists in foreground are examining plant fossils in blocks of sandstone float from upper unit; by R.L. Brenner.

THE TECTONIC HISTORY OF THE TRANSCONTINENTAL ARCH AND NEMAHA UPLIFT AND THEIR RELATIONSHIP TO THE CRETACEOUS ROCKS OF THE CENTRAL MIDCONTINENT REGION

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ABSTRACT

Laramide tectonism has modified the original depositional fabric of Cretaceous rocks in the northern Great Plains states. Studies of the Phanerozoic history of many of the tectonic features in the midcontinent region show that they have experienced episodic deformation since the Precambrian. These periods of tectonic activity correspond with regional cratonic unconformities as defined by Sloss (1963). Laramide orogenic events reactivated many of these older midcontinent features that were active during the Paleozoic. The Nemaha Uplift of southeast Nebraska and northeast Kansas has shown a consistent history of recurrent activity, having had its origins in pre-Middle Ordovician time (Southeast Nebraska Arch). Structural mapping of the Greenhorn Limestone in the central midcontinent indicates that Laramide orogenic events reactivated the Nemaha Uplift. Overstepping of Tertiary sediments on regionally truncated Cretaceous rocks can be recognized in eastern Nebraska and northwestern Iowa as the crest of the Nemaha Uplift is approached.

INTRODUCTION

Widely held misconceptions of the tectonic history of the "stable interior" of the North American continent have long been impediments to an understanding of the regional stratigraphy in the midcontinent area. An examination of the geologic history of this region shows that it has experienced episodic tectonism since the Precambrian and is still microseismically active today. Until the last couple of years conventional wisdom has dictated that no structural complications exist in the Cretaceous rocks of the eastern margin of the great Western Interior seaway.

The purpose of this report is to establish the present structural configuration of the Cretaceous rocks in the central midcontinent region through the use of a series of paleogeologic maps and a structure map of the top of the Greenhorn Limestone (Upper Cretaceous).

THE TRANSCONTINENTAL ARCH AND SIOUX QUARTZITE RIDGE: HISTORY OF TERMINOLOGY

The north-central midcontinent region is characterized by broad regional domes, arches, and basins with gently dipping strata. Because comparatively mild episodic crustal deformation has effected this region during the last half billion years of earth's history, much of the intervening rock record is preserved nearly in its original depositional fabric. Therefore, the midcontinent region of North America provides an opportunity to study in detail the tectonic behavior of a cratonic area spanning most of the Phanerozoic Eon.

Dividing the central interior of the North American continent is a major structural feature which is called the "Transcontinental Arch". Schuchert (1923) first made reference to the nucleus of North America, which has since the Proterozoic "lain but little above sea level, warping periodically up or down some hundreds of feet". This feature he termed "Siouia".

Keith (1928) in discussing the structural symmetry of North America suggested that a great syncline should have been formed in the continental interior between the folded continental margins. Closer examination, however, revealed that a major syncline (Denver Basin, McCoy, 1953) is represented at the surface, but does not propagate downwards very far before it becomes a major anticline. He termed this feature the "continental backbone" of the North American continent.

Levorson (1931) was the first to refer to it as the "continental arch". Eardley (1949) coined the term "Trans-Continental Arch". Figure 1 shows the general position of the Transcontinental Arch in the central midcontinent region.

Other names have similarly been applied to the Transcontinental Arch, such as the Sioux Falls "high" (Fuenning, 1942, p. 1535) and the "Sioux Uplift" (Ballard, 1942, p. 1571). These names were derived because of the exposures of Precambrian Sioux Quartzite around the Sioux Falls, South Dakota area. A poor understanding of the significance of the Precambrian Sioux Quartzite exposures has led to the mininterpretation of

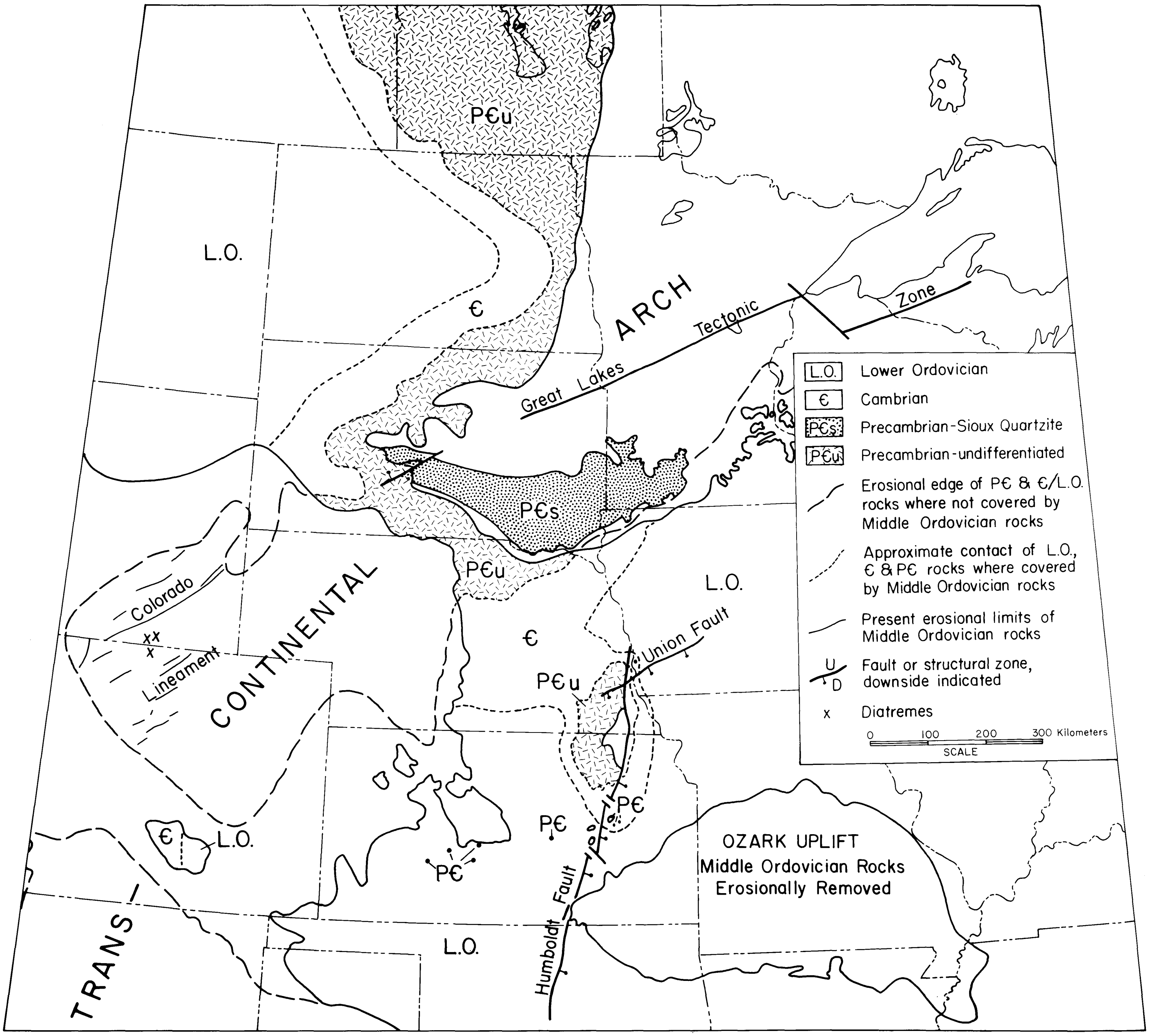

Figure 1. Pre-Middle Ordovician (pre-Tippecanoe) paleogeologic map of the north-central midcontinent region (modified from Adler, et al., 1971; Chronic, et al., 1969; Davison, 1979; Fuller, 1961; Lidiak, 1971; Merriam, 1963; Miller, 1971; Morey and Sims, 1976; Sims, 1970; Sims, et al., in prep.; Warner, 1978; and Witzke, 1980).

a major structural feature in the central midcontinent region.

Baldwin (1949, p. 12) states that "the Sioux Quartzite forms an east-west trending ridge, with dips that suggest the ridge is a partly buried erosional remnant of a greatly downwarped portion of the Sioux Quartzite which has been more resistant than the flanking bedrock units". He also considers that "the Sioux Quartzite structure is an east-west trending syncline or group of synclines" comparable to the well-known synclinal pattern of the Baraboo Quartzite in Wisconsin. Figure 1 shows the relative position of the Sioux Quartzite Ridge to the Transcontinental Arch.

Phanerozoic rocks have onlapped and overstepped the ridge repeatedly only to be erosionally removed and beveled back between successive transgressive cycles. The paleogeologic maps in this report illustrate that the zero and/or erosional edge of many Paleozoic rock units parallel the southern edge of the Sioux Quartzite Ridge.

HISTORY OF STRUCTURAL DEVELOPMENT

The sedimentary record from very late Precambrian to the present has been characterized by Sloss (1963) as being comprised of sedimentary rock sequences separated by major interregional unconformities. These unconformities have been used by Sloss (1963) to separate the Phanerozoic record into six major sequences (figure 2). Each sequence is represented by a major cycle of transgression and regression. Mapping of the distribution of geologic units beneath each of these major sequences is important in helping to understand the regional structural and geologic history.

The present structural configuration of rocks in western Iowa and eastern Nebraska is the result of several periods of discordant structural movement. These movements have warped the originally flat lying formations in different directions at different times in geologic history. A brief summary of these movements that occurred during the Phanerozoic, which effected western Iowa and eastern Nebraska follows.

Precambrian Antecedents

Warner (1978) suggests that the Transcontinental Arch may have had its origins in the Precambrian as a wrench fault system comparable to the San Andreas fault system of California and Phanerozoic fault belts elsewhere. He termed this ancient fault system the Colorado Lineament. He extended it into Minnesota where a northeast-southwest boundary condition between two Precambrian terranes (Morey and Sims, 1976) has been identified and called the Great Lakes Tectonic Zone (Sims, et al., in press). Lidiak (1971) also mapped a Precambrian fault along this same trend in South Dakota. The positions of these features along the axis of the Transcontinental Arch are illustrated in figure 1. The relative position of these features along the crest of the Arch suggests the possibility of recurrent movement during the Phanerozoic.

<table>
<tr><th>SYSTEM</th><th>SEQUENCE</th></tr>
<tr><td>Quaternary</td><td rowspan="2">Tejas</td></tr>
<tr><td>Tertiary</td></tr>
<tr><td>Cretaceous</td><td>Zuni</td></tr>
<tr><td>Jurassic</td><td rowspan="5">Absaroka</td></tr>
<tr><td>Triassic</td></tr>
<tr><td>Permian</td></tr>
<tr><td>Pennsylvanian</td></tr>
<tr><td>Mississippian</td><td rowspan="2">Kaskaskia</td></tr>
<tr><td>Devonian</td></tr>
<tr><td>Silurian</td><td rowspan="2">Tippecanoe</td></tr>
<tr><td>Ordovician</td></tr>
<tr><td>Cambrian</td><td rowspan="2">Sauk</td></tr>
<tr><td>Precambrian</td></tr>
</table>

Figure 2. Time-stratigraphic relationships of the sequences on the North American continent (modified from Sloss, 1963, p. 110).

Sauk Sequence

The first Phanerozoic structural movements in Iowa began during Upper Cambrian through Lower Ordovician time. The eastern Iowa and eastern Missouri area was a slowly subsiding north-south oriented basin (Ozark Basin, Lee, 1943, p. 103), while the southwestern Iowa and southeastern Nebraska region was rising to form the Southeast Nebraska Arch (Lee, 1943, p. 102). In northwestern Iowa, McKay (1980) noted the convergence towards the west of distinct lithologic sequences, within the Upper Cambrian, suggesting the shoreward wedging of units to a common depositional strand zone upon the Arch. However, the predominance of fine grained clastic material and carbonate rock units in northwest Iowa suggests that the Arch was not a prominent source area (McKay, 1980) during Upper Cambrian time.

A prolonged period of erosion then ensued prior to Middle Ordovician transgression and the Sauk sequence was removed down to the Precambrian along the crest of the Southeast Nebraska Arch and the Transcontinental Arch. Figures 1 and 3 illustrate the pre-Tippecanoe (pre-Middle Ordovician) paleogeologic surface in the central midcontinent region.

Tippecanoe Sequence

The Arch served as a terrigenous clastic sediment source region for Middle Ordovician marine deposits which flank both sides of the Arch (Witzke, 1980, p. 1). Major transgressive episodes during portions of the Tippecanoe sequence apparently inundated much or all of the Arch, as evidenced by the disappearance of terrigenous clastic source material and the deposition of pure carbonate rocks in all regions flanking the Arch as well as upon it (Witzke, 1980).

The initial transgression of Middle Ordovician seas into the midcontinent is represented by the St. Peter Sandstone. Following deposition of the St. Peter a change in structural orientation of the midcontinent region appears to have taken place. The previously defined Southeast Nebraska Arch, which had been a positive area, began a long period of differential subsidence. This resulted in the development of the North Kansas Basin (Rich, 1933, p. 796). Also eastern Iowa and eastern Missouri which had been a slowly subsiding north-south oriented basin was interrupted by the Ozark Uplift and the Northeast Missouri Arch (Lee, 1943, p. 85). This formed an east-west basin which is called the East-Central Iowa Basin by the Iowa Geological Survey. The general positions of the North Kansas and East-Central Iowa Basins can be recognized by the present distribution of the Silurian rocks as illustrated in figure 4. Separating the two basins is a feature which is called the Central Iowa Arch. It is illustrated in figures 4 and 5 by the north-south inlier of Middle Ordovician in Central Iowa.

Silurian age strata form a portion of the uppermost Tippecanoe sequence but are absent over a large portion of the central midcontinent region. The scattered distribution of Silurian rocks created a long-held view that the Silurian seas were originally restricted in area. This concept is the result of a poor assumption that the present limits of the Silurian

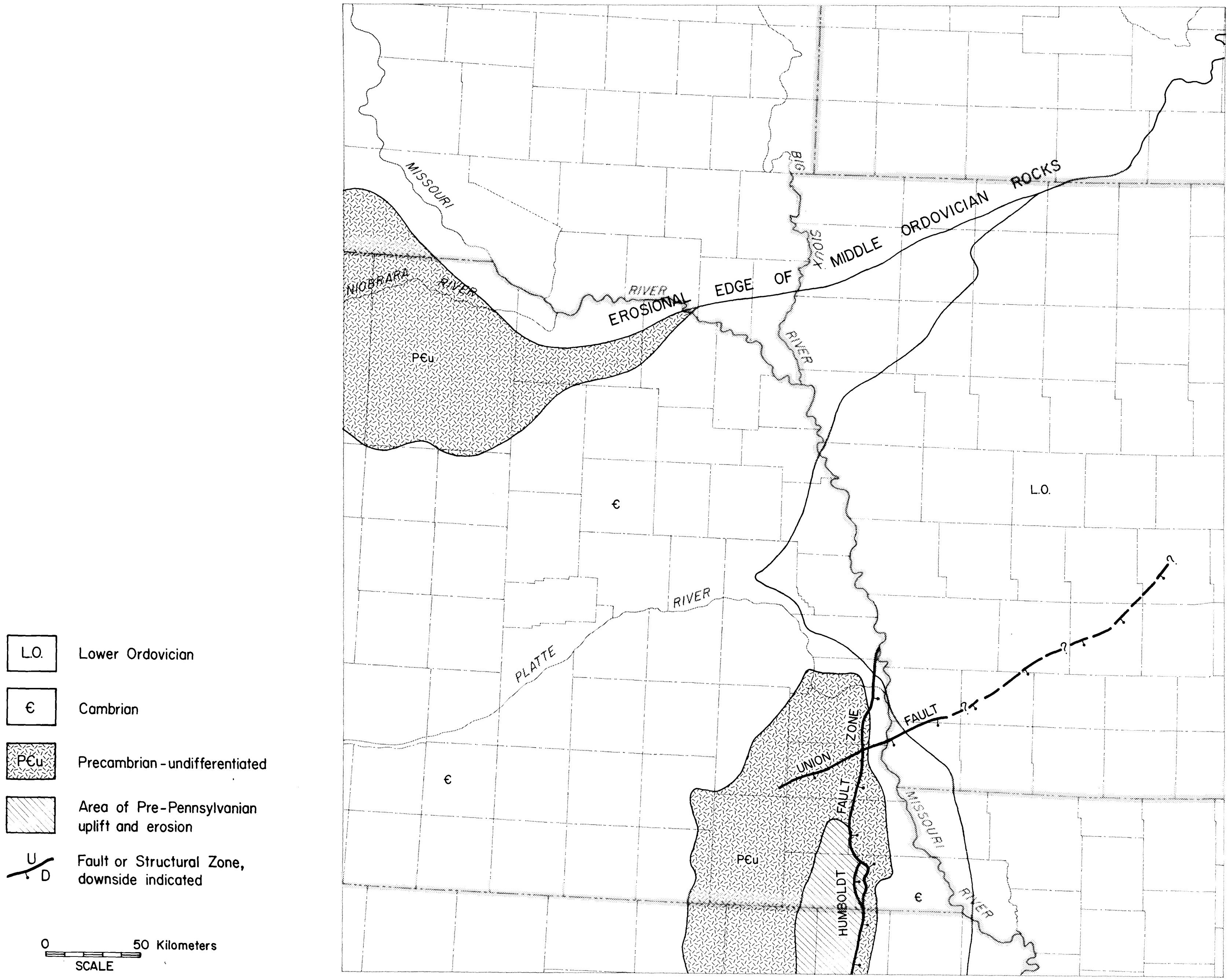

Figure 3. Paleogeologic map of the pre-Middle Ordovician surface in the central midcontinent (modified in part from Burchett and Carlson, 1966; Carlson, 1963; Merriam, 1963; and Sims, 1970).

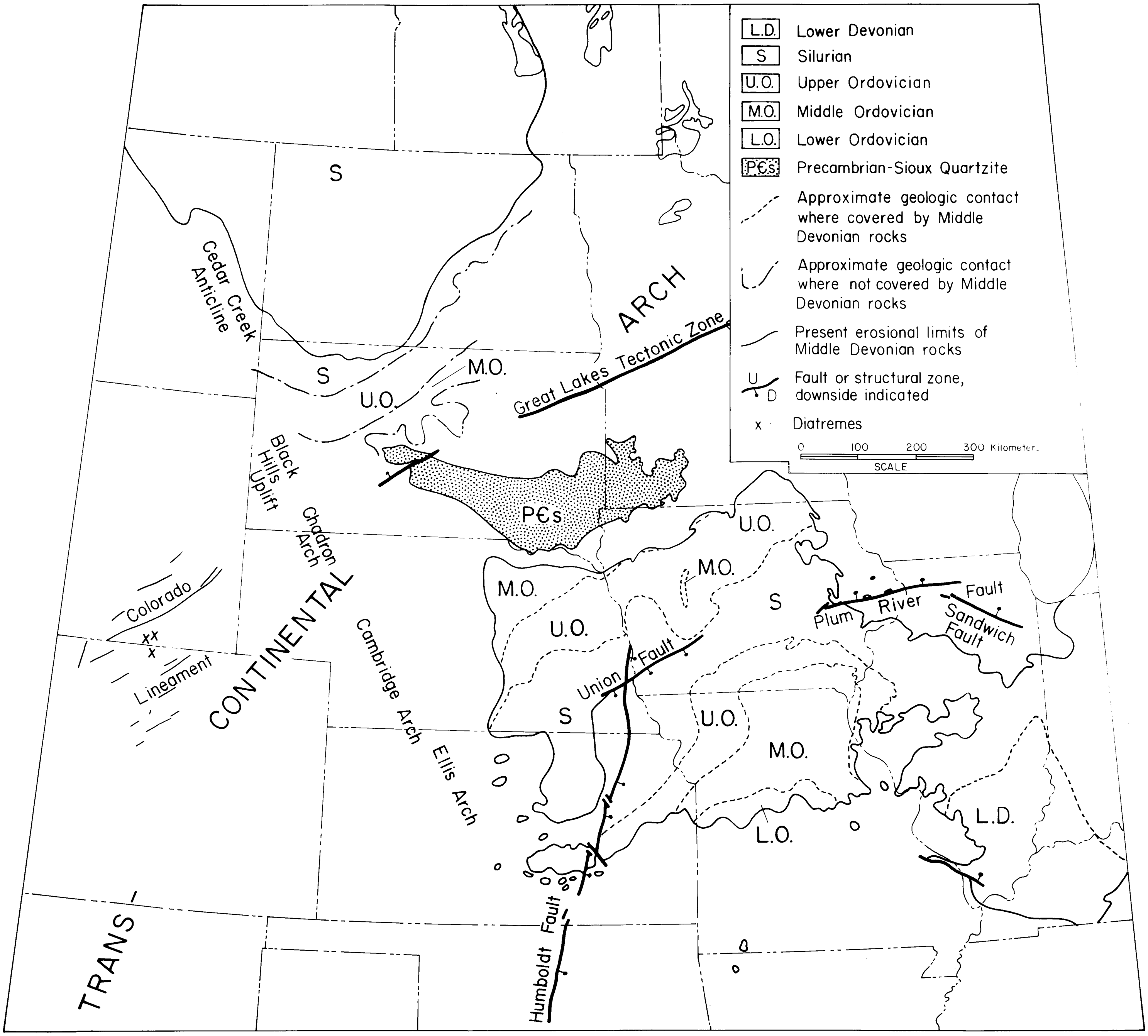

Figure 4. Pre-Middle Devonian paleogeologic map (in part reconstructed) of the north-central midcontinent region (modified from Adler, et al., 1971; Carlson, 1963, 1970; Chronic, et al., 1969; Church, 1967; Collinson, 1967; Fuller, 1961; Johnson, 1971; Lee, 1943, 1956; Lidiak, 1971; Ludvigson, et al., 1978; Merriam, 1963; Miller, 1971; Morey and Sims, 1976; Muehlberger, et al., 1967; Parker, 1971; Sandberg and Hammond, 1958; Sandberg and Mapel, 1967; Sims, 1970; Sims, et al., in prep.; Warner, 1978; Whiting and Stevenson, 1965; Willman and others, 1967.).

rocks closely approximates their original depositional limits.

An examination of the lithostratigraphy of the Silurian suggests a former shallow sea with uniform conditions over an immense area. Critical evidence for this is provided by the fortuitous structural preservation of lower Paleozoic blocks (upper Cambrian through Silurian) in diatremes located in southeastern Wyoming and northeastern Colorado (Chronic, et al., 1969; Chronic,1976). The preserved blocks include platform facies carbonate rocks of Middle Ordovocian and Silurian age and demonstrates the once widespread distribution of these rocks prior to pre-Middle Devonian erosion on the Transcontinental Arch. Figure 4 is a subcrop map of the pre-Middle Devonian surface in the north-central midcontinent region, which delineates the distribution of the Silurian rocks and shows the location of the diatremes (also noted in figure 1). Regional truncation of Lower Ordovician through Lower Devonian rocks, as illustrated in figure 4, implies emplacement of the diatremes prior to Middle Devonian transgression and deposition. Chronic (1976, p. 104) suggested late Silurian to early Devonian for their time of emplacement.

Kaskaskia Sequence

Figure 5 examines in closer detail the pre-Middle Devonian paleogeologic surface of the central midcontinent region. Possible extrapolation of the Humboldt Fault Zone northward can be inferred in western Iowa by the presence of Silurian rocks in a north-south trending geologic pattern paralleling the eastern (downthrown) side of the fault zone. Ireland (1967, p. 109) inferred the possibility of pre-Middle Devonian movement along the Humboldt Fault Zone. Lee (1956, p. 59) suggested the possibility of movement during Devonian time. Pre-Middle Devonian movement along the eastward extension of the Union Fault (Thurman-Redfield Structural Zone of Iowa) has been documented by Rouhani (1976).

Prior to Middle Devonian transgression, structural reorientation into a north-south direction of the axes of the North Kansas and East-Central Iowa Basins occurred. Middle Devonian sediments in Iowa [Cedar Valley and Wapsipinicon Formations] represent the southeasternmost deposits of a vast seaway that extended northwestward to western Canada [Collinson and James, 1969]. Ongoing biostratigraphic studies [G. Klapper, J. Barrick, K. Klug, and M. Tynan, University of Iowa, pers. comm.] of Middle Devonian rocks in Iowa, suggest that the Central Iowa Arch stood in mild positive relief during the initial incursions of the Middle Devonian seas (Wapsipinicon Formation) from the northwest. This would imply transgression across the Transcontinental Arch (figure 4) into the North Kansas and East-Central Iowa Basins respectively. Burial of the Central Iowa Arch and open marine conditions were then established during deposition of the Cedar Valley (Upper Middle Devonian) sediments. Mapping of the uppermost Devonian rocks in Iowa (Dorheim, et al., 1969) shows that the arch persisted through Devonian time.

A controlling factor in the direction of transgression of Middle Devonian seas into the central midcontinent region occurs along its western margins. Figure 4 illustrates the relative position of this feature, which has been termed the Black Hills-Central Kansas Uplift. This feature was active throughout the Phanerozoic having its origins in the Precambrian

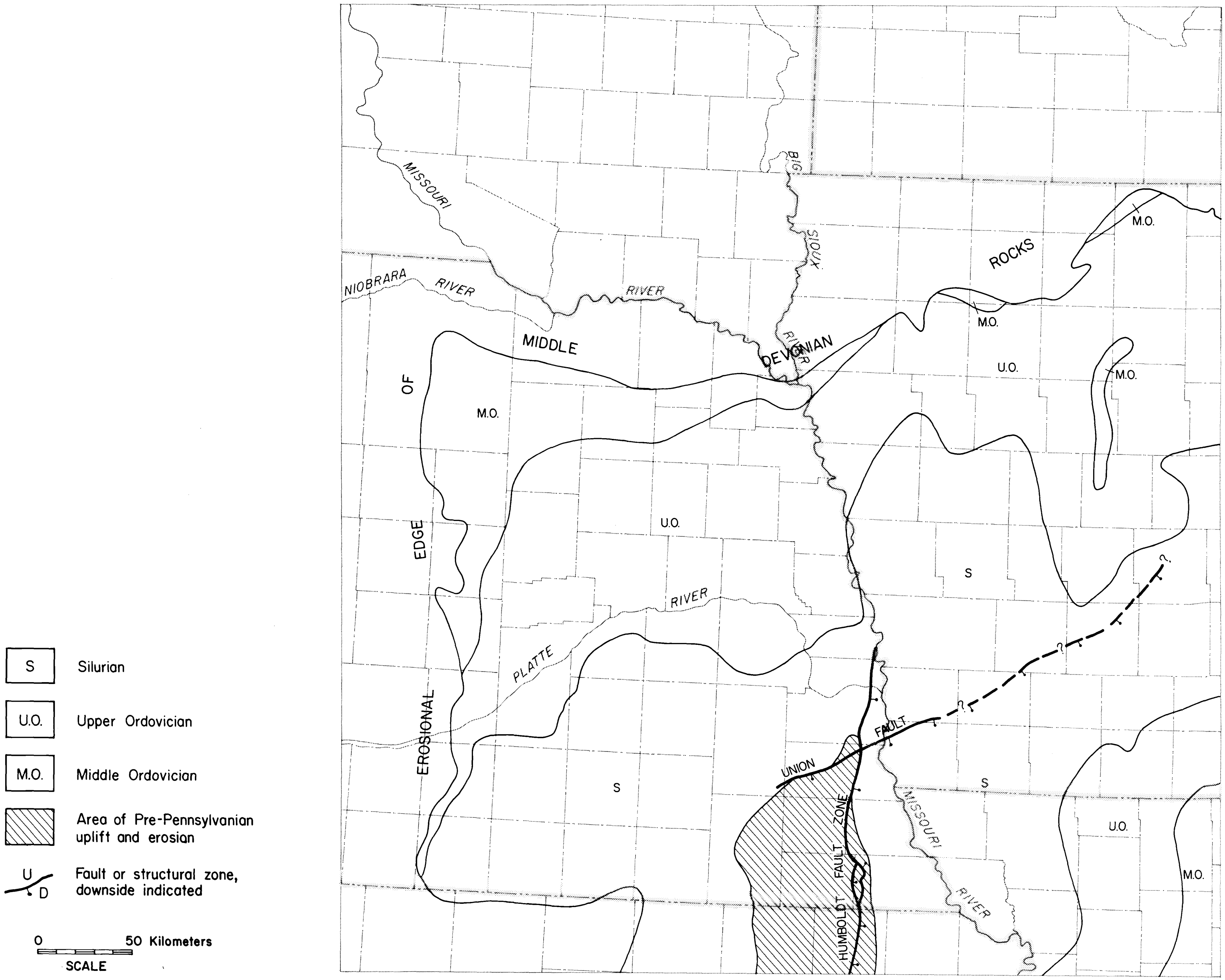

Figure 5. Paleogeologic map of the pre-Middle Devonian surface in the central midcontinent (modified from Burchett and Carlson, 1966; Carlson, 1963; Church, 1967; Merriam, 1963; Parker, 1971; Sims, 1970).

(Muehlberger, et al., 1967, p. 2360). The Ellis Arch is the older pre-Mississippian structural development of the Central Kansas Uplift (Merriam, 1963, p. 181) and therefore the term is utilized on this map.

Post-Middle Devonian uplift and erosion of the Transcontinental Arch is inferred by the overlap of Upper Devonian age rocks into South Dakota (Sandberg and Hammond, 1958; Johnson, 1971). The occurrence in northwestern Iowa of an outlier of Upper Devonian age (age determined from spores, Robert Ravn, Univ. Iowa, pers. comm.) rocks on Precambrian (figure 7; Ludvigson and Bunker, 1979), is consistent with this interpretation.

The upper portion of the Kaskaskia sequence (Mississippian) represents the last widespread carbonate-producing sea on the North American continent. Post-Kaskaskia erosion cut deeply into these deposits, to the degree that only carbonates of Early and Middle Mississippian age are preserved within the central midcontinent region.

Absaroka Sequence

During the Absaroka sequence the Transcontinental Arch disappeared as a controlling element in the distribution, facies, and thickness of preserved sediments (Sloss, 1963, p. 104). This sequence in the continental interior records a series of cyclic repetitions of marine and nonmarine sedimentation (cyclothems) with increasing dominance of continental environments eastward towards the rising Appalachians. Heckel (1980) provides an excellent eustatic model for the deposition of upper Pennsylvanian cyclothems in the midcontinent region.

The unconformity below Early Pennsylvanian rocks is considered to be the most widely developed and profound Paleozoic hiatus on the North American continent (Ham and Wilson, 1967). Figure 6 is a paleogeologic map of the pre-Pennsylvanian surface in the central midcontinent region. Geologic studies in many areas of North America indicate that the "pre-Pennsylvanian unconformity" is not a single surface but the result of several Pennsylvanian uplifts (Ham and Wilson, 1967, p. 372).

The Nemaha Uplift (Moore and Haynes, 1917, pp. 167, 169), which is the reactivation of the older Southeast Nebraska Arch, is apparent on the pre-Pennsylvanian paleogeologic map (figure 6). Beveling of the pre-Pennsylvanian rocks down to the Precambrian along the crest of the Uplift is illustrated. Recurrent activity of the Uplift during the Pennsylvanian (Lee, 1943, 1956) was accompanied by mild regional subsidence.

The transgressive-regressive cyclic patterns continued on into the Permian, with an overall slow regression of the seas to the western basins, which were synchronously formed during the uplift of the "Ancestral Rockies". Red bed deposition and evaporites characterize the upper portion of the Permian (Peterson, 1980). Nonmarine conditions existed in all cratonic and marginal basin depositional areas by the close of the Absaroka (Late Triassic and Early Jurassic time) sequence.

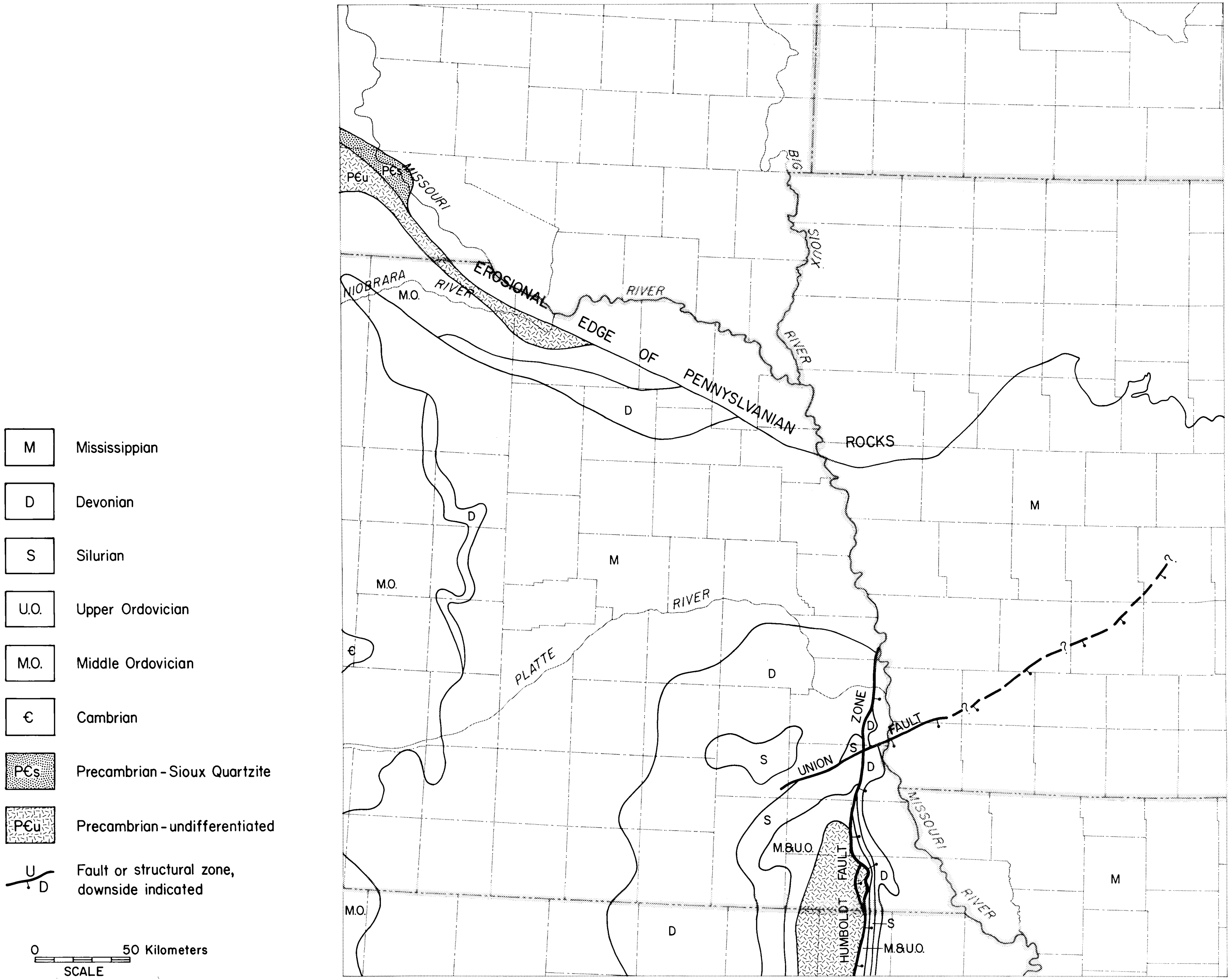

Figure 6. Paleogeologic map of the pre-Pennsylvanian surface in the central midcontinent (modified from Burchett and Carlson, 1966; Carlson, 1963; Hershey, 1969).

Zuni Sequence

The pre-Zuni (sub-Cretaceous) paleogeology of the central midcontinent region is the result of several periods of structurally discordant movements that have been previously summarized in this paper. Figure 7 illustrates the sub-Cretaceous paleogeology of the central midcontinent region. The configuration of the pre-Cretaceous surface in northwest Iowa is controlled by the distribution of the underlying lithologic units of Paleozoic and Precambrian age. A series of topographic highs and lows (Ludvigson and Bunker, 1979, p. 11) have been delineated, representing an eroded surface of strike-oriented valleys developed on the south-southeast dipping Paleozoic rocks (figure 7). Local relief on this surface is on the order of 200 to 300 feet (Ludvigson and Bunker, 1979).

Lithostratigraphic investigations have shown that the Dakota Formation (Lower to Upper Cretaceous age) was deposited in a fluvial environment, in which the pre-Cretaceous topography exerted a profound influence on its depositional characteristics (Whitley, 1980). The eastward convergence of the Dakota-Greenhorn depositional cycle with the pre-Cretaceous surface (Ludvigson and Bunker, 1979) is also consistent with the southwestward continental paleoslope established by Hattin (1975).

The effects of the Sioux Quartzite Ridge on the Phanerozoic rock record is evident from examination of the stratigraphic relationships of the Cretaceous rocks that are presently surrounding and overlying it. Ludvigson and Bunker (1979) noted a local convergence of the Greenhorn to base of Cretaceous interval in the extreme northwest corner of Iowa, suggesting possible onlap of the Greenhorn Limestone onto the Ridge. Onlapping and overstepping of the Ridge is further supported by biostratigraphic investigations of Cretaceous rocks on its northern flank (Shurr and Cobban, 1979; Shurr, this volume). Figure 8 is a structure contour map on top of the Greenhorn Limestone for the central midcontinent region. The structure contours along the northern (top) portion of the map reflects the presence of the Ridge and the onlapping characteristics of the Greenhorn Limestone. The Ridge appears to have remained in mild positive relief until its burial by the Niobrara Limestone.

Tejas Sequence

Late Paleocene and younger Teritary uplifts of numerous cratonic positive elements are strongly reminiscent of several midcontinent uplifts (Ancestral Rockies, Nemaha Uplift, Black Hills - Central Kansas Uplift) that were actively developed during Absaroka deposition (Sloss, 1963). This period of structural development has been referred to as the "Laramide Orogeny" (Dana, 1895, p. 359), which has been dated as occurring during late Cretaceous - early Tertiary time.

During the latter part of the Cretaceous a great basin existed in the western interior. Mapping of the thickness of the Pierre Shale (Upper Cretaceous) shows that the depositional center of this basin was in northwestern Colorado (Tweto, 1975). Laramide deformation (in particular uplift of the Colorado Front Range) divided this great basin and formed the western flank of the Denver Basin (McCoy, 1953). This basin occupies an area in northeastern Colorado and adjoining parts of southeastern Wyoming and western Nebraska. The depositional axis of the Denver Basin corresponds closely with that of

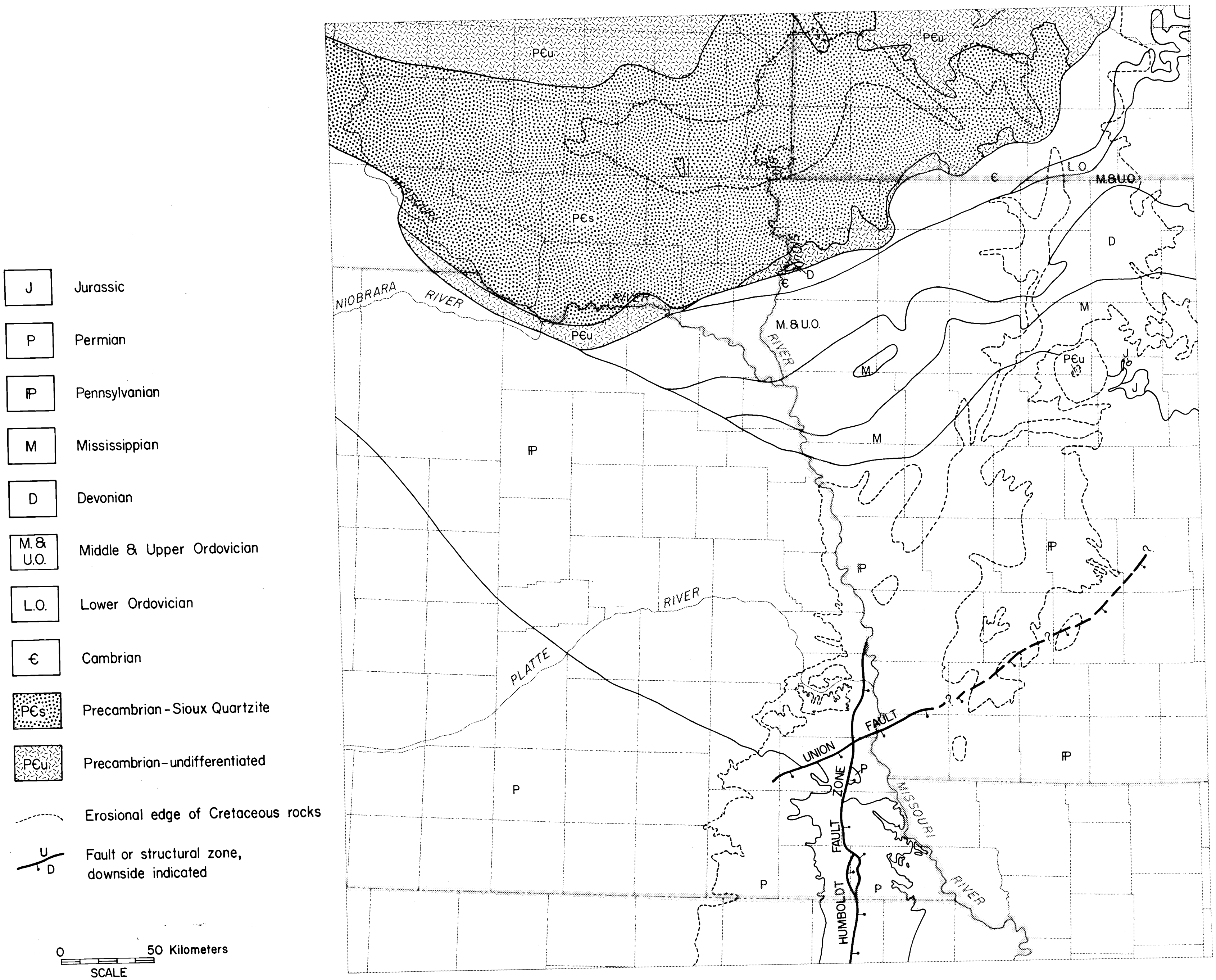

Figure 7. Paleogeologic map of the pre-Cretaceous surface in the central midcontinent (modified from Burchett and Carlson, 1966; Darton, 1951; Lidiak, 1971; Ludvigson and Bunker, 1979; Hershey, 1969; Sims, 1970).

older Late Paleozoic basin, which had been formed by the uplift of the "Ancestral Rockies".

Condra, et al. (1940), noted the truncation of the Pierre Shale, by younger Tertiary rocks, across the crest of the Cambridge Arch in western Nebraska. The Cambridge Arch is a portion of the much larger previously defined Black Hills - Central Kansas Uplift (figure 4; Chadron - Ellis Arch). Structural mapping (Merriam, 1963) of the base of the Niobrara Limestone in Kansas indicates that structural movement occurred along the Cambridge Arch during post-Niobrara time. These structural movements were the result of the subsidence of the Denver Basin.

Figure 8 is a structure map of the top of the Greenhorn Limestone in the central midcontinent region. As previously noted the Sioux Quartzite Ridge is reflected along the northern (top) portion of this map. Two other prominent features can also be seen on this map: 1) the deep structural low in central Nebraska (Nebraska Basin; Carlson and Reed, 1961) and 2) the broad north-south structural high in eastern Nebraska and western Iowa, which is the location of the previously defined Southeast Nebraska Arch and Nemaha Uplift. As stated earlier, Laramide orogenic features of the central midcontinent region are strongly reminiscent of earlier Late Paleozoic uplifts, such as the rocky Mountains (Ancestral Rockies), Black Hills - Central Kansas Uplift, and as identified by the Greenhorn structure (figure 8) for the first time, the "Nemaha Uplift".

Regional truncation and Tertiary overlap of Cretaceous rocks along the Front Range of the Colorado Rockies is easily recognized. Condra, et al. (1940, p. 42), as stated previously, note the truncation and Tertiary overlap of Cretaeous rocks along the crest of the Cambridge Arch. Fuenning (1942) also identifies post-Cretaceous deformation and local truncation along the crest of the Cambridge Arch. Examination of the geologic map (figure 9), of the central midcontinent region, shows the regional truncation and Tertiary overstep in an eastward direction towards the crest of the reactivated post-Cretaceous "Nemaha Uplift".

The general pattern of distribution of the Tertiary rocks in northeastern Nebraska (figure 9) strongly suggests that this pattern should continue on into northwestern Iowa. Vertebrate fossils of definite Tertiary age (H. Semken, University of Iowa, pers. comm.) have been identified from several Pleistocene sand and gravel localities in western Iowa. The sharp angularity and excellent preservation of these fossils indicate that they have not traveled far from their original site of burial. In all probability, the degree of Tertiary overlap across the Nemaha Uplift should have extended well into western Iowa. Unfortunately, the ability to reconstruct the extent of post-Cretaceous-pre-Tertiary truncation across the Nemaha Uplift is impossible. This is largely because of post-Tertiary erosion within the central midcontinent region. Also a thick covering of Pleistocene tills limits the ability to reconstruct possible post-Tertiary(?) movement along the Nemaha Uplift. A cooperative project between the U.S. Nuclear Regulatory Commission and the states of Iowa, Nebraska, Kansas, and Oklahoma, has shown the Nemaha Uplift to be a microseismically active area even today (Luza and Lawson, 1979).

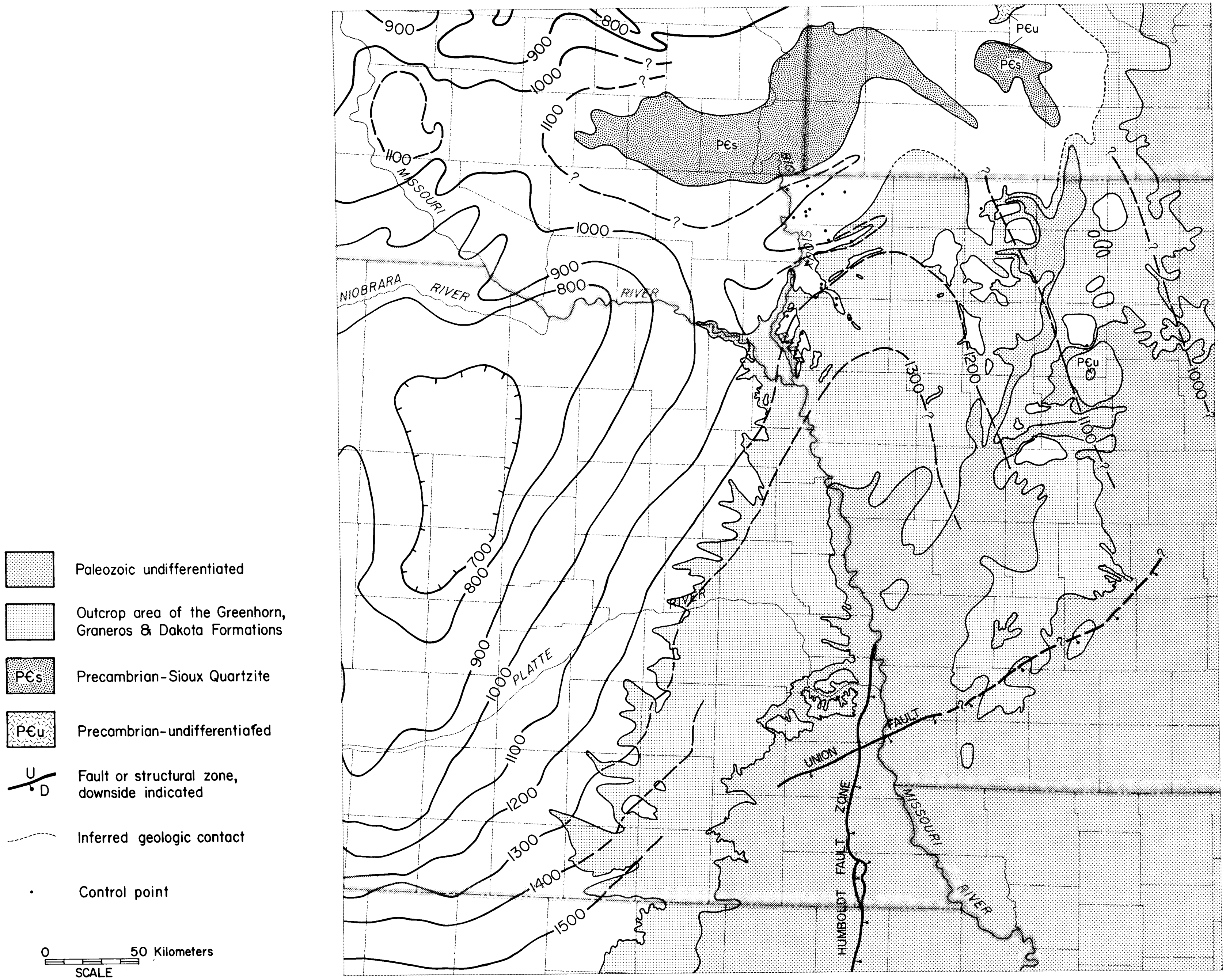

Figure 8. Structure contour map on top of the Greenhorn Limestone (Upper Cretaceous) in the central midcontinent (modified from Burchett and Carlson, 1966; Burchett, 1969; Carlson and Reed, 1961; Ludvigson and Bunker, 1979; Petsch, 1953; Schoon, 1971).

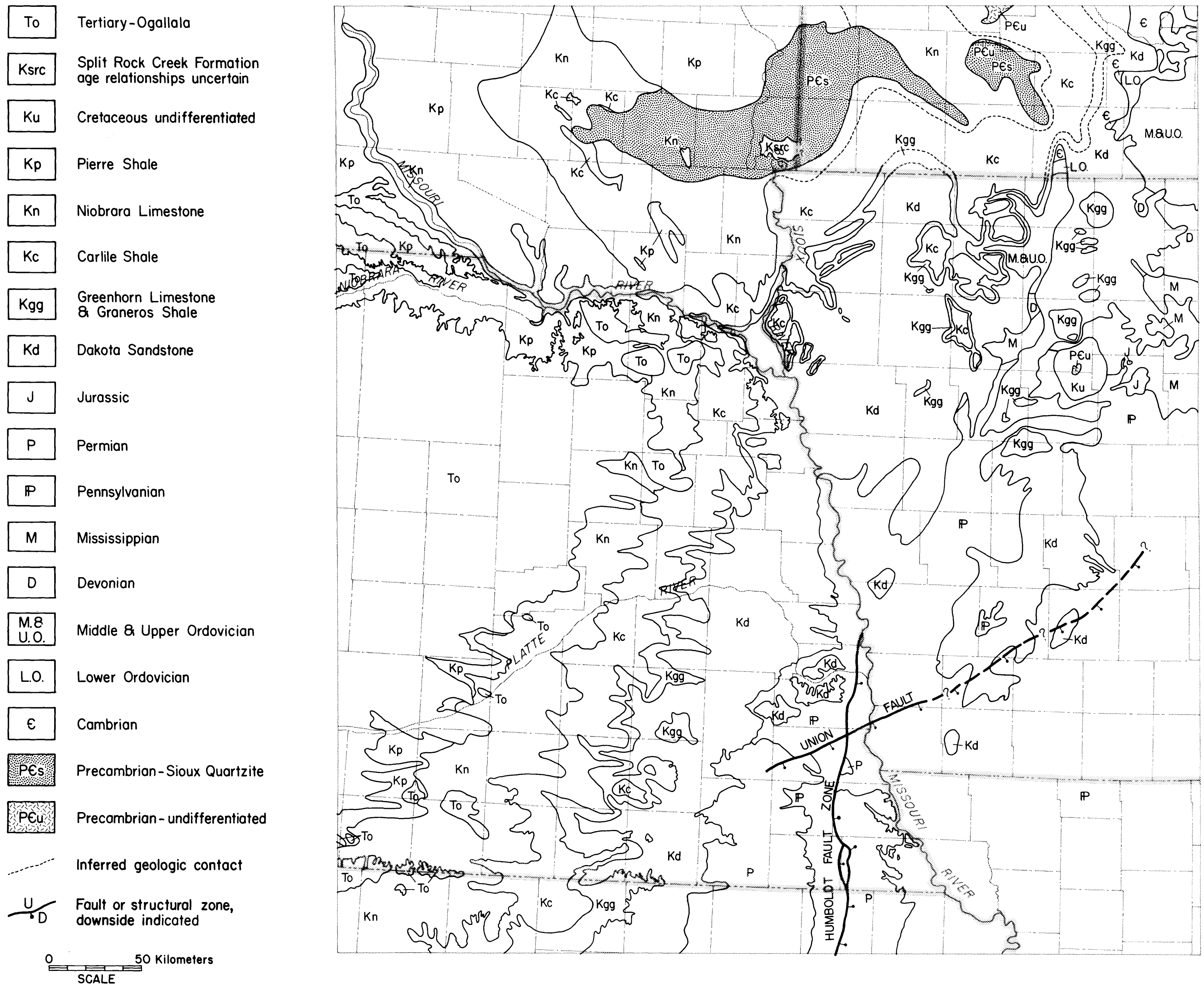

Figure 9. Generalized geologic map of the central midcontinent (modified from Burchett, 1969; Hershey, 1969, Ludvigson and Bunker, 1979; Merriam, 1963).

Shurr (Shurr and Cobban, 1979; Shurr, 1980; and this volume) describes structural deformation of Upper Cretaceous age rocks in the Lake Traverse area of western Minnesota. This area of structural deformation occurs along the southwestern extension of the Great Lakes Tectonic Zone, as previously defined in this paper. Dips of up to 27 degrees have been recorded in the deformed Cretaceous rocks. Shurr (1980) proposes a Late Cretaceous or Cenozoic age for reactivation of this major structural feature. Recent microseismic activity (Shurr, 1980) has also been noted in the Lake Traverse area along this zone.

SUMMARY

Structural features in the midcontinent have shown repeated periods of recurrent activity throughout the Phanerozoic, some having their origins in the Precambrian. Laramide orogenic events reactivated many older midcontinent structural features that had been actively developed during the Paleozoic. Recognition of Late Cretaceous - Early Tertiary deformation has been widely and easily recognized in the Rocky Mountain area of the western United States. Late Cretaceous deformation has also been noted along the crest of the Black Hills - Central Kansas Uplift. Misconceptions concerning the eastern margin of the Western Interior Seaway have presumed that the Cretaceous rocks in this area are preserved nearly in their original deposition framework, with no structural complications to consider.

Structure mapping of the Greenhorn Limestone and other geologic mapping imply post-Greenhorn to pre-Tertiary reactivation of the "Nemaha Uplift". Work by Shurr (this volume) on the northern flank of the Sioux Quartzite Ridge and along the axis of the Transcontinental Arch has also shown Late Cenozoic (Laramide) deformation in this area.

The Nemaha Uplift has shown a consistent history of recurrent activity, having had its origins in pre-Middle Ordovician time (Southeast Nebraska Arch) and Laramide orogenic events have apparently reactivated this feature as well. Accumulating evidence along the eastern margin of the Western Interior Cretaceous seaway shows that structural deformation (Laramide age) of Cretaceous rocks in this area is an important factor in their interpretation.

ACKNOWLEDGEMENTS

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CRETACEOUS SEA CLIFFS AND STRUCTURAL BLOCKS ON THE FLANKS OF THE SIOUX RIDGE, SOUTH DAKOTA AND MINNESOTA

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ABSTRACT

The Sioux Ridge of eastern South Dakota and southwestern Minnesota is a basement high, which is composed of Precambrian quartzite and is onlapped by Cretaceous stratigraphic units. A configuration map of the Precambrian basement shows flat surfaces on the north flank and crest of the ridge at elevations of approximately 305 m (1000 ft) and 366 m (1200 ft). The Dakota Sandstone and Graneros Shale thin onto the north flank of the ridge at the erosional surface characterized by elevations of 305 m (1000 ft); the Greenhorn Formation overlies this surface. The

Carlile Shale thins onto the second erosional surface at elevations of 366 m (1200 ft) and the Niobrara Formation rests on this surface. These generalizations are based upon a review of contrasting structure and stratigraphy in areas surrounding the Sioux Ridge and upon a summary of local study areas including: Traverse and Big Stone Counties, Minnesota; Lyon County, Minnesota; Sanborn County, South Dakota, Minnehaha County, South Dakota; and northwestern Iowa.

The Sioux Ridge is interpreted to occupy a discrete structural block which can be distinguished from surrounding blocks. Within the Sioux Ridge block, basement rocks display a Cretaceous paleotopography which consists of steps. During a rise of sea level in the Cenomanian and Turonian, successively higher steps were flooded and the ridge was first a rocky peninsula with steep coasts and later was an isolated, rugged island.

INTRODUCTION

The Sioux Ridge is an elevated part of the Precambrian basement in eastern South Dakota and southwestern Minnesota. The ridge was an important paleogeographic feature during the Cretaceous Period, and it has been an element of several published interpretations (for example, Reeside, 1957; and Sloan, 1964). The rise of sea level though the Cenomanian and Turonian caused marine environments to encroach upon the ridge as the Midcontinent region was progressively flooded.

The east-west trending Sioux Ridge is the highest part of the Transcontinental Arch. The Transcontinental Arch is a large tectonic feature which trends northeast-southwest and separates the Williston Basin of the western Dakotas from the Forest City Basin and Hollandale Embayment of Iowa and southeastern Minnesota (figure 1).

Cretaceous stratigraphic units, which overlie Precambrian rocks of the Sioux Ridge, are a part of the well-established sequence of formations in the northern Midcontinent (Merewether, in preparation). The basal Dakota Sandstone is dominantly nonmarine and is conformably overlain by the marine Graneros Shale. Conformably overlying the Graneros, the limestone of the Greenhorn Formation provides a widespread and distinctive unit useful for correlation and for mapping structural features. The marine Carlile Shale lies conformably on the Greenhorn and locally lies unconformably on Precambrian rocks at the higher elevations on the flanks of the ridge. The chalks of the Niobrara Formation, which rest disconformably on the Carlile (Hattin, 1975), are probably continuous across the crest of the ridge. The marine Pierre Shale conformably overlies the Niobrara and is generally the youngest Cretaceous formation preserved beneath the Pleistocene glacial drift which blankets the entire region.

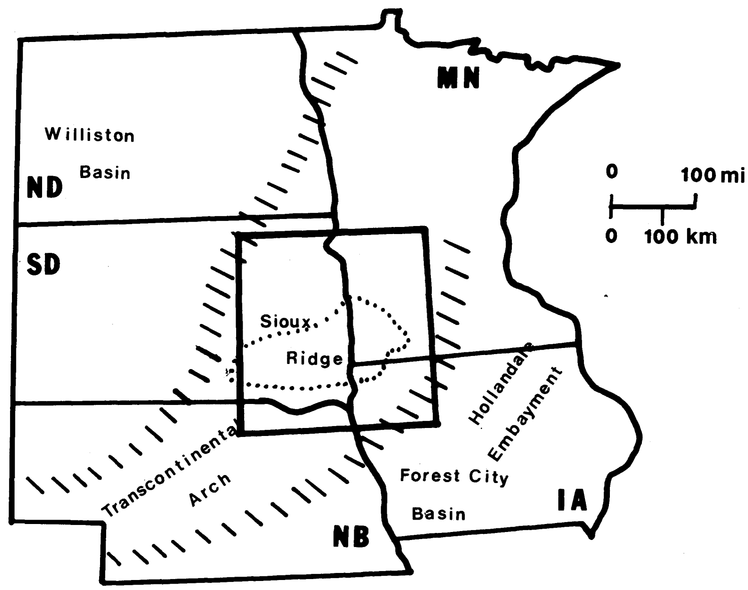
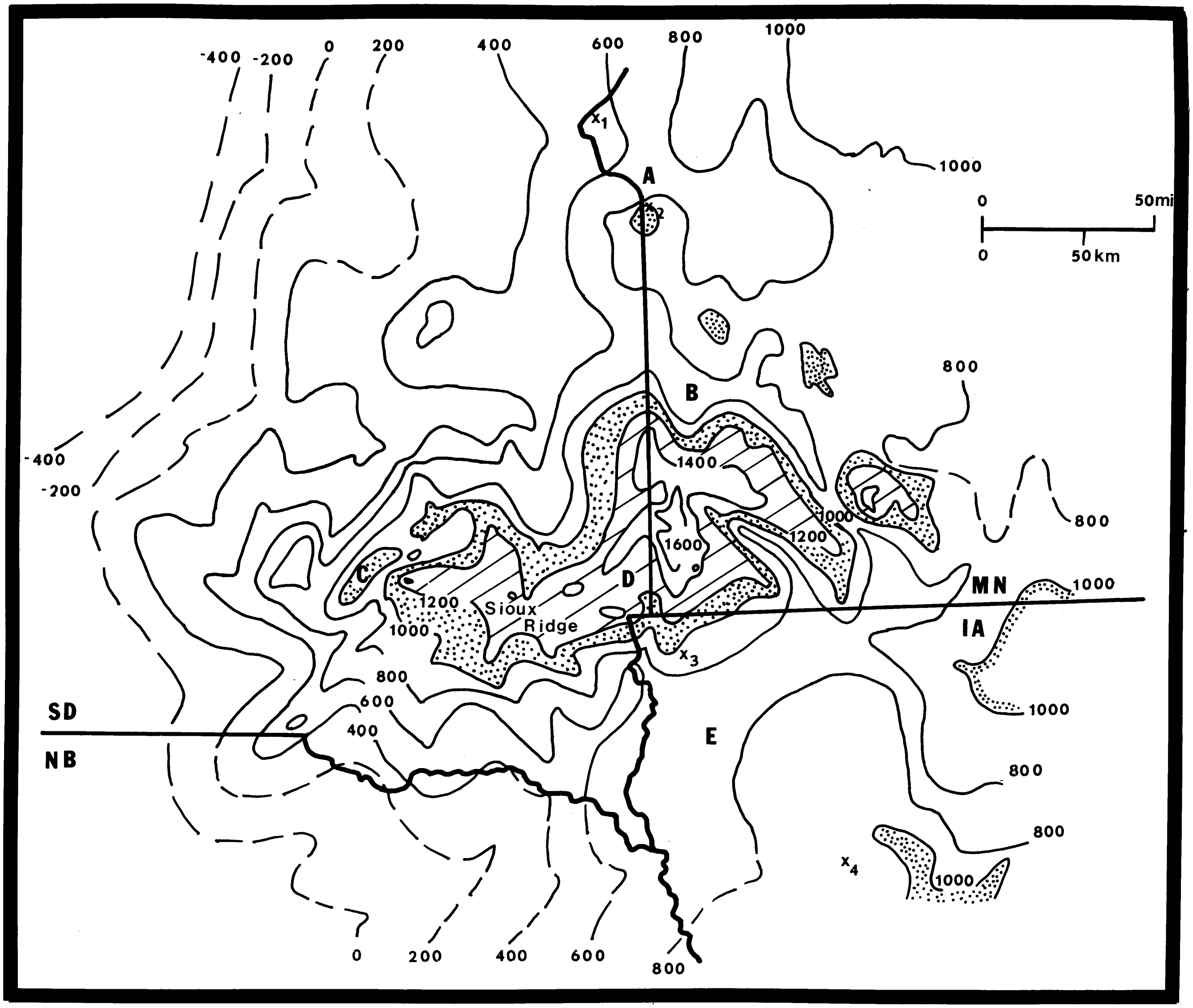


Figure 1. Map showing location of the report area, the Sioux Ridge, and other major tectonic elements.

The configuration of the sub-Cretaceous unconformity provides a record of both modification by erosion and tectonic movement. The effects of erosion are preserved for progressively younger time intervals because the Cretaceous units onlap local relief in the Precambrian basement. Post Early-Cretaceous tectonism in this part of the Midcontinent has been recently suggested by regional studies (Shurr, 1978; Sims and others, in press; Merewether, in preparation). The present report will attempt to assess the relative influence of tectonism and erosion on the flanks of the Sioux Ridge. This will be done by: 1) summarizing regions of contrasting structure and stratigraphy; and 2) comparing the attributes of some local areas of detailed study. It is concluded that the Sioux Ridge has been the site of minimal tectonism and consequently the stepped configuration of the basement surface in this area represents a Cretaceous paleotopography. This distinctive paleotopography may be the result of variations in the rate of sea-level rise.

CONFIGURATION OF THE SUB-CRETACEOUS

The configuration of the sub-Cretaceous unconformity is shown in figure 2. Throughout most of the South Dakota and Minnesota portions of the map area, Precambrian crystalline rocks are found beneath a nearly continuous cover of Cretaceous sedimentary rocks. Along the crest of the Sioux Ridge, defined by the higher elevations which broadly trend east-west, the basement is a Precambrian orthoquartzite known as the Sioux Quartzite. On the north flank of the ridge, the lower basement elevations are characterized by Precambrian granites and metamorphic rocks. On the south side of the ridge in Iowa and Nebraska, the Cretaceous unconformity was developed on strata of Paleozoic age.



Explanation

800 — Elevation, in feet, of unconformity at the base of the Cretaceous

Low-relief erosion surface characterized by elevations of approximately 1000 ft

Low-relief erosion surface characterized by elevations of approximately 1200 ft

Areas discussed in text:

A Traverse and Big Stone Counties, Minnesota
B Lyon County, Minnesota
C Sanborn County, South Dakota
D Minnehaha County, South Dakota
E Northwestern Iowa

Specific localities:

x_1 Browns Valley, Minnesota
x_2 Ortonville, Minnesota
x_3 Central Lyon County, Iowa
x_4 Eastern Woodbury County, Iowa

Figure 2. Configuration of the sub-Cretaceous unconformity. Location of the map area is shown in figure 1. Contour interval is 200 ft.

The map was prepared from data compiled by Robert L. Stach of the South Dakota Geological Survey and by George S. Austin of the Minnesota Geological Survey. The South Dakota data were contoured at a scale of 1:500,000 and the Minnesota data were contoured at a scale of 1:250,000. These components were then synthesized on a map at 1:1,000,000 and data from approximately 100 logs of bore holes in Iowa and Nebraska were added. More detailed work has subsequently become available in northwestern Iowa (Ludvigson and Bunker, 1979), but the contouring shown in figure 2 broadly agrees with this new data.

Although the four-state synthesis is highly generalized and cannot incorporate all available data, there are some obvious regional patterns which do emerge. Specifically, the crest of the Sioux Ridge is dominated by a broad area of low relief which lies at an elevation of approximately 366 m (1200 ft) (figure 2). A more narrow area of low relief lies at approximately 305 m (1000 ft) on the north flank of the ridge. Individual basement highs isolated from the main ridge are flat-topped and commonly have maximum elevations of about 305 m (1000 ft) (for example, near A and C, figure 2). Large areas with elevations between 244 m (800 ft) and 305 m (1000 ft) surround the eastern part of the Sioux Ridge in Minnesota and Iowa (B and E, figure 2). Elevations decrease westward into South Dakota and Nebraska.

REGIONAL CRETACEOUS STRATIGRAPHY AND STRUCTURE

Regional studies in South Dakota (Schoon, 1971) and in northwestern Iowa (Ludvigson and Bunker, 1979) show that areas of low elevation surrounding the Sioux Ridge are filled by nonmarine and marine Dakota Sandstone and by marine Graneros Shale. These units and the overlying Greenhorn Formation pinch out against the flanks of the ridge. The areas of low elevation surrounding the ridge can be separated into three regions that have different structural and stratigraphic attributes: 1) eastern South Dakota, north of the ridge; 2) central South Dakota, northwest of the ridge; and 3) northwestern Iowa, southeast of the ridge. Regional studies of the Cretaceous in southwestern Minnesota and northeastern Nebraska have not yet progressed to the stage of providing useful synthesis.

North of the Sioux Ridge in eastern South Dakota, basement elevations range between 122 m (400 ft) and 183 m (600 ft) (figure 2). Schoon (1971) has shown that regional dips on the Greenhorn are much less than 2 m/km (10 ft/mi), that the Greenhorn is commonly found at elevations of 244 m (800 ft), and that the total thickness of Cretaceous units below the Greenhorn is generally less than 122 m (400 ft). Figure 3 is a sketch of these observations.

Northwest of the ridge in central South Dakota, basement elevations are 61 m (200 ft) or less (figure 2). In this area, the Greenhorn has regional dips of as much as 6 m/km (30 ft/mi), has elevations that are locally higher than 356 m (1100 ft), and overlies Cretaceous rocks that are more than 244 m (800 ft) thick (Schoon, 1971).

Southeast of the ridge in northwestern Iowa, the elevation of the sub-Cretaceous unconformity is between 183 m (600 ft) and 305 m (1000 ft) over large areas (figure 2). Ludvigson and Bunker (1979) have documented regional dips on the Greenhorn of greater than 2 m/km (10 ft/mi). Their studies also indicate that the Greenhorn occurs at elevations above 366 m (1200 ft) and

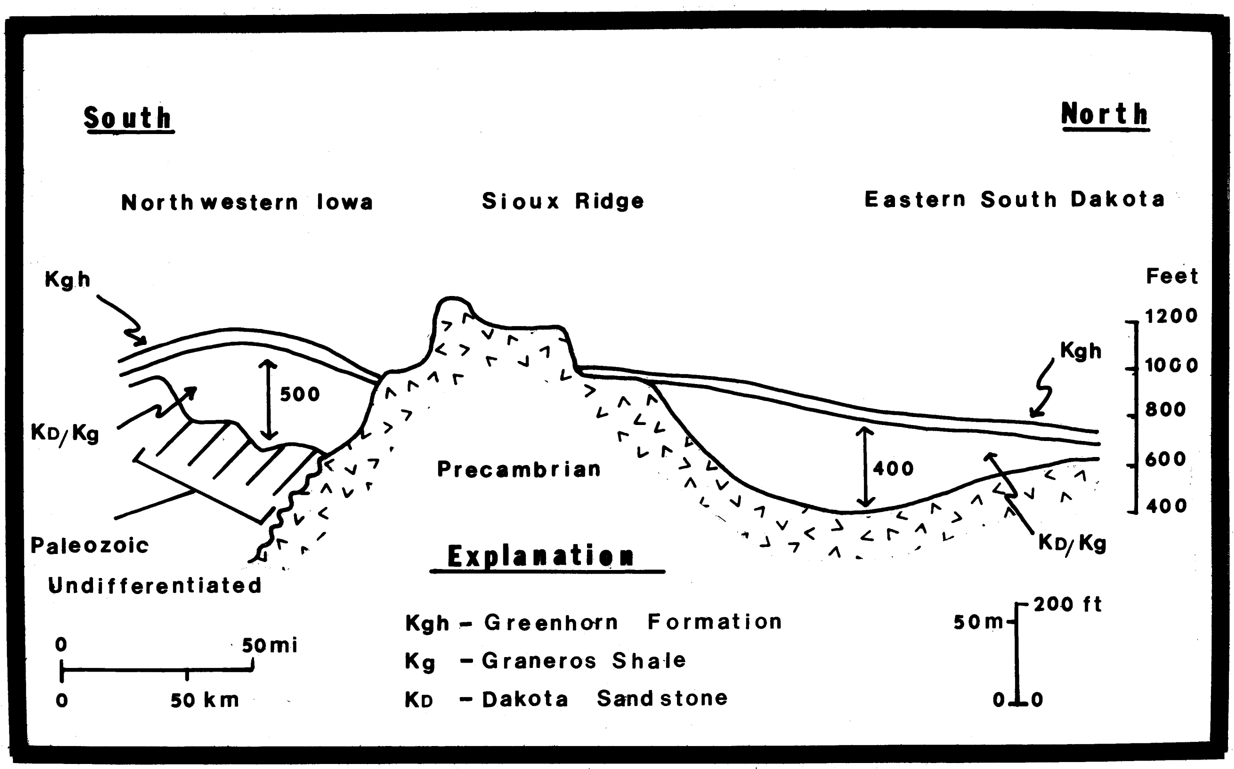


Figure 3. Sketch of contrasting structural and stratigraphic relationships north and south of the Sioux Ridge.

that the Cretaceous below the Greenhorn exceeds 153 m (500 ft) in thickness locally. Strike valleys in Paleozoic units are found beneath the Cretaceous. These generalizations are sketched in figure 3.

The Sioux Ridge stands at elevations above the three regions just described. Detailed studies in local areas provide information on the age of the Cretaceous rocks that onlap the flanks of the Ridge.

STUDIES IN LOCAL AREAS

Cretaceous stratigraphic units can be related to the sub-Cretaceous unconformity in five local study areas: 1) Traverse and Big Stone Counties, Minnesota (A, figure 2); 2) Lyon County, Minnesota (B, figure 2); 3) Sanborn County, South Dakota (C, figure 2); 4) eastern Minnehaha County, South Dakota (D, figure 2); and 5) northwestern Iowa (E, figure 2).

In Traverse and Big Stone Counties, Minnesota, the elevation of the sub-Cretaceous unconformity increases from less than 183 m (600 ft) near Browns Valley to greater than 305 m (1000 ft) near Ortonville, Minnesota (A, figure 2). An outcrop of Greenhorn Formation and Carlile Shale has recently been described near Browns Valley, Minnesota (Shurr, 1980). The generalized stratigraphic section is shown in figure 4. Biostratigraphic and lithostratigraphic correlations have been established from this locality southward 48 km (30 mi) to the vicinity of Ortonville, Minnesota. The correlations sketched in figure 5 incorporated subsurface studies carried out in Big Stone County by William Soukup of the U.S. Geological Survey. Near Ortonville, elements of the zone of *Mytiloides mytiloides* are found in limestone of the Greenhorn which lies on weathered granite and occurs as fracture-filling composed of chalk and chalky shale (Shurr and Cobban, 1979). The granite surface is characterized by low relief at elevations of 290 m (950 ft) to 305 m (1000 ft) and rises to the west (figure 6). Outcrops in granite quarries near Milbank, South Dakota, to the west, are at elevations of 330 m (1080 ft) and include rounded boulders enclosed in calcareous and noncalcareous shales. The shales carry elements of the zone of *Collignoniceras woollgari* (Shurr and Cobban, 1979). Thus from Browns Valley south to Ortonville, the Cretaceous rocks below the Greenhorn appear to converge on the low-relief surface cut into crystalline rocks at approximately 305 m (1000 ft) (figure 5).

The geology of Lyon County, Minnesota, has been described by Rodis (1963). In this area, the surface of Precambrian rocks decreases in elevation southward from approximately 305 m (1000 ft) near Ortonville to a minimum of less than 214 m (700 ft) in Lyon County, Minnesota (B, figure 2). Elevations increase approaching the Sioux Ridge in the southwestern part of the county, to more than 397 m (1300 ft); Sioux Quartzite, rather than granite, is found in this area of high elevations. Sandstones lying between elevations of 320 m (1050 ft) and 354 m (1160 ft) are mapped in Lyon County (Rodis, 1963). A preliminary study of available subsurface data west of Lyon County suggests that these sandstones may be correlative with the Greenhorn Formation and Codell Sandstone Member of the Carlile Shale in eastern South Dakota. These correlations are supported by biostratigraphic zonation of coccoliths recovered from a test hole west of Lyon County (Poppe, 1979) and by regional biostratigraphic studies based upon megafossils (Merewether, in preparation). The Cretaceous rocks below the Greenhorn thin northward to the 305 m (1000 ft) surface on the granite near Ortonville. To the south onto the Sioux Ridge, this flat surface has no expression; however, a flat surface at about 366 m (1200 ft) does appear to be present. Limestone is mapped between elevations of 378 m (1240 ft) and 384 (1260 ft) in Lyon County (Rodis, 1963). This calcareous unit may represent the Niobrara Formation (Merewether, in preparation) which shows onlap of the basement surface at 366 m (1200 ft) similar to that shown by the Greenhorn at 305 m (1000 ft).

Adjacent to Sanborn County in central South Dakota (C, figure 2), the north flank of the Sioux Ridge has surfaces of low relief at elevations of 305 m (1000 ft) and 366 m (1200 ft). Investigations by Steece and Howells (1965) suggest that the Greenhorn Formation lies on the Precambrian basement at approximately 305 m (1000 ft) in the southeastern part of the county. Further, the Cretaceous below the Greenhorn thins to the southeast onto the low-relief basement surface. The sub-Pleistocene surface in Sanborn County has been mapped with the top of the Niobrara Formation at approximately 366 m (1200 ft). This generally supports the correlation of the 366 m (1200 ft) surface with the Niobrara.

Near Mitchell, South Dakota, immediately south of Sanborn County, outcrops of Cretaceous rocks are found along Firesteel Creek. A sandstone tentatively correlated with the Codell (R. F. Bretz and R.L. Stach, personal communication,

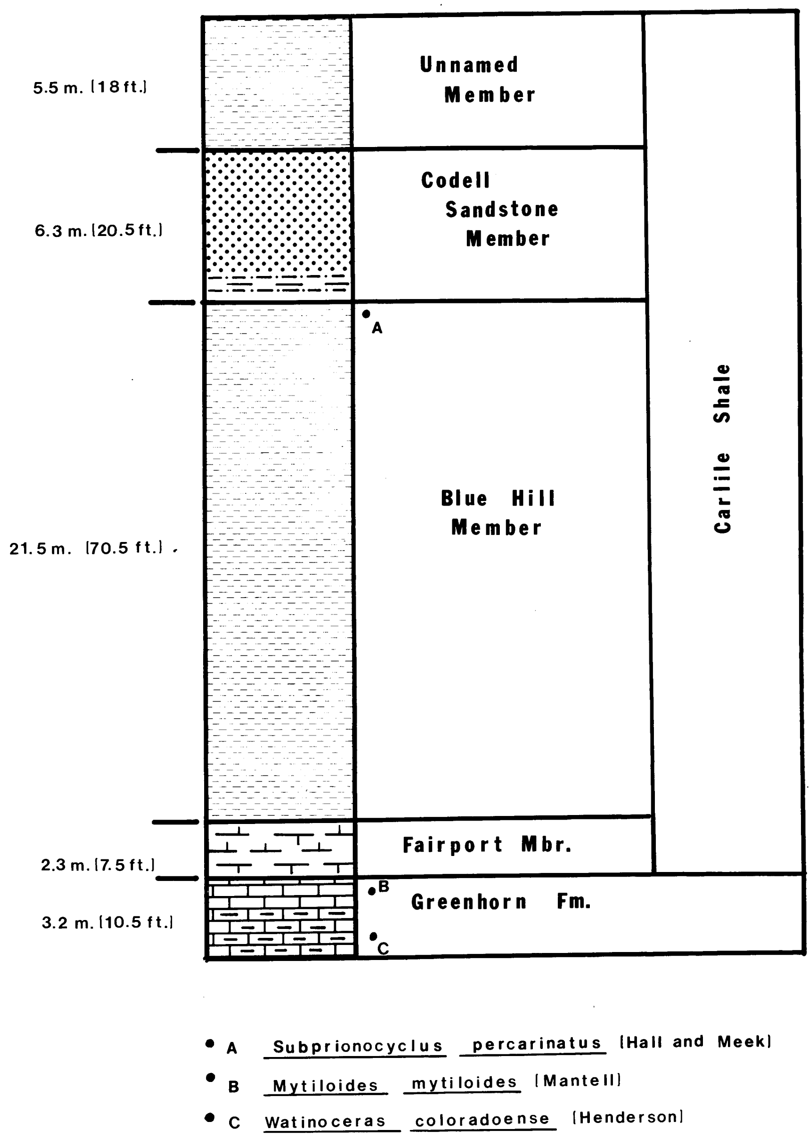


Figure 4. Measured section at Lake Traverse near Browns Valley, Minnesota. See Figure 2 for location.

1976) is characterized by a coarsening-upward sequence and contains *Ophiomorpha*. To the southeast of Mitchell, outcrops of Codell are possibly of very shallow marine origin (Merewether, in preparation).

In summary, local studies on the north flank of the Sioux Ridge indicate that Cretaceous rocks below the Greenhorn commonly converge toward areas of low relief on the sub-Cretaceous surface. The surface of Precambrian crystalline rocks in these areas of low relief generally lies at elevations

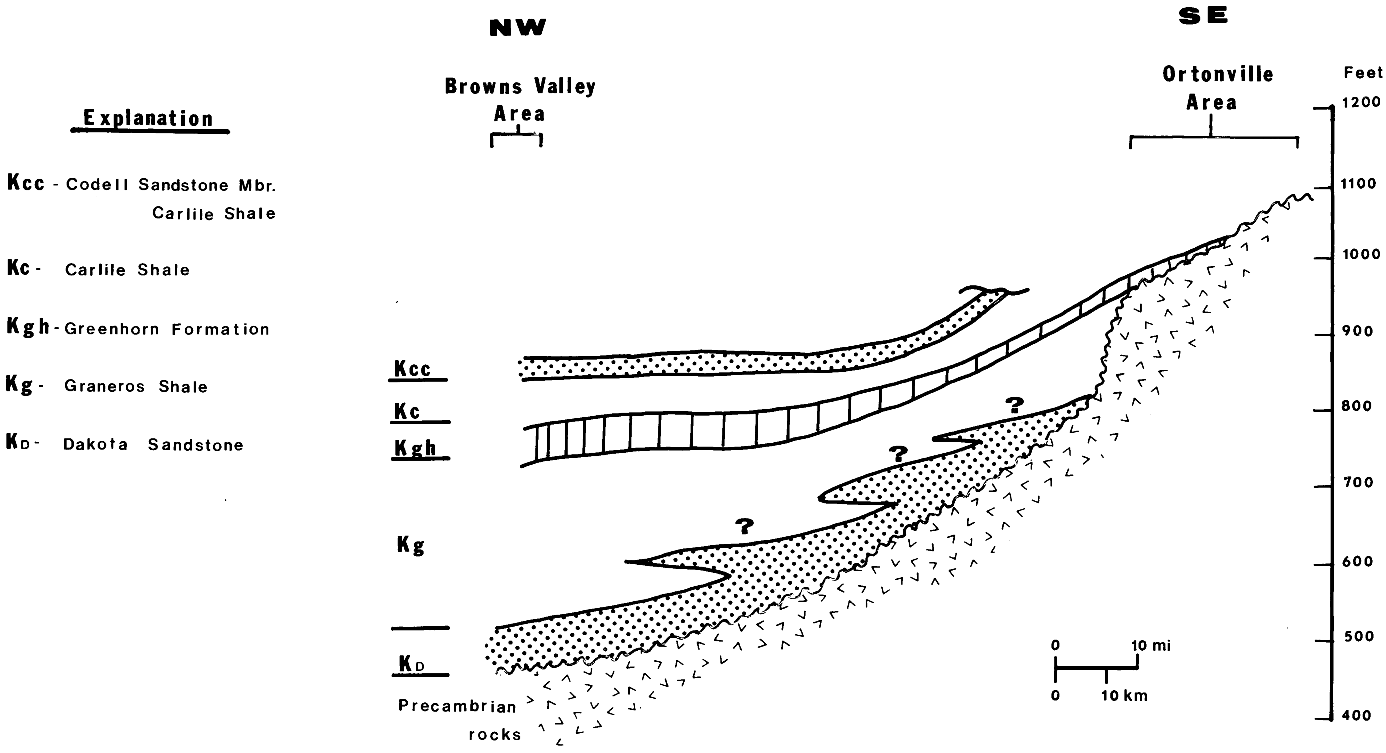
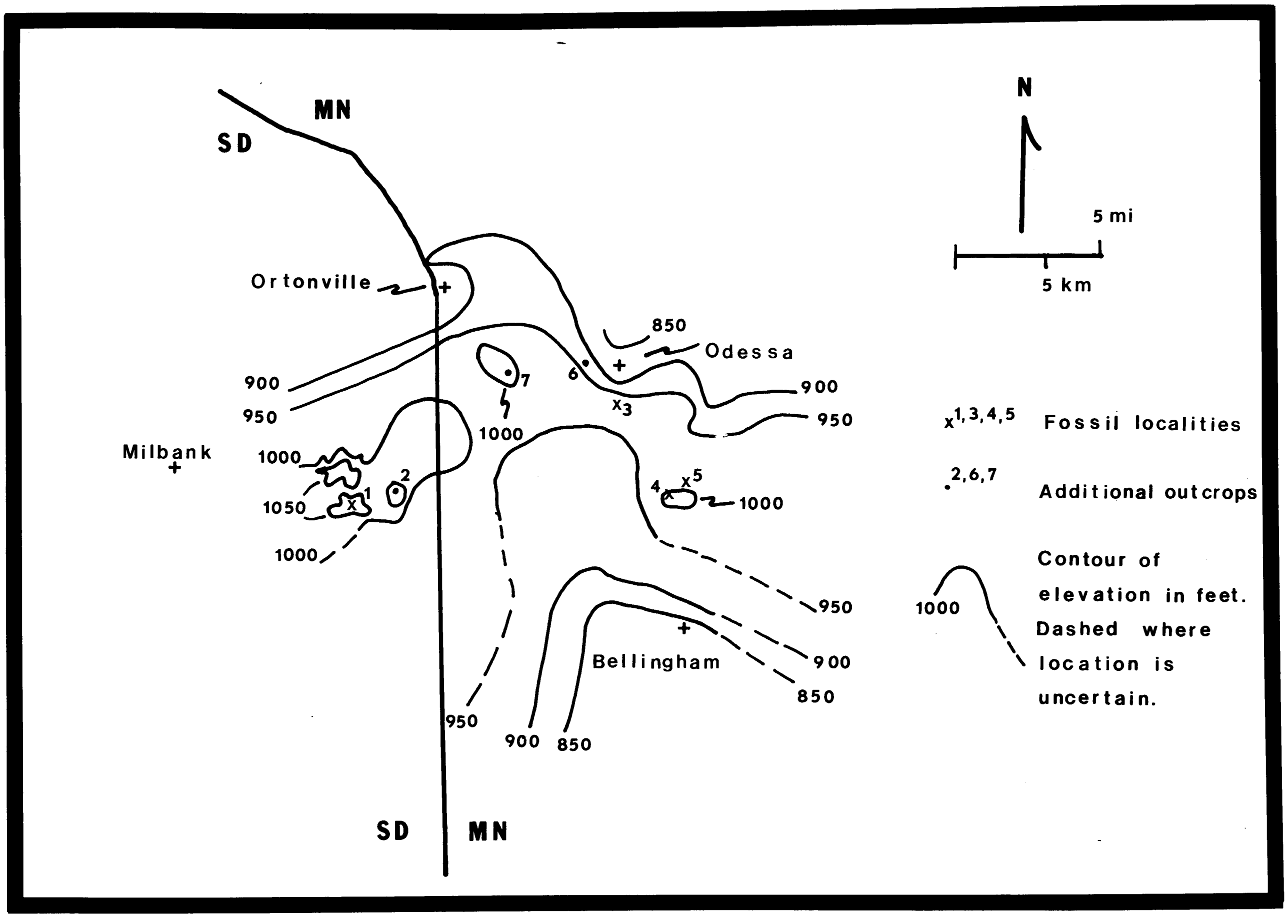


Figure 5. Generalized cross-section from Browns Valley to Ortonville, Minnesota. See figure 2 for location. Note convergence in the Dakota Sandstone and Graneros Shale below the Greenhorn Formation.

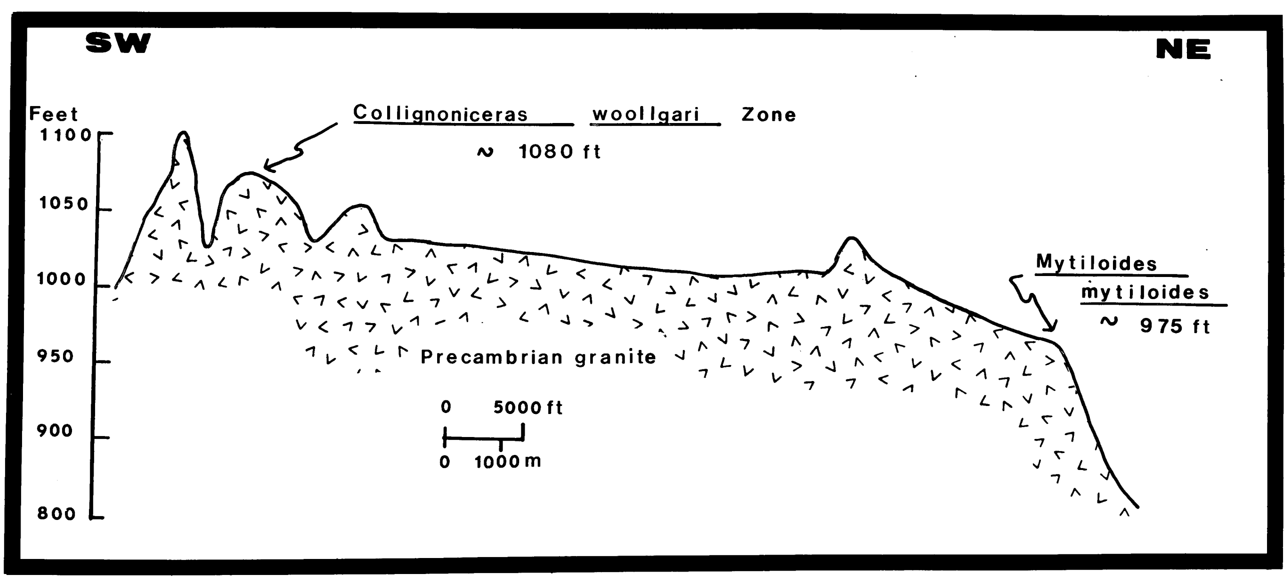
of approximately 305 m (1000 ft) and is covered by the Greenhorn Formation. A similar convergence may be present in the Carlile Shale, and the Niobrara Formation is found on low-relief basement surfaces with elevations of approximately 366 m (1200 ft). Study areas in eastern Minnehaha County, South Dakota, and northwestern Iowa (D and E, figure 2) are located on the south flank of the Sioux Ridge and the generalizations found useful on the north flank seem to have less utility.

In eastern Minnehaha County, South Dakota (D, figure 2) the surface of the Sioux Quartzite lies at elevations of about 397 m (1300 ft). In this area, scattered exposures of an enigmatic lithology have been tentatively termed Niobrara Formation (Beyer, 1896). However, no paleontologic data are available to support this correlation and the rocks generally are not calcareous (Baldwin, 1949). This lithostratigraphic units has been known informally as the Pathfinder Formation and is described in detail elsewhere in this guidebook, and is now defined as the Split Rock Creek Formation (Ludvigson, et al., this volume).

Ludvigson and Bunker (1979) have recently described the Cretaceous rocks in northwestern Iowa (E, figure 2) where strike valleys are developed on



A. Map showing Cretaceous outcrops and the elevation of the surface of Precambrian rocks. Contour interval is 50 ft.



B. Cross section illustrating the elevations of specific biostratigraphic zones in Cretaceous rocks overlying the Precambrian crystalline rocks.

Figure 6. Configuration of surface of Precambrian rocks near Ortonville, Minnesota.

Paleozoic units that subcrop beneath the Cretaceous. Although figure 2 generally approximates the configuration of the sub-Cretaceous surface, the density of control points used here is not sufficient to document the strike valleys. The work by Ludvigson and Bunker (1979) does indicate two local areas in which the Cretaceous below the Greenhorn thins to an elevation of 305 m (1000 ft) on the sub-Cretaceous surface; these areas are west-central Lyon County and eastern Woodbury County (3 and 4, figure 2). However, in extreme northwestern Iowa the units below the Greenhorn thin onto the Sioux Ridge at approximately the 397 m (1300 ft) elevation near the area of the Split Rock Creek Formation.

INTERPRETATIONS OF TECTONISM

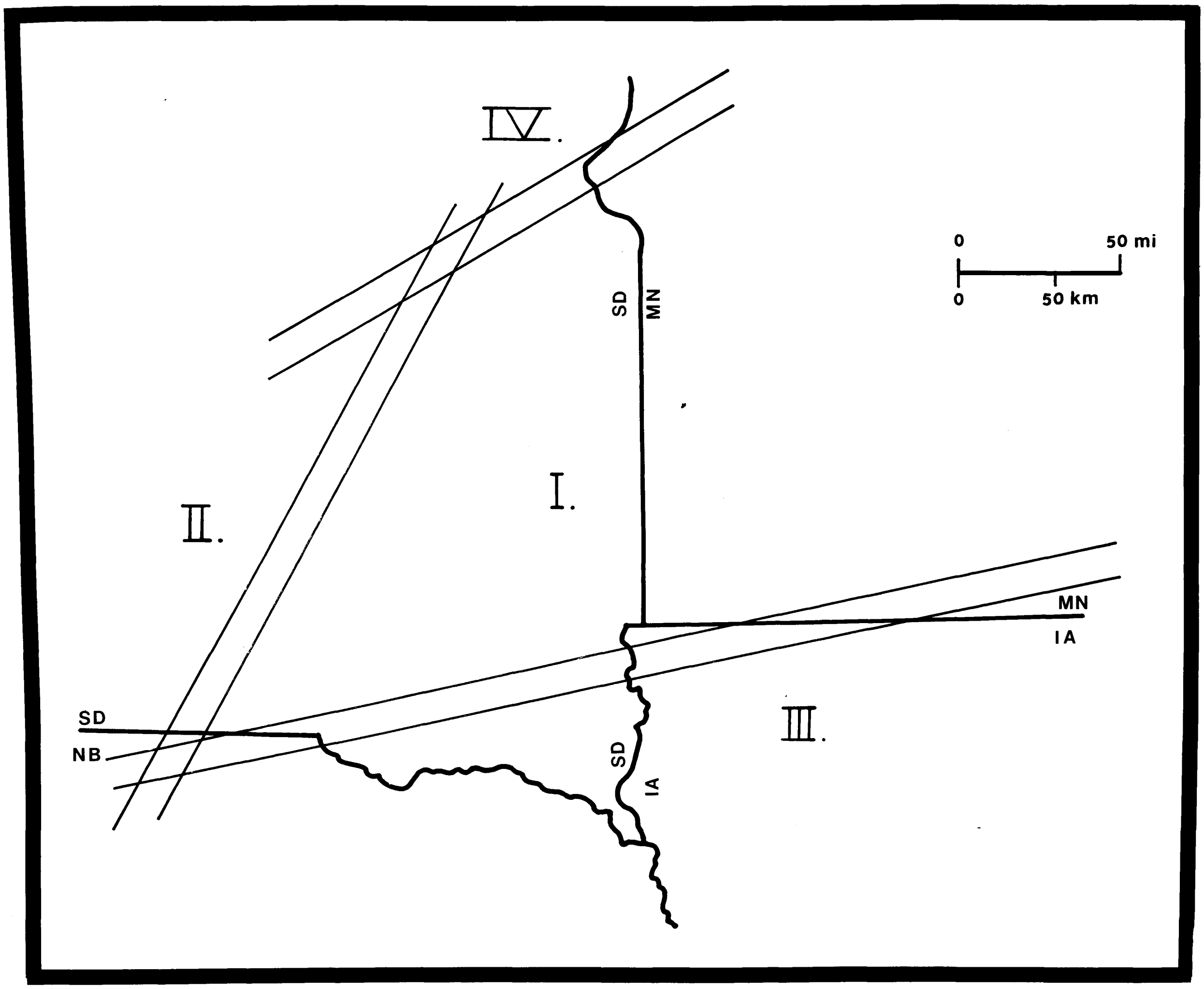
Detailed studies in local areas on the north flank of the Sioux Ridge indicate that the low relief surface at 305 m (1000 ft) are covered by the Greenhorn. On the south flank of the ridge this generalization does not seem to apply. In addition, our summary of regional stratigraphic and structural studies has indicated that the area to the south of the Sioux Ridge was one of three distinct regions. It is here suggested that these regions which surround the ridge and the ridge itself are separate and distinct structural blocks.

A tectonic model that visualizes discrete structural blocks bounded by zones of basement weakness has been successfully used throughout large parts of the northern Great Plains (Thomas, 1974) and in western South Dakota (Shurr, 1978). A postulated block geometry is shown in figure 7 for the Sioux Ridge and surrounding area.

The Sioux Ridge and the region to the north are thought to occupy the same block (I, figure 7) because the convergence in units below the Greenhorn consistently terminates at the 305 m (1000 ft) elevation along the north flank of the ridge. The regions to the northwest and south are taken as separate blocks (II and III, figure 7) because of the contrasting regional stratigraphic and structural patterns. Specifically, the Greenhorn elevation and regional dips are different and the Cretaceous units below the Greenhorn are thicker in these two regions. The block in northeastern South Dakota (IV, figure 7) is not well-characterized in this study, but the existence of a bounding zone of basement weakness is suggested by several lines of evidence.

The boundary between blocks I and IV corresponds with a Precambrian boundary which has recently been shown to be a long-lived tectonic feature (Sims and others, in press). The outcrop of Greenhorn and Carlile near Browns Valley lies within this boundary with dips 27° (Shurr, 1980). This structural attitude suggests that there was post-Carlile tectonism. In addition, a study of the Precambrian basement in South Dakota (Lidiak, 1971) indicates that faults may occur along the postulated boundary between blocks I and IV.

The other two block boundaries are not as clearly defined as the northern boundary. The boundary between blocks I and II corresponds with marked change in configuration of the sub-Cretaceous unconformity on the crest of the Sioux Ridge (figure 2). The boundary between blocks I and III may have expression in the series of small anticlines and synclines mapped in northwestern Iowa (Ludvigson and Bunker, 1979). This boundary also



Explanation

I through IV — Basement Blocks

══ — Boundaries of basement blocks

Figure 7. Postulated geometry of structural blocks near the Sioux Ridge in eastern South Dakota and contiguous areas.

approximates the sub-Cretaceous contact between the Paleozoic units found in block III and the Sioux Quartzite found in block I. The outcrops along the Big Sioux River, (which are described in the road logs in this guidebook), are therefore the result of erosion and differential tectonism between blocks I and III.

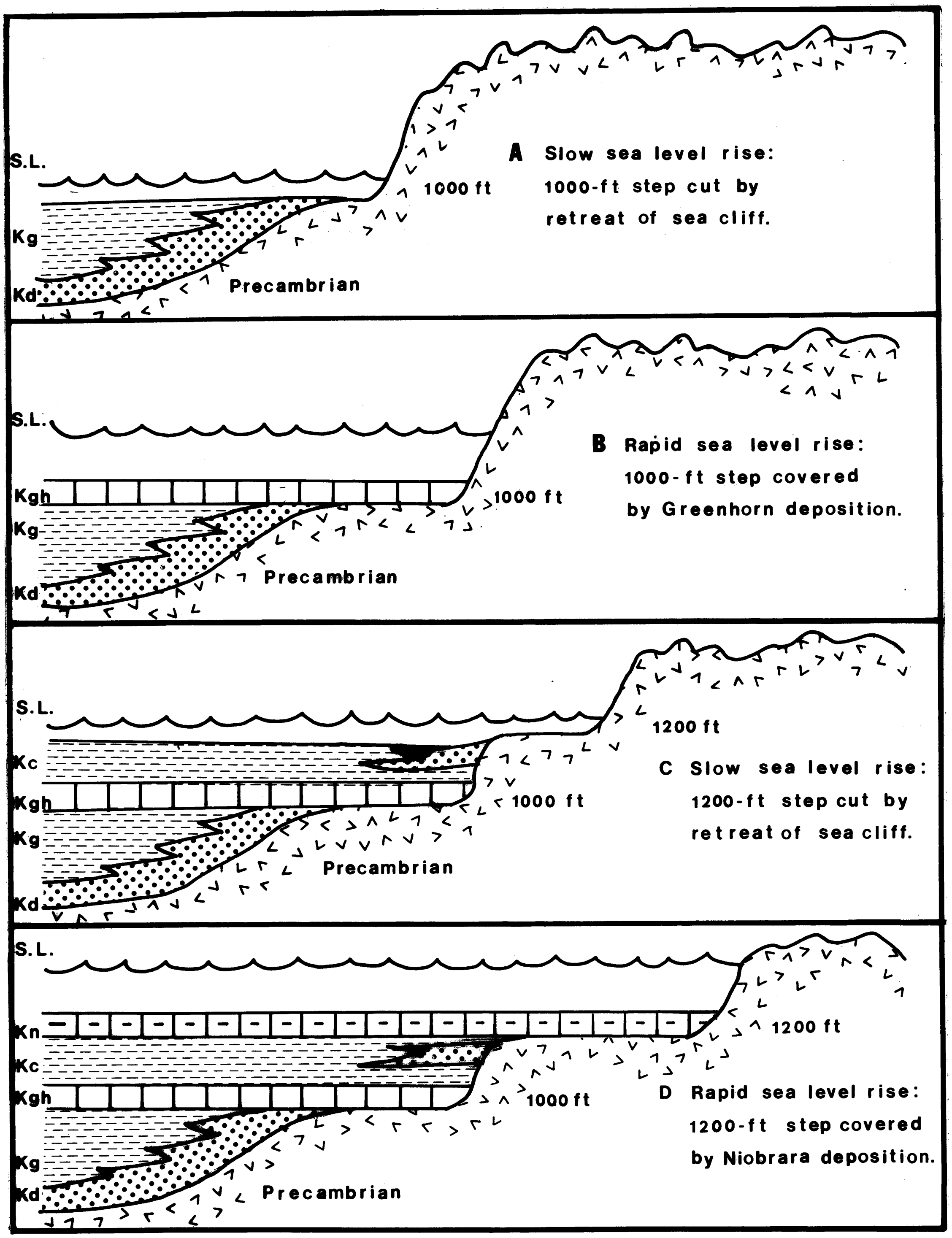
Delineation of the distinct structural blocks shown in figure 7 implies that the relative influences of tectonism and erosion on the configuration of the sub-Cretaceous unconformity can be separated. Specifically, the low regional dips on the Greenhorn in block I and the consistent convergence of the Cretaceous below the Greenhorn to the 305 m (1000 ft) surface on the basement, suggest that there has been little tectonic activity within block I. The configuration map in block I (figure 2 and 7) may reflect the topography of the sub-Cretaceous unconformity that is little modified by tectonism. This Cretaceous paleotopography consists of a series of steps. The "treads" of the step are low-relief surfaces at elevations of 305 m (1000 ft) and 366 m (1200 ft); the "risers" are areas with 61 m (200 ft) of local relief that separate the "treads".

PALEOGEOGRAPHIC INFERENCES

The stepped paleotopography cut into the north flank of the tectonically stable Sioux Ridge can be explained in terms of varying rates of sea-level rise during the Late Cretaceous. Interpretations of transgression and regression as controlled by rates of sea-level rise have recently been discussed by Pitman (1978). The idea is herein applied to the stepped sub-Cretaceous paleotopography. The flat "treads" are produced by parallel retreat of sea cliffs during a time of relatively slow sea-level rise. During a rapid rise of sea level, the flat "treads" are flooded, sea level rapidly moves up the sea cliffs, and the cliffs are preserved as "risers". Figure 8 summarizes the sequential development of the stepped paleotopography. In the regions of low basement elevation surrounding the Sioux Ridge, deposition during the Cretaceous initiated with the nonmarine environments that produced the Dakota Sandstone. In northwestern Iowa and northeastern Nebraska, the lower part of the Dakota was deposited in braided-stream environments and the upper part of the Dakota was deposited in meandering channels (Bowie, 1972). This change in channel characteristics accompanied filling of the stream valleys (Ludvigson and Bunker, 1979). The Sioux Ridge probably marked a divide between major drainages north and south of the ridge (figure 2). The topographic low extending eastward from South Dakota into Lyon County, Minnesota (B, figure 2) was probably the site of a fluvial system which had a history similar to the system in northwestern Iowa. Nonmarine conditions were replaced by marine conditions as sea level slowly rose and the Graneros Formation was deposited. During this transgression, sea water flooded the remnants of the aggraded drainage systems and the flat surface at 305 m (1000 ft) was cut by parallel retreat of sea cliffs (figure 8-A).

The Greenhorn Formation was deposited over the surface at 305 m (1000 ft) during a subsequent increase in the rate of sea-level rise (figure 8-B). The resulting coastline in block I would have been at an elevation of approximately 305 m (1000 ft) as suggested by Sloan (1964) and the Sioux Ridge probably stood as a peninsula or rocky cape at the time of maximum transgression. During this time the marine incursion perhaps spread east, where it covered a "peneplain" postulated to exist in southern Minnesota (Parham, 1970).

During a deposition of the Carlile, the rise of sea level slowed and sea cliffs again retreated in parallel to produce the flat surface at an elevation of 366 m (1200 ft) (figure 8-C). The apparent regression commonly interpreted at the time of Carlile deposition is perhaps the result of a seaward migration of nearshore environments in response to the slower rate of sea



Explanation

S.L.	Sea Le el	Kgh	Greenhorn Formation
Kn	Niobrara Formation	Kg	Graneros Shale
Kc	Carlile Shale	Kd	Dakota Sandstone

Figure 8. Interpretation of the sequential development of the stepped paleotopography on the north flank of the Sioux Ridge.

level rise. However, the lack of tectonism in block I and the progressive covering of the knob near Ortonville, Minnesota, by marine sediments (figure 5), clearly shows that sea level continued to slowly rise while the Carlile was deposited.

A subsequent increase in the rate of sea-level rise flooded the 366 m (1200 ft) surface and the Niobrara was deposited (figure 8-D). By the time of maximum transgression, only the highest elevations of the ridge were emergent as isolated islands with steep and rocky coasts. Biostratigraphic zones of the Western Interior corresponding with Niobrara deposition in eastern South Dakota (Rice, 1976) have been calibrated by radiometric dates and are between 86.8 (zone of *Inoceramus deformis*) and 82.5 (zone of *Desmocaphites bassleri*) million years old (Obradovich and Cobban, 1975). Thus, between 86.8 and 82.5 million years ago, the coastlines stood at just over 366 m (1200 ft) on the crest of the Sioux Ridge and the ridge has been interpreted to be situated on a stable tectonic block.

It is an interesting coincidence that Pitman (1978) has suggested that 85 million years ago, sea level stood approximately 374 m (1225 ft) above the present position. This coincidence implies that the structural block occupied by the Sioux Ridge essentially has not moved relative to sea level for the past 85 million years. This tectonic stability is in marked contrast with the blocks around the ridge that have undergone post-Cretaceous tectonism.

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MID-CRETACEOUS FORMATIONS IN EASTERN SOUTH DAKOTA AND ADJOINING AREAS--STRATIGRAPHIC, PALEONTOLOGIC, AND STRUCTURAL INTERPRETATIONS

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ABSTRACT

Sedimentary rocks of early Late Cretaceous age in eastern South Dakota, northeastern Nebraska, and northwestern Iowa, are assigned to, in ascending order, the Dakota Formation, Graneros Shale, Greenhorn Formation, Carlile Shale, and Niobrara Formation. Upper Cretaceous beds of the Dakota and the Graneros grade laterally and northward into the Belle Fourche Shale of eastern North Dakota. The lower Upper Cretaceous strata consist largely of shale, siltstone, sandstone and limestone of marine origin, although most of the Dakota accumulated in nonmarine environments, and all of these rocks were deposited near the eastern shore of a transgressing and regressing epeiric sea. The rocks are about 220 m thick in eastern North Dakota and about 200 m thick in northeastern Nebraska, thinning eastward to a featheredge in Minnesota and Iowa. The thinning is caused by onlap of the basal beds, structural deformation, and truncation during the mid-Cretaceous and the Cenozoic.

Invertebrate fossils of Cenomanian to Santonian ages in outcrops and cores of the strata indicate regional lateral changes in lithofacies. Part of the Belle Fourche of eastern North Dakota and the Graneros of eastern South

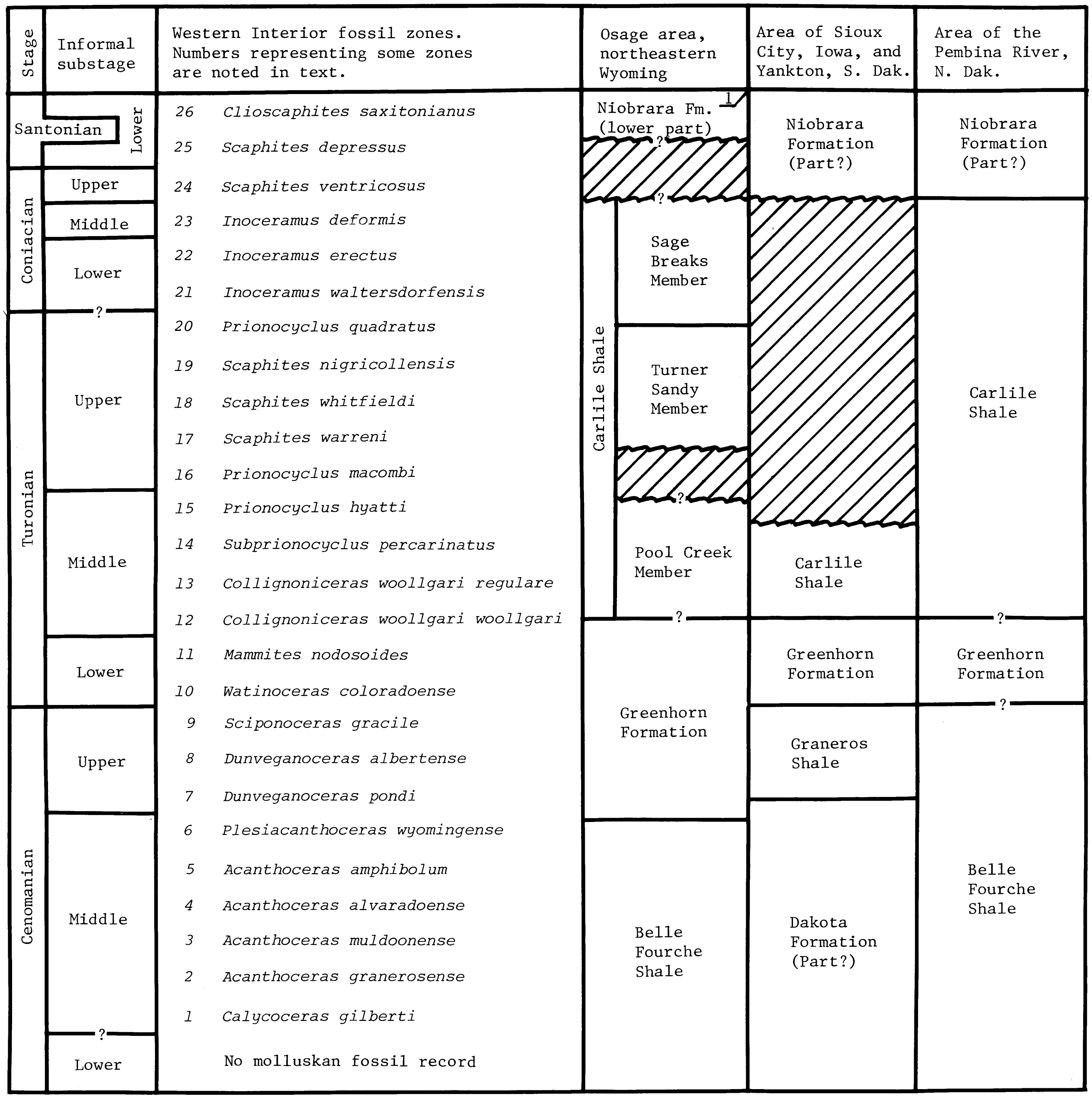
Dakota, which are of offshore-marine origin, grade eastward into the Coleraine Formation of northeastern Minnesota and probably into an unnamed sequence in south-central Minnesota, which are of nearshore-marine and nonmarine origin. During Graneros time, a strandline in Minnesota was oriented generally north-northeast.

The regional structure of the Greenhorn includes broad shallow synclines in eastern North and South Dakota and northeastern Nebraska and a west-trending anticline in southeastern South Dakota. The structure of the Greenhorn, local truncation of the Carlile, and elevations of fossiliferous beds provide evidence of mild mid-Cretaceous deformation.

Several of the fossil species from outcrops in the region and from Pleistocene drift in Minnesota, Iowa, and Illinois have also been found in outcrops in western Greenland. The similarity of the fauna at these widely separated localities is interpreted as indicating a direct connecting seaway across Canada through Hudson Bay during Turonian, Coniacian, and Santonian time.

INTRODUCTION

In early Late Cretaceous time, clastic and calcareous sediments accumulated in eastern North Dakota, eastern South Dakota, northeastern Nebraska, Minnesota, and northwestern Iowa near the eastern shore of a transgressing and regressing epicontinental sea. The sediments were deposited in marine and nonmarine environments and contain fossils of Cenomanian to Santonian age. In eastern South Dakota and contiguous areas, the beds are assigned to, in ascending order, the Dakota Formation, Graneros Shale, Greenhorn Formation, Carlile Shale, and Niobrara Formation (figure 1). This sequence rests on igneous and metamorphic rocks of Precambrian age and, in northwestern Iowa, on sedimentary rocks of Paleozoic age. In eastern North Dakota, mid-Cretaceous strata include, from older to younger, the Belle Fourche Shale, Greenhorn Formation, Carlile Shale, and Niobrara Formation. The Belle Fourche is conformably underlain by beds of Early Cretaceous (or Mowry) age. These lower Upper Cretaceous sequences are about 220 m thick in eastern North Dakota, about 200 m thick in northeastern Nebraska, and thin irregularly eastward to a featheredge in Minnesota and Iowa. Thinning is caused by transgressive overlap at the base, local tectonism and nearshore erosion during the mid-Cretaceous, and differential regional truncation during the Cenozoic. The surface of the underlying Precambrian and Paleozoic rocks is deeply dissected and slopes irregularly westward from higher areas in Minnesota (Sloan, 1964, p. 5; Ludvigson and Bunker, 1979 figure 5). Upper Cretaceous strata in the region are generally overlain by glacial deposits and alluvium of Quaternary age.



1/ Age of basal contact of Niobrara Formation from Evetts (1976, p. 121).

Figure 1.--Correlation of the lower Upper Cretaceous formations at selected localities in northeastern Wyoming, southeastern South Dakota, and northeastern North Dakota. Pattern represents a hiatus in the sequence of beds.

The purpose of this report is to summarize the biostratigraphy and regional structure of the lower Upper Cretaceous formations in eastern North and South Dakota and adjacent areas. This paper includes published and unpublished information from many scientists, most of whom are not cited. A more comprehensive description of the mid-Cretaceous beds, which will contain suitable acknowledgements, is currently being prepared.

The biostratigraphy was inferred from invertebrate fossils that have been collected from Cretaceous outcrops and Pleistocene drift during the past century. The molluscan species were identified by W. A. Cobban. These fossils were compared with specimens of Western Interior index fossils (figure 1), to establish the relative age of beds in the Cretaceous formations. Many of the mollusks listed on figure 1 represent several genera with the same age span, and the listed species do not occur in every collection used in this investigation.

STRATIGRAPHY

In southeastern South Dakota and adjoining areas, the basal strata of the lower Upper Cretaceous sequence are assigned to the Dakota Formation (Meek and Hayden, 1862). This formation, as much as 140 m thick, is composed of sandstone and some interbedded siltstone, shale, and lignite (Darton, 1909, p. 46; Simpson, 1960, p. 16; Schoon, 1971, figure 1). At outcrops in the vicinity of Sioux City, Iowa, the sandstone is commonly light brownish gray, very fine grained to medium grained, and cross-stratified; and contains carbonaceous material, root casts, fossil leaves, and bivalves. Some of the shale in the formation contains burrows. Tester (1931, p. 280-281) concluded that the Dakota in this area had been deposited in nonmarine and marginal-marine environments near the shoreline of a shallow sea. Resting conformably on the Dakota is the Graneros Shale, the lower part of which contains marine fossils of late Cenomanian age (figure 1, zone 7). It is inferred from the age of these fossils that the Dakota near Sioux City includes strata of Cenomanian age.

In northeastern North Dakota, the Mowry Shale, of Early Cretaceous age, is conformably overlain by the Upper Cretaceous (Cenomanian) Belle Fourche Shale (Bluemle, 1973, figure 3). Bluemle (1973) reported that the Belle Fourche consists of dark-gray shale about 76 m thick. The Belle Fourche was deposited in an offshore-marine environment; the lower part presumably grades southward into the Dakota Formation of northwestern Iowa and northeastern Nebraska.

In the area of Sioux City, the Dakota is overlain by the Graneros Shale, which is mainly dark-gray shale. Locally, the shale is sandy and silty near the base of the formation and calcareous near the top (Todd, 1908, p. 2). Near Yankton, South Dakota, the Graneros is as much as 50 m thick (Simpson, 1960, p. 18). The formation contains burrows and marine fossils in outcrops in northwestern Iowa, and most of it probably was deposited in an offshore-marine environment. Molluscan fossils of late Cenomanian age in the lower part of the Graneros are in fossil zone 7 (figure 1), and those in the upper part of the formation are in zone 8. These strata seem to be laterally equivalent to the upper part of the Belle Fourche Shale in eastern North Dakota.

Marine fossils of late Cenomanian age (figure 1, zone 8) have also been collected from the Coleraine Formation in the Mesabi iron range of northeastern Minnesota. Where encountered in strip mines, the formation was reported to be locally more than 30 m thick and to be composed of conglomerate, sandstone, and shale (Bergquist, 1944). These strata were deposited in shallow-marine environments in the western part of the Mesabi Range, and in nonmarine environments in the eastern part of the range (Bergquist, 1944, p. 8).

The Cretaceous rocks in south-central Minnesota are an unnamed sequence that consists mainly of a basal regolith and shale, siltstone, and sandstone of largely nonmarine origin (Thiel, 1944; Sloan, 1964; Parham, 1970; Austin, 1970). Near New Ulm, the sequence is a least 60 m thick and the constituent sandstone is fine-grained to coarse-grained, locally pebbly and friable, and either horizontally stratified, planar cross-bedded, or trough cross-bedded. Some outcrops contain a few vertical burrows. Lesquereux (1895) concluded, from a study of fossil leaves, that some of these beds were of Cenomanian age. Outcrops of nonmarine strata near New Ulm, Redwood Falls, and Richmond yield palynomorphs that Pierce (1961) assigned to the Cenomanian. Cretaceous beds in clay pits in the vicinity of Springfield contain bored fossil wood, burrows, fish bones, shark teeth, and molluscan fossils of near-shore-marine and brackish-water origin. The mollusks include a marine bivalve that is also found in the upper Cenomanina Coleraine Formation of northeastern Minnesota. A late Cenomanian ammonite (figure 1, zone 8) was obtained from red shale typical of the Cretaceous rocks at New Ulm, in an excavation about 17 km southeast of Springfield. Although this specimen might have been transported by Pleistocene glaciation, it probably reflects the age of strata in this area. In the vicinity of New Ulm and Springfield, the Cretaceous sequence is mainly of Cenomanian age and of shallow-marine and nonmarine origin. Part of this sequence and the Coleraine in the Mesabi Range are approximately the same age and both units probably are nearshore facies of the Graneros Shale. The nonmarine and marine Cenomanian rocks in south-central Minnesota apparently grade laterally into the nonmarine Windrow Formation of southeastern Minnesota.

In eastern South Dakota and contiguous areas, the Graneros is conformably overlain by fossiliferous limestone and calcareous shale of the Greenhorn Formation, which is largely of open-marine origin. The Greenhorn is about 9 m thick in the vicinity of Yankton, South Dakota, and Sioux City, Iowa (Todd, 1908, p. 2; Simpson, 1960, p. 18-19). Molluscan fossils in the formation are of early and middle Turonian age (figure 1, zones 10-12). Where penetrated by a borehole near Tyler, Minnesota, the Greenhorn is mainly calcareous shale about 13 m thick. In northeastern South Dakota and the adjacent part of Minnesota, the formation is in outcrops, quarries, and boreholes. Shurr (1979) described thin beds of limestone and chalk in the upper part of the Greenhorn at an outcrop near Browns Valley, Minnesota. The formation in this area is 9-11 m thick and is of early and probably middle Turonian age (figure 1, zones 10-12). Moore (1979, p. 122 and 129) reported that the Greenhorn in boreholes in southeastern North Dakota consists of 9-12 m of fossiliferous, calcareous, silty shale. The Greenhorn near Grand Forks, North Dakota, is as much as 29 m thick and is composed of interstratified limestone, marlstone, calcareous shale, and bentonite (Hansen and Kume, 1970, figure 4).

Samples of calcareous and noncalcareous shale obtained from a borehole near Richmond in central Minnesota, contain foraminifera which are characteristic of the Greenhorn and the lower part of the overlying Carlile (B. R. North and W. G. E. Caldwell, written commun., 1978). In southeastern Minnesota, marine rocks that overlie the nonmarine Windrow Formation (Austin, 1972), may represent the Greenhorn Formation.

The Greenhorn is conformably overlain by the Carlile Shale in eastern South Dakota and ajoining areas. At outcrops and in boreholes near Vermillion, the Carlile consists of 40-80 m (figure 2) of noncalcareous shale and minor calcareous shale and sandstone (Todd, 1908, p. 2; Condra, 1908, p. 12). These strata were deposited mainly in offshore-marine environments and contain fossils of middle Turonian age (figure 1, zones 13 and 14). The Carlile in this area is unconformably overlain by the Niobrara Formation (Hattin, 1975).

In water wells in eastern South Dakota and at outcrops along the James River near Mitchell, the upper part of the Carlile generally includes the Codell Sandstone Member. Todd (1903, p. 2) reported that the member occurs locally at the top of the formation and as much as 15 m below the top, and is 6-15 m thick. At localities between Mitchell and Olivet, the lower part of the Codell is composed of interstratified calcite-cemented sandstone, friable sandstone, and clay, and the upper part of the member consists of thinly and thickly crossbedded sandstone. The sandstone is fine grained to coarse grained and locally, near the top of the member, it contains pebbles as much as 5 cm in diameter, composed of shale, sandstone, limestone, chert and phosphatic material. Most outcrops of sandstone are cross-stratified and some show herringbone crossbeds and other planar crossbeds that indicate several paleocurrent directions. *Thalassinoides* and other burrows occur in some beds. Fossils in the Codell include bored wood, leaves, shark teeth, and bone fragments. The member was evidently deposited in shallow-marine environments near the eastern shore of the Turonian sea.

In northeastern South Dakota and southeastern North Dakota, the Carlile Shale is 60-80 m thick (figure 2) in boreholes and is composed of noncalcareous shale and minor calcareous shale, siltstone, and sandstone. The Carlile at quarries and outcrops in the area contains marine fossils of middle Turonian age (figure 1). The formation is largely of offshore-marine origin, although locally it overlies Precambrian rocks.

In northeastern North Dakota, the Carlile is about 80-120 m thick (figure 2). Arndt (1975, p. 5-6) described the Carlile at outcrops along the Pembina River, where the upper part of the formation consists of noncalcareous shale that intertongues with the overlying Niobrara Formation. Fossils collected in this area by Wosick (1977), from about 40 m below the top of the Carlile, include ammonites that are interpreted to be of latest Turonian or earliest Coniacian age (figure 1, zones 20 or 21).

The Carlile Shale has also been found in wells and boreholes in central Minnesota, near Richmond. Part of the formation in that area consists of clay, shale, and minor lignite as reported by Kloos in 1872. The sequence he described is about 22 m thick and contains marine fossils of middle Turonian age (figure 1, zones 12, 13, or 14). Samples of shale obtained from a

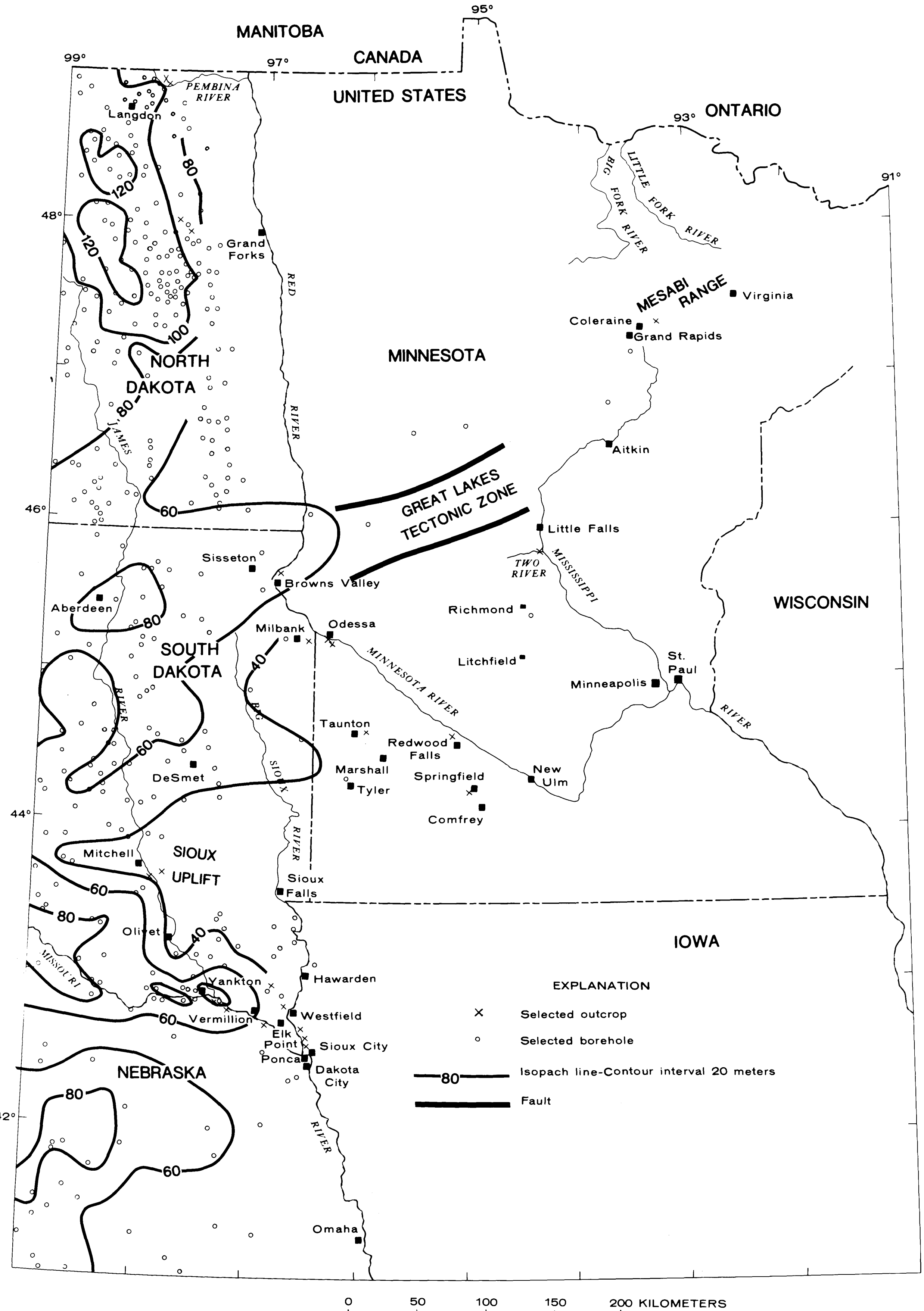


Figure 2.--Approximate thickness of the Carlile Shale where overlain by the Niobrara Formation in eastern South Dakota and adjoining areas.

borehole near Richmond contain foraminifera that are characteristic of the lower part of the Carlile (B. R. North and W. G. E. Caldwell, 1978, written commun.).

In southeastern South Dakota and adjacent areas in Nebraska and Iowa, the Niobrara Formation of offshore, open-marine origin unconformably overlies the Carlile (Hattin, 1975). The Niobrara, in the area between Yankton and Sioux City, is as much as 62 m thick and is composed mostly of argillaceous limestone (Simpson, 1960, p. 21). Near Yankton, the outcropping formation contains molluscan fossils of late Coniacian age (figure 1, zone 24) in the basal beds and fossils of Santonian age in the overlying beds.

The Niobrara also crops out in eastern North Dakota near Grand Forks, where it consists of marlstone and shale and is as much as 35 m thick (Hansen and Kume, 1970, p. 15 and figure 4). In northeastern North Dakota, the formation conformably overlies the Carlile Shale at outcrops along the Pembina River. Arndt (1975, p. 6) reported that the Niobrara in that area is composed largely of calcareous shale and is at least 46 m thick. This sequence includes basal beds of calcareous shale, which contains late Coniacian fossils (figure 1, zone 24), and overlying beds of noncalcareous and calcareous shale, which contain Santonian fossils. These rocks were deposited in an offshore, probably open-marine environment.

The Niobrara has not been positively identified in Minnesota although fossils typical of the formation have been found in several parts of the State. Presumably, the fossils came from glacial drift.

STRUCTURE

The regional structure of the Upper Cretaceous strata is illustrated by a structure-contour map of the top of the Greenhorn Formation (figure 3). The Greenhorn is easily recognized, comparatively widespread, and is probably about the same age throughout the region. Altitudes for the structure-contour-map were obtained mainly from logs of boreholes. In eastern North Dakota and northeastern South Dakota, the Greenhorn has been folded into a northwest-trending syncline that plunges into the Williston Basin. In northeastern Nebraska, the formation is in a southwest-plunging syncline. These broad folds are separated by the Sioux Uplift, a west-trending anticlinal feature. The structural relief is at least 250 m between eastern North Dakota and northeastern Minnesota, and at least 200 m between northeastern Nebraska and northwestern Iowa (figure 3).

Evidence of crustal deformation was also derived from mines and quarries, from fossiliferous outcrops, and from cores, where the depth and age of formations has been established. In the Mesabi Range, the Coleraine Formation contains Cenomanian fossils of zone 8 (figure 1) and rests on Precambrian rocks at an altitude of about 390 m. Some of the Cretaceous strata near Springfield, in southern Minnesota, are probably about the same age as the Coleraine but they crop out at an altitude of about 314 m. Fossils of zone 8 (figure 1) in the Graneros Shale of northwestern Iowa were found in cores from an altitude of about 340 m. These species were also found in outcrops along the Big Sioux River at an altitude of approximately 370 m. Younger fossils, from the Greenhorn and Carlile Formations, were collected from quarries and outcrops near Odessa and Browns Valley in western Minnesota.

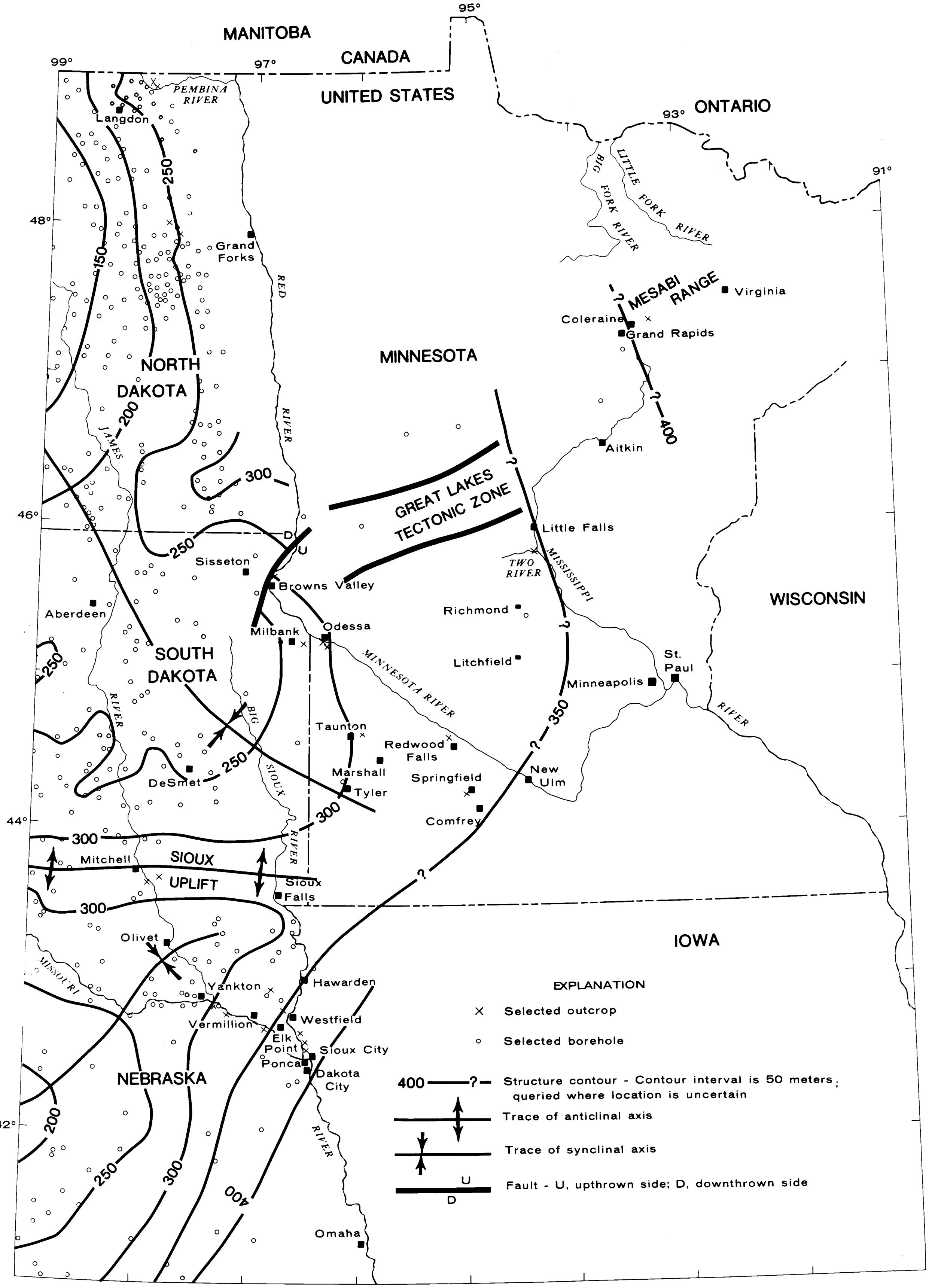


Figure 3.--Map showing structures at the top of the Greenhorn Formation in eastern South Dakota and adjoining areas.

The Greenhorn in the area contains fossils of zones 10-12 (figure 1) and locally overlies Precambrian rocks at an altitude of about 300 m. In nearby quarries, the Carlile contains fossils of zone 13 and overlies Precambrian rocks at an altitude of approximatley 320 m. The structural relief between beds of Graneros age in the Mesabi Range and younger beds in the Greenhorn near Odessa is at least 90 m.

In northeastern South Dakota, the structure-contour lines (figure 3) and outcrops of steeply dipping beds are sparse evidence of a north-northeast-trending fault. Strata on the west side of this inferred fault are approximately 60 m lower than the same beds on the east side of the fault. Shurr (1979) determined that the Greenhorn at an outcrop about 8 km north of Browns Valley, on the east side of the fault, strikes N. 70° W. and dips 27° NE. He also noted that the outcrop is within the Great Lakes tectonic zone of Sims and others (in press), which trends west-southwest through this area. The zone separates two crustal bodies of Precambrian age and probably has been the loci of intermittent tectonism since Archean time. Sims and others (in press) suggested that minor faulting occurred along the zone during Late Cretaceous or Cenozoic time. However, the unusual attitude of the Greenhorn near Browns Valley could have been caused by either local tectonism or by an advancing Pleistocene ice sheet. If the dip and altitude of this Greenhorn has been increased by glacial activity, there would be little supporting evidence for a fault in northeastern South Dakota (figure 3).

Deformation during early Late Cretaceous time is indicated by the stratigraphy of the Carlile and Niobrara Formations. In eastern South Dakota, the Carlile ranges in thickness from less than 40 m on the Sioux Uplift to more than 80 m near Aberdeen and along the Missouri River, on the northwest and southwest flanks of the uplift, respectively (figure 2). At outcrops in southeastern South Dakota, middle Turonian shale in the Carlile is disconformably overlain by upper Coniacian limestone of the Niobrara (figure 1). Georgesen (1931, p. 31) and Simpson (1960, p. 20) reported that the Carlile-Niobrara contact has as much as 60 cm of local relief. Hattin (1975, text-figure 5) indicated that the contact represents a significant hiatus. The hiatus was probably caused by uplift and erosion in late Turonian and Coniacian time. Furthermore, the local thickening of the Carlile in the southwest-trending area in northeastern South Dakota (figure 2) and in the northwest-trending area along the Missouri River may be interpreted as indicating that some of the Cretaceous deformation is related to movement along fault zones in the underlying Precambrian rocks.

In the subsurface of northeastern North Dakota, the Carlile thickens westward from less than 80 m to about 120 m (figure 2). At outcrops near the Pembina River, the uppermost strata in the Carlile intertongue with the basal strata of the overlying Niobrara. The Carlile contains fossils of latest Turonian age and the lower part of the Niobrara contains fossils of late Coniacian age. Because the formations are conformable and gradational and the Carlile thickens westward, eastern North Dakota probably was subsiding more than northwestern Minnesota during part of Turonian and Coniacian time. This deformation and the uplift in southeastern South Dakota could reflect mid-Cretaceous tectonism along the Transcontinental arch, which trends generally northeast from southwestern Colorado to north-central Minnesota (Ludvigson and Bunker, 1979). Studies of mid-Cretaceous stratigraphy by Weimer (1978) indicate movement of the Transcontinental arch in Colorado and some contiguous states during the Late Cretaceous.

CONCLUSIONS

The mid-Cretaceous rocks in the eastern parts of North Dakota, South Dakota, and Nebraska, and in Minnesota and northwestern Iowa, indicate changes in the location of the eastern shoreline of the Cretaceous epicontinental sea and periods of structural subsidence and uplift. Largely nonmarine strata of Cenomanian age in the Dakota Formation near Sioux City grade northward into offshore-marine shale of the same age in the Belle Fourche Shale of eastern North Dakota. Presumably, the trend of the shoreline between Sioux City and the Canadian border at that time was approximately northeast. The upper Cenomanian Graneros Shale, which conformably overlies the Dakota in southeastern South Dakota, was deposited mostly in offshore-marine environments. Shallow-marine and nonmarine facies of the Graneros occur in northeastern Minnesota (Coleraine Formation) and probably in south-central Minnesota (unnamed sequence). The shoreline in the late Cenomanian apparently was oriented generally north-northeast and was east of the earlier Dakota shoreline in the Sioux City area. Calcareous strata of the Greenhorn Formation conformably overlie the Graneros and are persistent in the western part of the region. They are mostly of early Turonian age and of offshore, open-marine origin. The Greenhorn may be represented by calcareous and noncalcareous shale in central Minnesota near Richmond, and by marine rocks, which overlie the Windrow Formation, in southeastern Minnesota (Austin, 1972). In eastern South Dakota and adjacent areas, the Dakota, Graneros, and Greenhorn form a sequence that was deposited continuously during a marine transgression (Schoon, 1965; Austin, 1972) in Cenomanian and early Turnian time.

The Carlile Shale rests conformably on the Greenhorn and was deposited mainly in offshore-marine environments. In southeastern South Dakota, near the Sioux Uplift, the Carlile is of middle Turonian age and is unconformably overlian by the Niobrara Formation. In northeastern North Dakota along the Pembina River, the Carlile is probably of middle Turonian through middle Coniacian age, and apparently is conformably overlain by the Niobrara. The basal Niobrara in both areas was deposited during late Coniacian time in offshore, open-marine environments. Beds in the lower part of the Carlile have also been recognized in central Minnesota near Richmond. Interpretations of the stratigraphy of the Greenhorn, Carlile, and Niobrara include the following: 1, a widespread marine regression during the middle Turonian (early Carlile time); 2, a marine transgression during the late middle Turonian in eastern South Dakota; 3, slight regional deformation, a marine regression, and truncation of some of the Carlile in eastern South Dakota, probably during the late Turonian; and 4, a widespread marine transgression and deposition of the basal Niobrara in the Coniacian.

Marine fossils of Turonian, Coniacian, and Santonian ages have been collected from outcrops in the region and from Pleistocene drift at localities in Minnesota, Iowa, and Illinois. The species in the drift generally do not occur in nearby formations and presumably have been transported southward from former outcrops in Minnesota, Wisconsin, and perhaps Ontario by glacial activity. Furthermore, these fossils represent a relatively continuous sequence of marine beds in the Carlile and Niobrara. Some species found in the outcrops and drift of the northern mid-continent region of the United States have also been collected from outcrops in western Greenland by Birkelund (1965). The similarity of the fauna in these widely separated regions is additional evidence of a direct connecting seaway across Canada through Hudson Bay, at least during late Turonian, Coniacian, and Santonian time, as Williams and Stelck (1975, p. 10-12) suggested.

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Subsurface Stratigraphic and Sedimentologic Analyses of Cretaceous Rocks in Northwest Iowa

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ABSTRACT

By combining subsurface geological and geophysical (natural gamma-ray logs) information with outcrop observations, the stratigraphy and depositional history of Cretaceous (Albian to Turonian) rocks in Northwest Iowa were delineated. The Dakota Formation appears to have been deposited as a complex of braided stream systems which evolved into coarse-grained meander belt systems under decreasing gradient conditions. Marine transgression eastward through the study area replaced fluvial deposition with deltaic deposition represented by the

uppermost part of the Dakota. The overlying Graneros Shale and Greenhorn Limestone represent open marine deposition which took place as a result of continued eustatic transgression and burial of the pre-Cretaceous topography. A resumption of siliciclastic input is represented by prodelta mudstones of the Carlile Shale. Post-Cretaceous erosion has removed any units that may have been deposited above the Carlile Shale in Northwest Iowa.

INTRODUCTION

Although very little work has been done on the Cretaceous rocks of Iowa since the early works by Meek and Hayden (1861), Bain (1895), and Tester (1931), the water resource potential of the Dakota aquifer may play a critical role in the near future of this part of the country. During the past 4 years, the Iowa and U.S. Geological Surveys have been engaged in a drilling program designed to evaluate this important water resource potential. Drilling localities were selected in a way that would allow the determination of the stratigraphic and sedimentologic controls on the Dakota aquifer in Northwest Iowa (Ludvigson and Bunker, 1979). One of the survey test holes was cored prior to the completion of this study (well D-7, figure 1). Each of the other wells have a suite of rock cuttings, generally collected every 5 feet, and most wells have gamma-ray logs (figure 1).

In this study, lithologic sequences were first described from the Hawarden (D-7) core and from the surface outcrops that will be visited on this field trip. Strip logs were then constructed for each of the other wells using rock-cuttings and the accompanying gamma-ray logs. Data derived from outcrops, core, well-cuttings and gamma-ray logs were combined to form the data base from which stratigraphic and sedimentologic interpretations were made. Since the outcrops are described elsewhere in this volume, and you will have the opportunity to view them yourselves, we will concentrate on the subsurface aspects of this study and summarize the stratigraphic and sedimentologic results. It should be noted that although the formations which overlie the Dakota (i.e., Graneros Shale, Greenhorn Limestone and Carlile Shale) can be observed in outcrops, only the uppermost portion of the Dakota Formation is exposed at the surface.

SUBSURFACE ANALYSIS

The subsurface data obtained from 14 test wells were used to construct two geologic cross-sections, A-A' and B-B' (figure 1, 2 and 3). These cross-sections show the distribution of dominant lithologic facies rather than bed-by-bed correlations. These generalizations had to be made because of rapid lateral variations in rock type, especially in the Dakota Formation which made bed-by-bed correlations impossible. Characteristics observed in each of these facies will be described from wells containing sections typical of each facies.

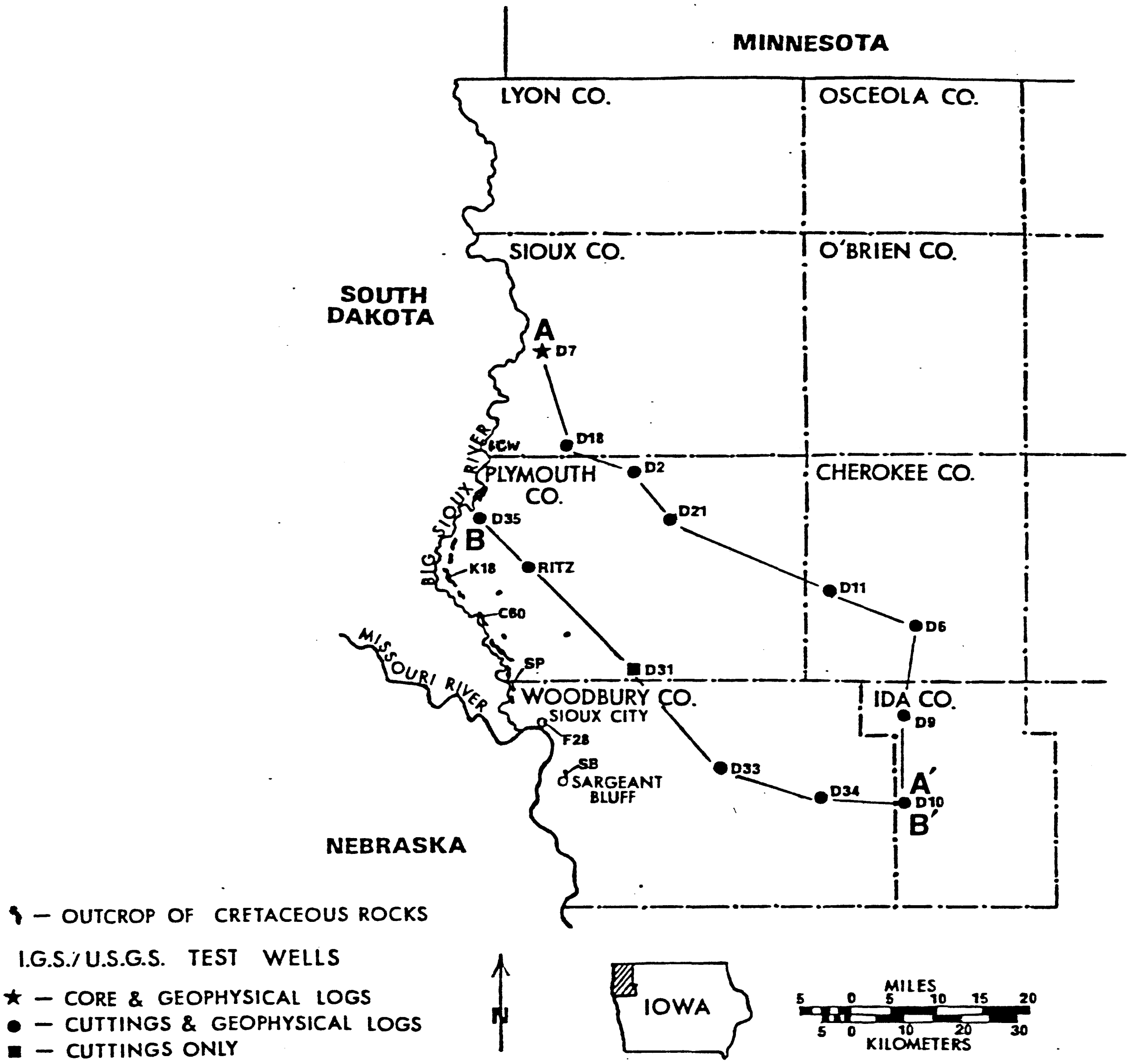


Figure 1. Map showing locations of I.G.S.-U.S.G.S. test wells and outcrops of Cretaceous rocks in Northwest Iowa. Lines A-A' and B-B' show positions of cross-sections in Figures 2 and 3.

Dakota Formation

Three facies can be recognized in the Dakota Formation. These are: 1) dominant sandstone facies; 2) dominant mudrock facies; and 3) subequal sandstone and mudrock facies. As can be seen from the cross-sections (figures 2 and 3), the lower portion of the Dakota consists primarily of the dominantly sandstone facies. Going upward in the sequence, increasing amounts of mudrock are found, which eventually become dominant in the upper portions of the Dakota.

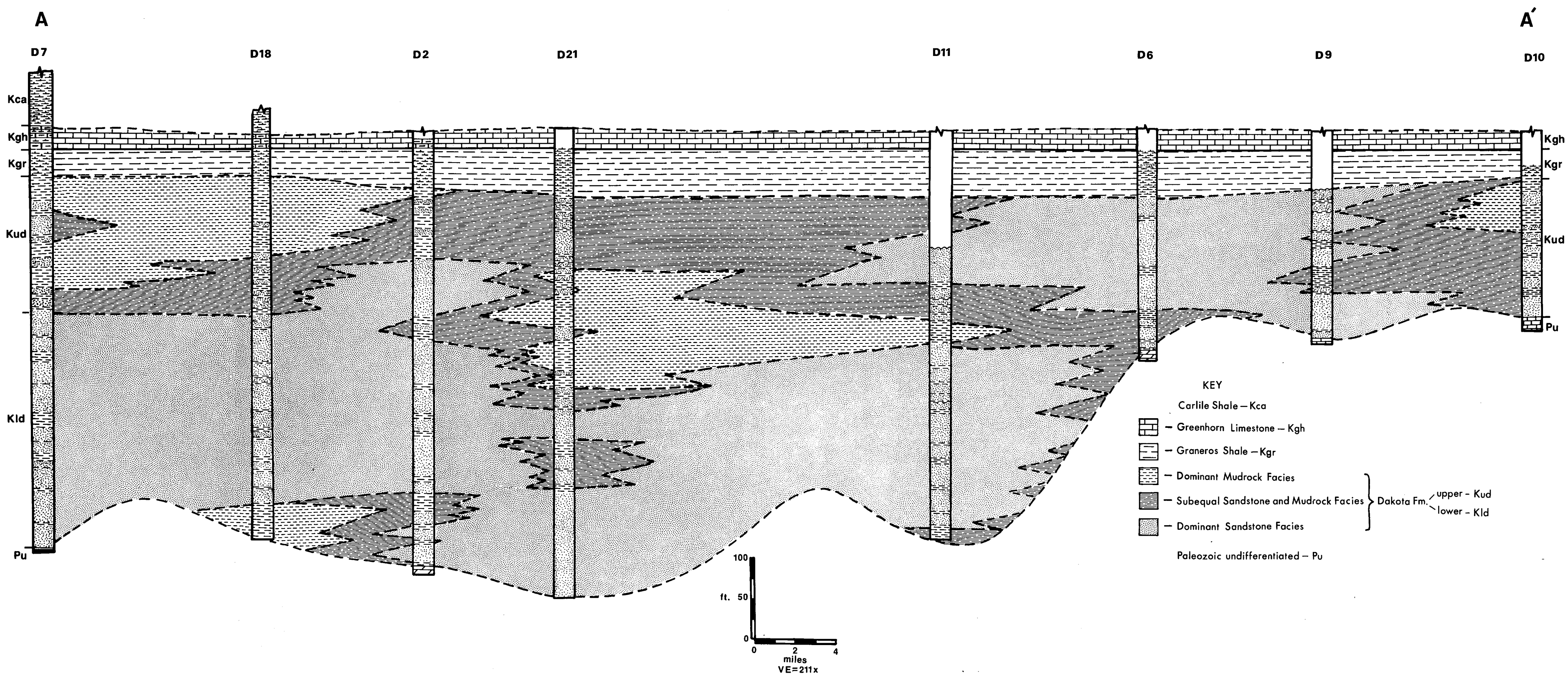


Figure 2. Generalized cross-section A-A'. See Figure 1 for location.

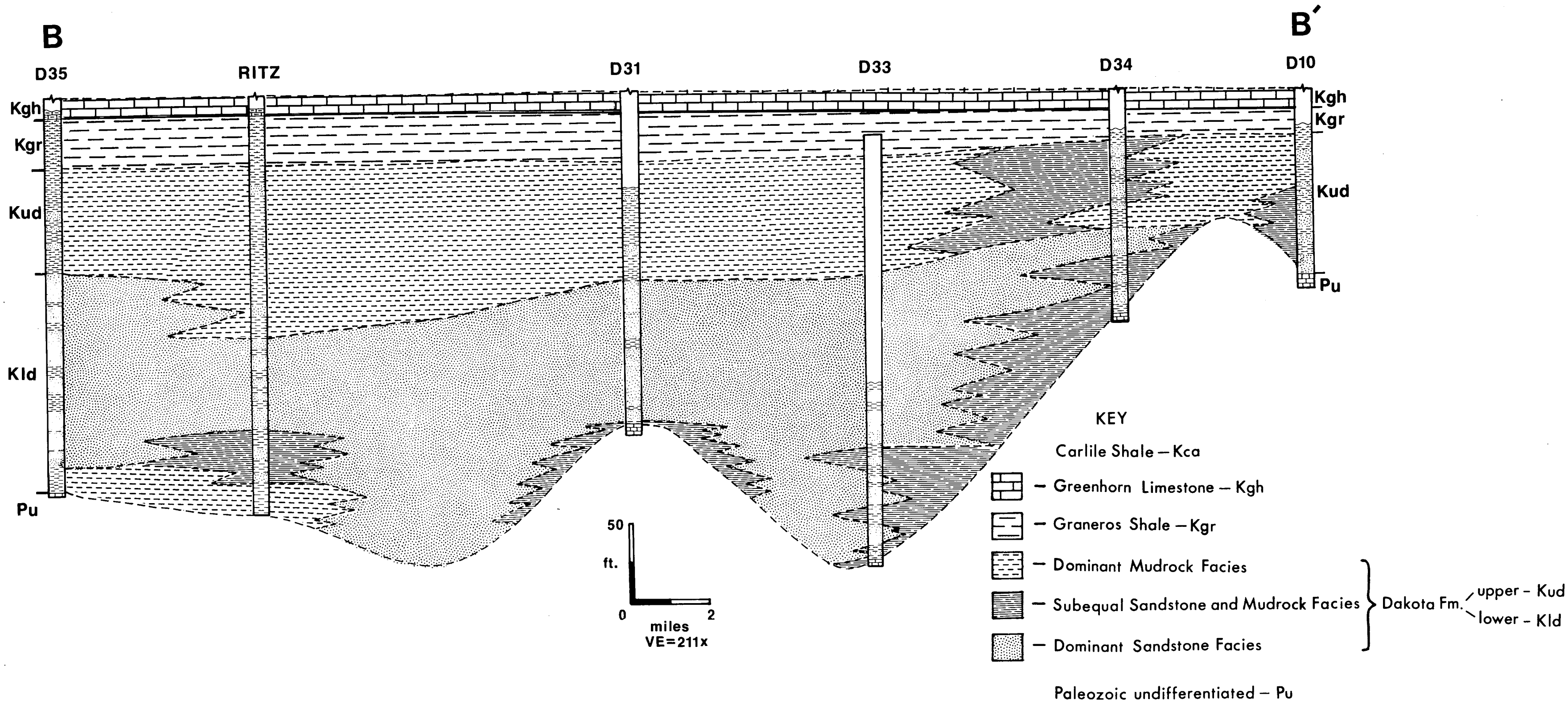


Figure 3. Generalized cross-section B-B'. See Figure 1 for location.

Dominant Sandstone Facies

The dominant sandstone facies is best displayed in the Hawarden Core from 352.8 - 643.0 feet in depth (figure 4). The facies consists primarily of coarse-grained sand-size and pebble-size quartz with thin interbeds of shale and siltstone. Sedimentary structures and vertical grain-size variations could not be observed in the core because of poor recovery of non-cemented sand units. Gamma-ray logs were utilized for determining gross-grain-size changes as well as contact relationships. Gradual increases in gamma radiation suggest gradual decreases in grain size because of an increasing abundance of K_{40} contained with clay. Rapid increases or decreases in gamma counts indicate sharp contacts between units, while gradual changes suggest gradational contacts between lithologies.

The lower part of the dominant sandstone unit shows both uniform (homogenous textures) and coarsening-upward sequences. Uniform sequences of poorly sorted sand are seen in the cuttings from well D-21 (445-575 ft, figure 5). Several zones of pebble size clasts, probably channel-lags, produce increases in gamma radiation, possibly resulting from their content of igneous rock material.

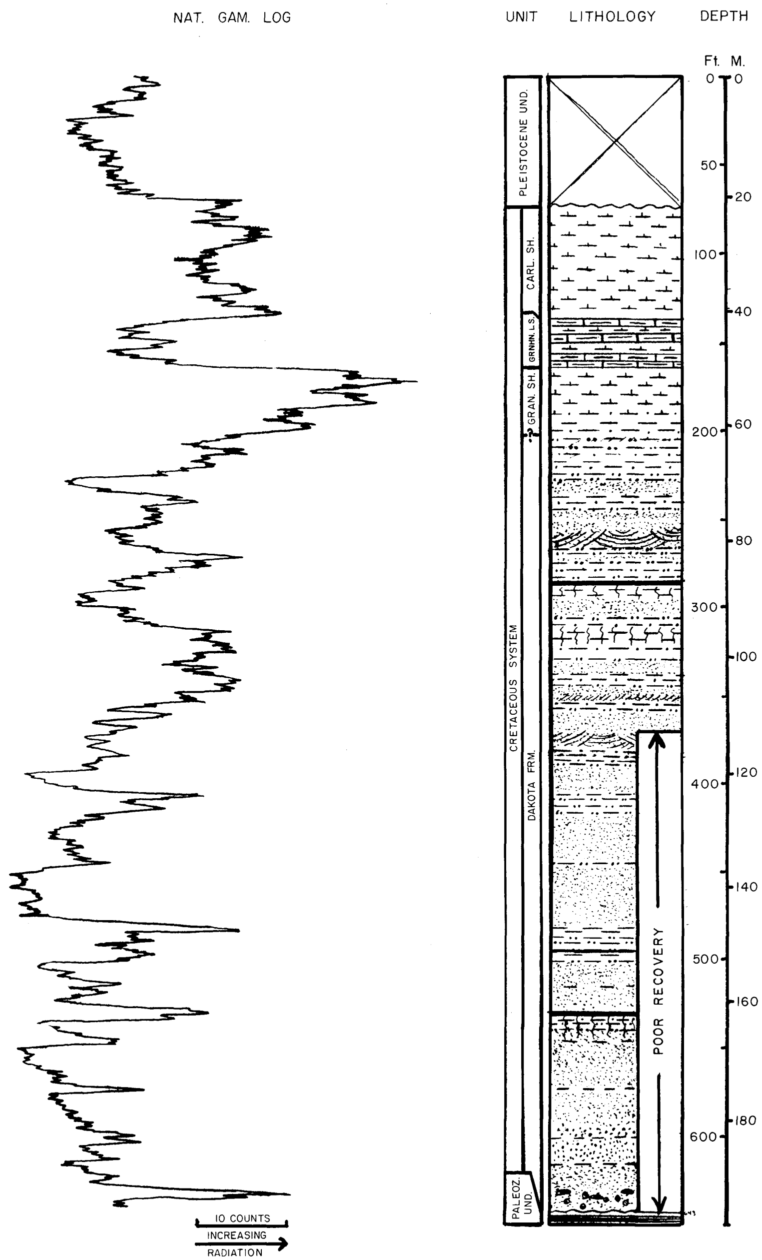
Coarsening-upward sequences are more dominant, with fining-upward sequences becoming more common toward the top of the dominant sand facies. A series of these sequences is seen in the Hawarden core (543-614.5 ft, 415-480 ft, figure 4). The thicker sequences of siltstone, shale and lignite, probably represent channel-fill deposits.

The dominant sandstone facies seen in well D-6 (87-255 ft, figure 6), shows crude fining-upward sequences from coarse channel-lags of coarse sand to pebble-size material, grading upward to silt and clay. The apparent coarsening-upward zones as indicated by decreasing gamma counts upward, are not evident in the samples. This log signature may have resulted either from an upward decrease in igneous rock fragments from the basal channel-lag, where they are most commonly found, or possibly from an error in sampling the well-cuttings.

Dominant Mudrock Facies

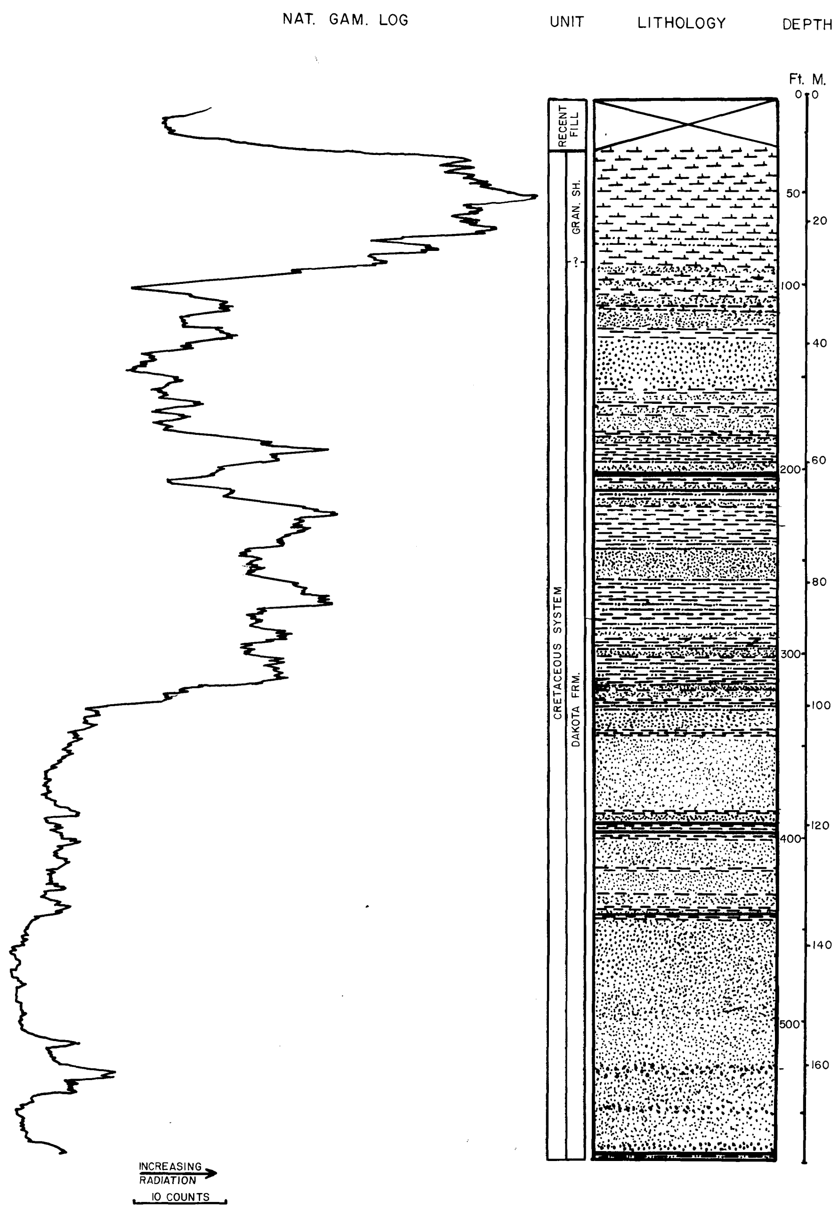
Lithologies consisting primarily of silt and clay size material are commonly found in the upper portions of the Dakota. The dominant mudrock facies consists of claystone, silty clay shale and clayey siltstone with occasional interbeds of fine- to medium-grained sandstone. Lignite beds are common, and the clays and silts often contain abundant woody organic debris.

The dominant mudrock facies seen in the Hawarden core (265-335 ft, 194-220 ft, figure 4) consists of thinly laminated clays and silts, suggestive of quiet-water deposition. Mottling associated with root casts is common, especially beneath lignitic zones. Sandstone interbeds show distinct fining-upward sequences from fine- to medium-grained sand upward to silt and clay, with sharp basal contacts. This is seen in the Hawarden core (265-305 ft, figure 4), and in test well D-21 (220-260 ft, figure 5). Sedimentary structures are seldom preserved in the coarser units of the core, because of poor cementation. Some siltstone show small-scale trough and ripple cross-laminae (194-211 ft, figure 4), typical of deposition under lower flow regime conditions.



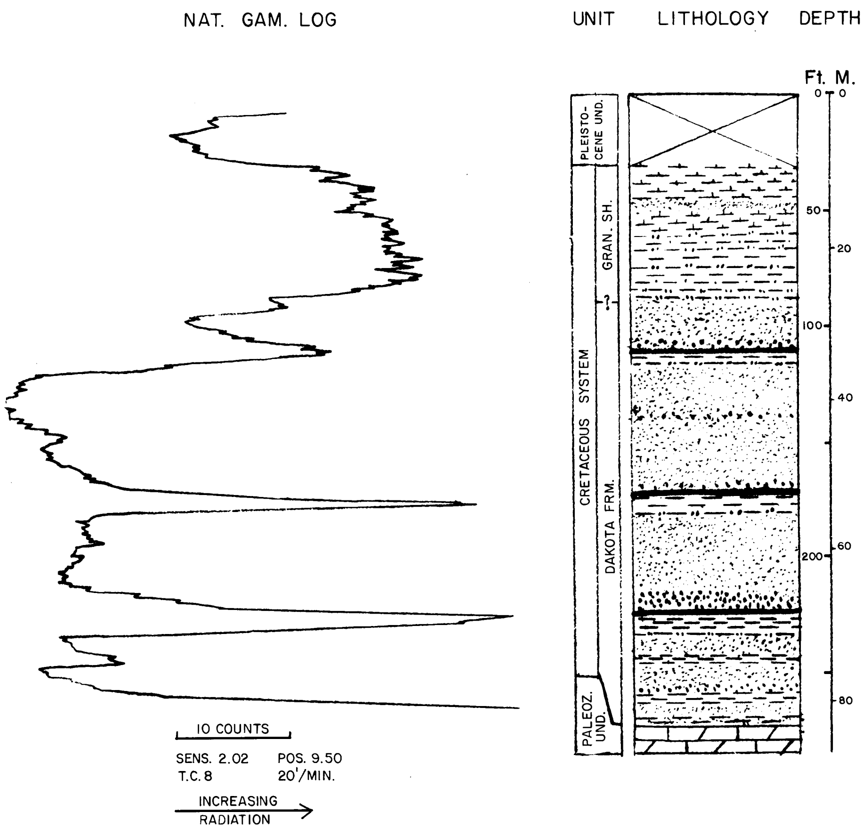
INTERVAL	DESCRIPTION
0 - 73 ft. (0 - 22.3 M)	Post-Cretaceous sediment, (not cored) undifferentiated.
73 - 137 ft. (22.3 - 41.8 M)	Clay shale, grey, thinly laminated, fissile, calcareous, fossiliferous - predominantly fish bones and scales, some pelecypods, ammonites, and wood fragments, some chalk and gypsum on bedding surfaces, gradational basal contact.
137 - 165 ft. (41.8 - 50.3 M)	Interbedded chalky, shaly, limestone and chalky shale, limestone is white to light brown, thin rippled bedding, fossiliferous - predominantly pelecypods with some fish scales and bones, shale is medium to dark grey, calcareous, thin laminated, rippled, fossiliferous - fish fragments and pelecypods, gradational basal contact.
165 - 194 ft. (50.3 - 59.1 M)	Clay shale, grey, thinly laminated to thin bedded, calcareous, fossiliferous - pelecypods, fish fragments, and plant remains, sulphate rich showing blebs of selenite growing on non-fresh bedding surfaces, becomes increasingly silty, decreasingly calcareous downward, gradational basal contact.
194 - 211 ft. (59.1 - 64.3 M)	Siltstone,light to dark grey, ripple cross-laminated, darker laminae are clayey, unit consists of a number of fining upward sequences to grey, silty clay shale, contains some fish fragments, sharp basal contact.
211 - 220.5 ft. (64.3 - 67.2 M)	Siltstone, buff to grey, thin laminated to thin bedded, predominantly quartz and mica silt, fines upward to grey, fissile clay shale, sharp basal contact.
220.5 - 238.8 ft. (67.2 - 72.8 M)	Sandstone, buff to grey, fine to medium grained quartz sand with some mica, feldspar and pyrite, some clay shale clasts, certain finer grained beds cemented by pyrite, fines upward to siltstone to grey silty clay shale, some scattered woody fragments, sharp basal contact.
238.8 - 265 ft. (72.8 - 80.8 M)	Sandstone, light grey to buff, fine to very fine grained quartz and muscovite, well sorted, basal 10 ft. cross-laminated, no apparent cement except some nodular pyrite, fines upward to siltstone to clay shale, some woody fragments, sharp basal contact.
265 - 292 ft. (80.8 - 89.0 M)	Interbedded siltstone and grey, silty clay shale, siltstone is buff, silt to very fine grained quartz and mica, contains abundant plant fragments and a lignite interbed at 287 ft., some root bioturbation beneath lignite, gradational basal contact.
292 - 305 ft. (89.0 - 93 M)	Sandstone, light to very light grey to white, medium to very fine grained quartz and mica, some pyrite nodules, fines upwards, contains some woody plant fragments, sharp basal contact.
305 - 309.9 ft. (93 - 94.5 M)	Interlaminated light grey clayey siltstone and silt to very fine grained sandstone, very light grey, quartz and mica, no cement, sharp basal contact.
309.9 - 336 ft. (94.5 - 102.4 M)	Claystone, light grey bedding disrupted by root casts which contain lignitic material, becomes very thin bedded toward base, becomes mottled grey to yellow brown toward base, yellow brown patches are more silty, scattered woody plant fragments, coarsens down to silt to fine grained quartzose sandstone, sharp basal contact.
336 - 352.8 ft. (102.4 - 107.5 M)	Sandstone fining up to clay shale, see description for 238.8 - 265 ft.
352.8 - 382.8 ft. (107.5 - 116.7 M)	Sandstone, very fine to medium grained quartz sand with some mica, feldspar and pyrite, poorly cemented, cross-bedded toward base, recovery becomes poor toward base, fines upward to siltstone to silty clay shale, sharp basal contact.
382.8 - 405 ft. (116.7 - 123.4 M)	Sandstone fining up to silty clay shale, see description 352.8 - 382.8 ft.
405 - 643 ft. (123.4 - 196 M)	Poor recovery, shaley and silty breaks interpreted from gamma log.
405 - 415 ft. (123.4 - 126.5 M)	Siltstone - silty shale, no samples.
415 - 480 ft. (126.5 - 146.3 M)	Sandstone, fine to medium grained quartz sand with some mica, feldspar and pyrite, no apparent cement, some silt to very fine grained interbeds, sharp basal contact.
480 - 501.5 ft. (146.3 - 152.9 M)	Siltstone and silty clay shale, no samples, lignite interbed possibly one tree fragment, gradational basal contact.
501.5 - 540 ft. (152.9 - 164.6 M)	Samples consist of coarse to very coarse grained sandstone, subangular to subrounded quartz, quartzite and chert grains, very poorly cemented. Gamma log shows some shaley to silty interbeds but samples were not recovered.
540.3 - 543 ft. (164.6 - 165.5 M)	Mottled claystone, siltstone and coarse grained sandstone beneath lignite (540 - 540.3 ft.) due to bioturbation, sandstone stained yellow-brown by limonite, gradational basal contact.
543 - 593 ft. (165.5 - 180.7 M)	Sandstone, light grey to buff, medium to very coarse grained quartz, quartzite, chert, and mica, some units well cemented by siderite toward base, some shaley to silty interbeds according to gamma ray log, sharp basal contact.
593 - 614.5 ft. (180.7 - 187.3 M)	Sandstone, coarse to pebble size clasts of quartz, quartzite and chert cemented by siderite and some pyrite, some clayey to silty interbeds according to gamma ray log, sharp basal contact.
614.5 - 615 ft. (187.3 - 187.4 M)	Clay shale, grey, fissile, contains some pyrite concretions, sharp basal contact.
615 - 633 ft. (187.4 - 192.9 M)	Sandstone, buff to grey, medium to very coarse grained quartz, mica, quartzite, chert, pyrite and feldspar, subangular to subrounded, 615-618 well cemented by siderite, 618-633 poorly cemented by limonite, sharp basal contact.
633 - 643 ft. (192.9 - 196 M)	Sandstone, grey, coarse to very coarse grained quartz, quartzite, chert, feldspar, and clay shale clasts, well cemented by siderite, contains white clayey concretionary bodies .25 - .5 in. diameter, sharp basal contact.
643 - 650 ft. (196 - 198.1 M)	Brown to light grey laminated claystone, with dolomitic interbeds.

Figure 4. Gamma-ray log, lithologic log and descriptions of core samples from the Hawarden (D-7) well. See Figure 1 for location.



INTERVAL	DESCRIPTION
0 - 27 ft. (0 - 8.2 M)	Back fill in quarry.
27 - 90 ft. (8.2 - 27.4 M)	Shale, grey, silty, calcareous, some mica and gypsum on bedding surfaces, fissile, becomes increasingly more silty and less calcareous downward. Gradational basal contact.
90 - 130 ft. (27.4 - 39.6 M)	Silty shale, grey, slightly calcareous, interbedded with sandstone, light brown to grey, very fine grained quartz, mica, poorly cemented by limonite and some calcite, gradational basal contact.
130 - 155 ft. (39.6 - 47.2 M)	Sandstone, light brown, very fine grained, quartz, mica, limonite cement, fines upward, sharp basal contact.
155 - 187 ft. (47.2 - 57 M)	Interbedded sandstone, siltstone and shale, sandstone is light brown, very fine grained, siltstone is light brown to grey, some limonite cement, shale is grey, silty, fissile, basal contact gradational.
187 - 201 ft. (57 - 61.3 M)	Sandstone fining upward to a shale, sandstone, light brown, very fine grained fining to a grey clay shale, fissile, sharp basal contact.
201 - 210 ft. (61.3 - 64 M)	Sandstone, buff very fine grained, fines upward to a grey clay shale to lignite, sharp basal contact.
210 - 220 ft. (64 - 67.1 M)	Sandstone, buff, very fine grained, fining upward to a grey clay shale, to lignite, sharp basal contact.
220 - 260 ft. (67.1 - 79.2 M)	Sandstone, buff, very fine grained, quartz, mica, slightly calcareous, some limonite cement, fines upward to siltstone, buff, silt size quartz and mica, to grey clay shale, fissile, sharp basal contact.
260 - 290 ft. (79.2 - 88.4 M)	Interbedded siltstone and shale, siltstone is buff, clayey, some limonite cement, shale, buff to grey, silty, some mica, chunky, very fine grained sandstone at base, sharp basal contact.
290 - 305 ft. (88.4 - 93 M)	Sandstone, buff, very fine grained fining upward to siltstone to clay shale, sharp basal contact.
305 - 340 ft. (93 - 103.6 M)	Interbedded sandstone, siltstone, and shale, overall fining upward from fine grained sandstone, buff, quartz, mica, feldspar, and rock fragments, no apparent cement, siltstone has some limonite cement, clay is grey, fissile, gradational basal contact.
340 - 385 ft. (103.6 - 117.3 M)	Sandstone, buff, fine to medium grained, coarser at base, subangular to well rounded quartz, mica, feldspar, quartzite, granite, and metamorphic rock fragments, moderately well sorted, no apparent cement, fines upward, thin grey clay shale interbed, gradational basal contact.
385 - 392 ft. (117.3 - 119.5 M)	Interbedded fine grained sandstone and fissile grey clay shale, sharp basal contact.
392 - 405 ft. (119.5 - 123.4 M)	Clay shale, medium to dark grey, fissile interbedded with lignite, gradational basal contact.
405 - 440 ft. (123.4 - 134.1 M)	Sandstone, buff, medium to coarse grained, quartz, mica, pyrite, feldspar subangular to rounded, moderate to poor sorting, fines upward, some shaley interbeds, sharp basal contact.
440 - 445 ft. (134.1 - 135.6 M)	Clay shale, grey, fissile, thin interbedded lignite, gradational basal contact.
445 - 525 ft. (135.6 - 160 M)	Sandstone, white to buff, fine to coarse grained, predominantly quartz with mica, pyrite, and various igneous and metamorphic rock fragments, angular to well rounded, poorly cemented, sharp basal contact.
525 - 570 ft. (160 - 173.7 M)	Sandstone, white to buff, fine to coarse grained, quartz, mica, quartzite and other rock fragments, angular to well rounded, poorly cemented, sharp basal contact.
570 - 575 ft. (173.7 - 175.3 M)	Assorted coarse grained to pebble size clasts of coal, siltstone, shale, sandstone, quartzite, copper minerals, end of cuttings.

Figure 5. Gamma-ray log, lithologic log and descriptions of well-cuttings from test well D-21. See Figure 1 for location.



INTERVAL	DESCRIPTION
0 - 32 ft. (0 - 9.8 m)	Post-Cretaceous sediment (Pleistocene?) undifferentiated.
32 - 45 ft. (9.8- 13.7 m)	Claystone, buff to light grey, silty, calcareous, some sandy interbeds, basal contact gradational.
45 - 50 ft. (13.7- 15.2 m)	Sandstone, loose, fine grained, subangular to subrounded quartz grains, some mica, pyrite, and quartzite rock fragments, moderately sorted, poorly cemented. Gradational basal contact.
50 - 87 ft. (15.2- 26.5 m)	Interbedded siltstone and shale, siltstone is lignt grey to buff, clayey, shale is light grey, slightly fissile, calcareous, gradational basal contact.
87 -110 ft. (26.5-33.5 m)	Sandstone, loose, fine to very coarse grained quartz sand with some mica, pyrite and quartzite rock fragments, moderate to well sorted, poorly cemented, sharp basal contact.
110 -125 ft. (33.5-38.1 m)	Sandstone, buff to yellow brown, fine to pebble size grains of quartz, mica, quartzite and specular hematite, some limonite cement toward base, fines upward to silty clay shale capped by lignite, sharp basal contact.
125 -145 ft. (38.1-44.2 m)	Sandstone, fine to medium grained quartz, mica, quartzite and pyrite fines upward, poorly cemented, sharp basal contact.
145 -170 ft. (44.2- 51.8 m)	Sandstone, fine to coarse grained, quartz, mica and quartzite clasts, moderate to well sorted, poorly cemented, sharp basal contact.
170 -225 ft. (51.8-68.6 m)	Sandstone, fine sand to pebble size clasts of quartz, mica, chert, and quartzite, angular to subrounded, moderate to well sorted, poorly cemented, fines upward to clay shale, fissile, capped by lignite, sharp basal contact.
225 -243 ft. (68.6-74.1 m)	Sandstone, fine grained, quartz, mica, chert, and quartzite, well sorted, poorly cemented, fining upward to a fissile clay shale, capped by lignite, sharp basal contact.
243 -260 ft. (74.1-79.2 m)	Sandstone, very fine to coarse grained, quartz, chert, mica, and quartzite, moderate to well sorted, poorly cemented, fining upward to grey, fissile clay shale, sharp basal contact.
260 -278 ft. (79.2- 84.7 m)	Sandstone, very fine to medium grained, portions well cemented by hematite and/or limonite, fines upward to a fissile clay shale. Contains some copper minerals, interbeds of light brown claystone, sharp basal contact.
278 -293 ft. (84.7- 89.3 m)	Dolomitic limestone, light grey, some copper mineralization, bottom of well.

Figure 6. Gamma-ray log, lithologic log and descriptions of well-cuttings from test well D-6. See Figure 1 for location.

Some claystones are mottled red to greenish-grey and contain siderite nodules (e.g., 230-263 ft and 275-305 ft in test well D-31, figure 7), similar to the unit exposed at Sergeant Bluff. This supports the idea that these features are not related to recent weathering at the surface, but were formed prior to exposure in the quarry.

Dominant mudrock zones seen near the base of the Dakota, contain a wide variety of angular sand to pebble size clasts along with brown to grey clay and silt. The clasts usually consist of fragments of the underlying Paleozoic limestone and cherts, which suggest that these deposits are probably debris slides from adjacent bedrock highs. Others might represent soils developed on the bedrock surface prior to burial and reworking by streams.

Subequal Sand and Mudrock Facies

Sequences showing relatively equal amounts of sandstone and shale are commonly found as transition zones between the dominant mudrock and dominant sand facies. The characteristics of these lithologies more closely resembles those of the upper dominant mudrock sequences, in which the mudrock facies consist of thinly laminated clays and silts with some lignitic zones. Sand units primarily show fining-upward sequences.

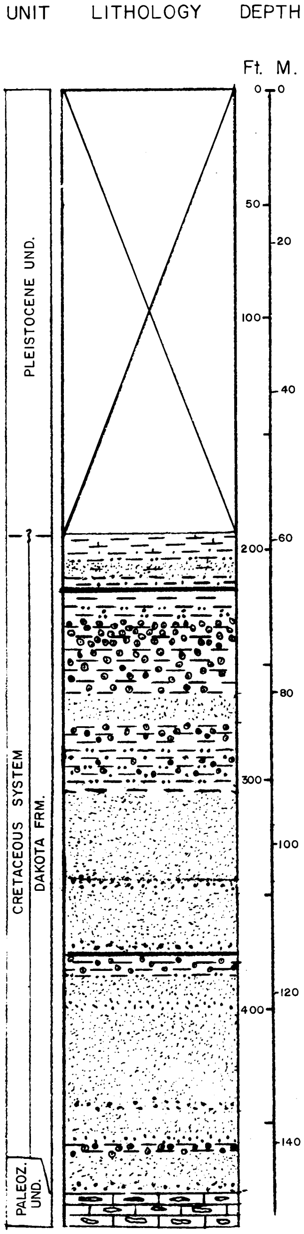
The subequal sand-mudrock facies that is found in the Hawarden core (336-352.8 ft, and 238.8-265 ft, figure 4) shows fining-upward sequences from fine to medium-grained sand at the base to silt and clay at the top. An upward decrease in flow conditions is indicated by an upward decrease in scale of the sedimentary structures and grain sizes, which range from moderate to small-scale cross-bedded sands upward to ripple cross-laminated silts (238.8-265 ft, figure 4).

Graneros Shale

The Graneros Shale, as seen in the Hawarden core (165-194 ft, figure 4) consists of thinly laminated, calcareous clay shale with some silty interbeds. Some beds are fossiliferous, containing pelecypods, fish fragments and plant remains. The Graneros is decreasingly calcareous downward, as it grades into non-calcareous clay shales of the Dakota. This gradation is also seen in the gamma-ray logs where the uppermost Dakota consists of clay shale and siltstones rather than sandstones. There is a continual increase in gamma-radiation from the Dakota upward, with the Graneros showing much higher levels of gamma-radiation than the shales of the Dakota (see 165-211 ft, figure 4, and 27-100 ft, figure 5). Where the Graneros overlies sandstones of the Dakota, the transition is much sharper, but is still gradational (see 32-100 ft, figure 6).

Greenhorn Limestone

The lithology of the Greenhorn is best observed in the Hawarden core. In other wells, sample recovery was poor because of the friable nature of the rock and solutional openings causing loss of fluid circulation. The Greenhorn is fossiliferous throughout, showing pelecypod and fish fragments surrounded by chalky carbonate mud or clay. Ripple stratification is present



INTERVAL	DESCRIPTION
0 -193 ft. (0 - 58.8 m)	Post-Cretaceous sediment (Pleistocene?), basal contact erosional.
193 -210 ft. (58.8- 64 m)	Sandstone, fine grained, clayey, fines upward to clay shale, medium to dark grey, fissile, silty, slightly calcareous, gradational basal contact.
210 -230 ft. (64 - 70.1 m)	Claystone, light to dark grey, sandy to silty, increasing sand downward, lignitic interbed with some pyrite, sharp basal contact.
230 -263 ft. (70.1- 80.2 m)	Claystone, mottled, light greenish-grey to reddish-brown, contains abundant siderite-quartz nodul out 1 m.m. in diameter, the nodules decrease in abundance downward, g. .cional basal contact.
263 -275 ft. (80.2-83.8 m)	Sandstone, fine to very fine grained, silty, predominantly quartz, with some mica, quartzite, and chert, moderately well sorted, no apparent cement, sharp basal contact.
275 -305 ft. (83.8- 97 m)	Clay shale, medium to dark grey, silty, contains some siderite nodules, some lignitic beds with pyrite, siltstone interbeds, brown, quartz silt with some mica cemented by siderite (390-395 ft.), gradational basal contact.
305 -350 ft. (97 -106.7 m)	Sandstone, fine to coarse grained, predominantly quartz with some mica, siderite, pyrite, and chert, increase in siderite and pyrite near base, overall fining upward, sharp basal contact.
350 -375 ft. (106.7-114.3 m)	Sandstone, medium to coarse grained, mostly quartz, some mica, chert, siderite and pyrite, no apparent cement, fines upward, sharp basal contact.
375 -400 ft. (114.3-121.9 m)	Sandstone, fine to coarse grained, mostly quartz with some pyrite, chert, and siderite, gastropod fragment in cuttings, fines upward to silty clay shale, medium to dark grey, some siderite nodules, capped by lignitic shale, basal contact sharp.
400 -445 ft. (121.9-135.6 m)	Sandstone, fine to coarse grained quartz, mica, chert, quartzite, pyrite and siderite, no cement, fines upward, sharp basal contact.
445 -460 ft. (135.6-140.2 m)	Sandstone, similar to 400-445 ft.
460 -480 ft. (140.2-146.3 m)	Sandstone, fine to medium grained quartz, mica, chert and siderite, no apparent cement, fines upward to clay shale containing abundant siderite-quartz nodules, sharp basal contact.
480 -487 ft. (146.3-148.4 m)	Cherty limestone, white to light brown, base of well.

Figure 7. Lithologic log and descriptions of well-cuttings from test well D-31. See Figure 1 for location.

in the chalky limestone and chalky shales, and suggest lower flow regime conditions.

The gamma-ray log of the Greenhorn shows a sharp decrease in radiation from the Graneros, suggesting a rapid cutoff of clastic influx. The interbeds of chalky, calcareous clay shale are seen as small peaks within the low radiation values and probably represent small pulses of clastic input into the area. The upper contact with the Carlile is more gradational suggesting a gradual increase in siliciclastic influx.

Carlile Shale

The Carlile is present in only two of the test wells, the Hawarden core (73-137 ft, figure 4) and D-18 (75-105 ft, figure 8). It consists of thinly laminated, highly calcareous clay shale, fossiliferous in spots, containing pelecypods, ammonites, fish fragments and carbonized woody plant debris. This suggests quiet water disposition under normal, near-shore marine conditions as evidenced by the fairly diverse fauna. Fluctuations in the gamma-ray log are probably related to variations in the relative amounts of carbonate to clay rather than being related purely to clay content. Silty interbeds may be an exception to this generalization.

DEPOSITIONAL ENVIRONMENTS

The depositional sequence, from the Dakota Formation through the Greenhorn Limestone, consists of a long term transgression, which is followed by regression represented by the Carlile Shale. Descriptions of the vertical change in depositional environments are presented in order from the Dakota through the Carlile.

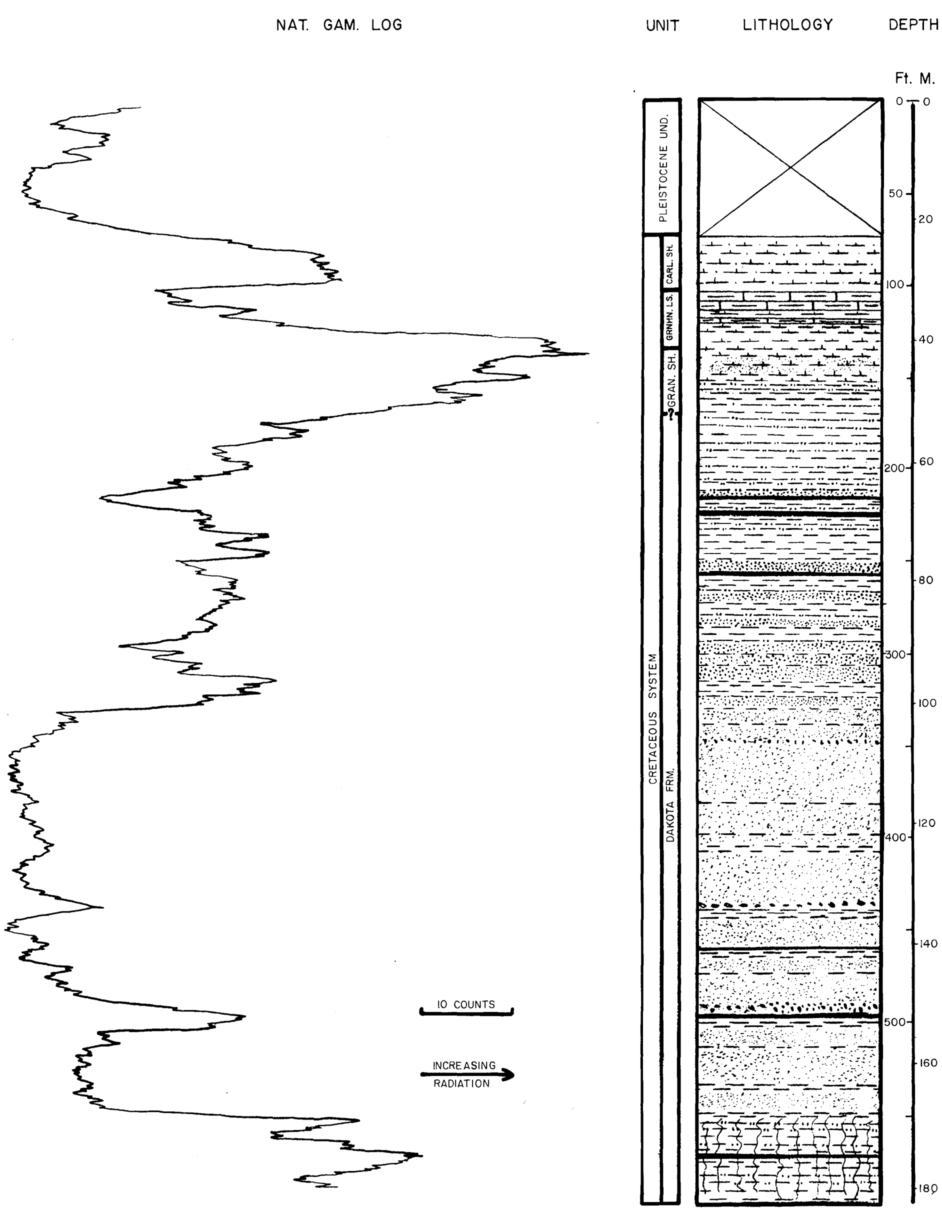
Dakota Formation

The Dakota Formation consists primarily of non-marine deposits formed in a series of fluvial environments, capped by sediments deposited in a complex of marginal marine environments. Because the majority of the Dakota is not exposed at the surface in the study area, environmental interpretations are made by analysis of vertical variations in grain size seen in lithic samples or in radioactivity variations shown in the natural gamma-ray logs. In addition, where possible, vertical sequences of sedimentary structures were used. Evidence from fossils were used where present, but other than woody plant remains, they are rare. Bowe (1972) has shown that at least part of the lower Dakota was deposited by braided stream systems. This interpretation was based upon exposures in southwest Iowa and the factors controlling those stream systems may not have been the same as those found in northwest Iowa.

As seen in the cross-sections (figures 2 and 3), the Dakota Formation may be split into two major units: 1) the lower Dakota, which consists primarily of sandstone; and 2) the upper Dakota, which consists of the dominant shale facies, subequal sand and shale units and some dominant sand facies. The dominance of sand in the lower Dakota and dominance of mudrocks in the upper Dakota suggest deposition by different types of fluvial systems.

Lower Dakota

Since all of the wells that penetrate the lower Dakota show thick sandstone sequences separated by relatively thin shale units, it is reasonable to assume that the geometry of the deposits is that of a "sheet" sand. Two possible fluvial environments could have produced this type of sand geometry: 1) braided; and 2) coarse-grained meandering streams. Depositional models proposed by Ore (1963, 1965), Smith (1970), Brown (1973), and McGowen and Garner (1970) for these types of systems, appear to be somewhat analogous to systems that account for deposition of lower Dakota sediments.



INTERVAL	DESCRIPTION
0 - 75 ft. (0 - 22.9 M)	Post-Cretaceous sediments (Pleistocene?) undifferentiated.
75 - 105 ft. (22.9 - 32 M)	Shale, light grey, silty, calcareous, fissile, some gypsum on bedding, sharp basal contact.
105 - 125 ft. (32 - 38.1 M)	Shaley limestone, light brown - grey, chalky some aragonite between bedding, some fish scale fragments, increasing amount of calcareous clay shale interbeds toward base, gradational basal contact.
125 - 155 ft. (38.1 - 47.2 M)	Shale, grey, calcareous, gypsiferous, slightly fossiliferous (fish scale fragments), fissile, some sandy interbeds, gradational basal contact.
155 - 215 ft. (47.2 - 65.5 M)	Interbedded calcareous clay shale (as above) and siltstone, buff to orange-brown, increasing siltstone, pyrite and limonite cement downward, fine grained sandstone at base, buff, subangular to subrounded quartz, pyrite, mica and assorted igneous and metamorphic rock fragments, little if any cement, sharp basal contact.
215 - 225 ft. (65.5 - 68.3 M)	Siltstone, light brown, quartzose, fines upward to clay shale, grey, fissile, silty, capped by lignite, sharp basal contact.
225 - 260 ft. (68.3 - 79.2 M)	Sandstone, fine to medium grained quartz sand with some mica, some limonite cement fines upward to siltstone to clay shale, grey to dark grey, lignite at top, sharp basal contact.
260 - 275 ft. (79.2 - 83.8 M)	Sandstone, brown, fine grained quartz, mica, and assorted rock fragments, well sorted, some limonite cement, fines upward to siltstone to fissile clay shale, grey, capped by lignite, sharp basal contact.
275 - 350 ft. (83.8 - 106.7 M)	Interbedded sandstone, siltstone and shale, sandstone units are coarse to very fine grained quartz sand with some mica, pyrite, and quartzite rock fragments, only finer grained units cemented by limonite fines upward in each case to limonite cemented siltstone, and further to a grey fissile clay shale, some lignitic fragments, sharp basal contact.
350 - 460 ft. (106.7 - 140.2 M)	Sandstone, coarse to fine grained quartz sand with some mica, pyrite, quartzite, and igneous rock fragments, no evident cement, generally fines upward, contains interbeds of grey fissile clay shale, sharp basal contact.
460 - 495 ft. (140.2 - 150.9 M)	Sandstone, white to buff, silt to coarse grained quartz with some mica, hematite, chert, pyrite, quartzite, and granite rock fragments, some of the finer grained beds cemented by hematite, generally fines upward to grey clay shale, fissile, lignite at top, sharp basal contact.
495 - 550 ft. (150.9 - 167.6 M)	Sandstone, very fine to medium grained quartz sand, with some mica, hematite, pyrite and quartzite rock fragments, no evident cement, generally fines upward, clay shale interbeds with upper shale capped by lignite, sharp basal contact.
550 - 601 ft. (167.6 - 183.2 M)	Assorted fragments of grey silty clay shale, light brown siltstone, reddish brown siltstone and shale, light greenish grey claystone, quartzite, loose fine to coarse grained quartz, and some lignite, all interbedded? Base of well.

Figure 8. Gamma-ray log, lithologic log and descriptions of well-cuttings from test well D-18. See Figure 1 for location.

Studies by Ore (1965) and Smith (1970) have shown that braided streams develop under high gradients, high sediment loads, highly variable discharges, and lack of bank cohesion. Sediments consist predominantly of coarse sand and gravel with thin interbeds of clay and silt. The multi-lateral or sheet-sand geometry is created by constantly shifting channels, which rework much of the overbank fines.

Coarse-grained meanderbelts develop under moderate to low gradients, high bedload-to-suspended-load ratio, and low to highly variable discharge conditions (McGowen and Garner, 1970). These sediments usually consist predominantly of coarse sand with some gravel. Clay and silt deposits are more common than in braided streams, having been formed as floodplain and channel-fill deposits. These fine-grained deposits are still limited in extent, because of extensive reworking by the laterally migrating channel.

Braided streams commonly show relatively uniform grain-size throughout the vertical sequence, although coarsening-upward sequences have been described for certain braided stream deposits. As described before, homogeneous vertical sequences of coarse sand are found in the lower Dakota (445-575 ft, figure 5). Coarsening upward sequences are also commonly found, however, a coarsening upward texture is not distinctive of braided stream deposits. Coarse-grained meanderbelts commonly show coarsening upward sequences, often with a relatively thin fining-upward sequence at the base of the coarsening upward sequence (McGowen and Garner, 1970; Brown, 1973). Coarsening-upward sequences, some with fining-upward basal units can be seen in the Hawarden core (543-614.5 ft, 415-480 ft, figure 4). Fining-upward sequences become more apparent toward the top of the upper Dakota, along with a decrease in average grain size. This suggests better development of point-bar sequences and represents a gradation from a braided stream -- coarse-grained meanderbelt complex at the base through dominantly coarse-grained meanderbelt deposits and finally grading into a transitional, coarse-grained to fine-grained meanderbelt system.

Mudrock units at the base of the lower Dakota probably represent colluvium and debris-flow deposits associated with Paleozoic bedrock highs. Mudrock units within the middle and upper portions of the lower Dakota probably represent channel fill or floodplain deposits.

These interpretations would be less definite if they were based only upon lateral and vertical sequences of textures and sedimentary structures observed in outcrops and cores, along with interpretations from gamma-ray logs. However, when these criteria are placed in the proper geologic setting, i.e., that of a basin that was continually filling, with steadily decreasing stream gradients, a sequence of braided stream deposits overlain by sediment deposited in coarse-grained meanderbelts and finally fine-grained meanderbelts, seems to be the most plausible interpretation for the Dakota.

Upper Dakota

The upper portions of the Dakota show a distinct increase in the relative amounts of mudrock to sandstones from that of the lower Dakota. Sandstone units consist dominantly of fine-to medium-grained sand displaying well developed fining-upward sequences. Much better control as to lateral and vertical relationships is available from surface exposures.

The abundance of mud and the fining-upward sand sequences is further evidence of reduction of gradient leading to the formation of fine-grained meanderbelt systems. Fine grained meanderbelts develop under low gradients, a high ratio of suspended load to bedload, and less variable discharge. These systems develop thick overbank deposits because of reduced lateral migration of the channel. This results in multistoried or shoestring sands, surrounded by thick sequences of mud.

Point-bar deposits typically show fining-upward sequences from coarse sand and gravel of the channel lag, to medium to fine-grained sand, to silt and clay at the top. The vertical sequence of sedimentary strcutures from large scale trough cross-beds at the base, to ripple cross-laminae at the top, shows an upward decrease in flow regimes (Bernard and Major 1963; Brown 1973).

The upper sandstone unit at the Sergeant Bluff section, shows the entire vertical sequence commonly found in fine-grained point bars (see description - stop 3). The associated mudrock unit contains mostly laminated claystones and siltstones with thin interbeds of fine grained sandstone. All contain a certain amount of plant material, which becomes abundant enough in places to form thin lignite beds. All of these features strongly suggest a fine-grained meanderbelt deposit, with the thick sandstones representing channel (point-bar) deposits and the dominant mudrock unit representing floodbasin deposits. Lignites suggest a fairly humid climate, in which marshy areas developed in the lower floodbasin.

Subsurface analysis also shows that fining-upward sequences are dominant in the upper Dakota. Units showing an upward decrease in flow regimes are seen in the Hawarden core (238.8-265 ft, figure 4). Thick deposits of laminated clays and silts with common lignitic interbeds are found throughout the upper Dakota.

Further evidence for a fluvial system lies in the relationship of lateral variations in grain size and vertical sequences. Cross-section A-A' (figure 2) shows two areas of dominant sandstone grading laterally into units with a greater percentage of mudrock. The sands predominantly display fining-upward sequences with a few of the sandstones showing coarsening-upward textures. Studies by Bowe (1972) have shown that the mean current transport direction of these Cretaceous sediments in Iowa was from northeast to southwest; thus, cross-section B-B' (figure 3) probably represents the downstream facies equivalent of cross-section A-A'.

Cross-section B-B' shows upper Dakota lithologies consisting dominantly of mudrock, with a zone of subequal sandstone and mudrock. The sandstones show fining-upward sequences with few if any coarsening upward units. This displays the predictable downstream decrease in grain size and a transition from the coarse- to fine-grained transitional meandering stream environment of the upper Dakota in A-A', to fine-grained meanderbelt deposits of B-B'.

The lateral variations in grain size reflect proximity to major stream systems. The two dominant sandstone units seen in the upper Dakota of cross-section A-A', probably represented two such systems. At the base of the upper Dakota, the two stream systems were relatively far apart. A dominant mudrock unit developed between the two systems indicating a lack of influence by levee and crevasse splay deposits which would have brought a great deal of sand into these areas. Toward the upper portions of the upper Dakota, the stream systems migrated closer to one another, resulting in greater influence of these coarser-grained overbank deposits on the finer deposits of the floodbasin, producing a subequal mixture of sandstone and mudrock.

Graneros Shale

The uppermost Dakota and lower Graneros consist of a complex system of marginal marine (paralic) deposits that represent the transition from fluvial deposits of the Dakota to marine deposits of the upper Graneros.

Hattin (1964) describes a similar sequence of environmental changes from the top of the Dakota Formation in Kansas. Hattin describes the fluvial sediments as being overlain by brackish-water deposits of shore lagoons, interdistributary bays, a delta front platform, and a salt marsh which are represented respectively by carbonaceous or silty shale, dark grey fissile shale, evenly bedded sandstone, and lignite. These lithologies are present in the Iowa sections, and it seems likely that similar environments were responsible for their deposition. Unfortunately, characteristic fossils, which would have aided in proving this interpretation, were not found. The upper sandstone units at the Stone Park West section, lack conspicuous cross-strata except for some ripple cross-laminae. Hattin (1964) suggests that these sands might represent beach deposits that were reworked during transgression. Other possibilities include crevasse splays or small distributary channel deposits.

This complex of paralic deposits grades upward to increasingly marine deposits of the Graneros. The Graneros was deposited under fluctuating salinities at the base, accounting for the reduced fauna. Salinity approached that of normal marine conditions toward the end of the Graneros deposition as evidenced by the more diverse fauna.

The Graneros Shale represents prodelta or shelf muds deposited in a transgressive setting. This vertical sequence of delta plain deposits overlain by offshore mud deposits is reversed from the typical prograding delta and is greatly reduced as a result of marine transgression.

Greenhorn Limestone

With continued transgression, clastic input into the area was greatly reduced, allowing deposition of the chalks and shaly chalks of the Greenhorn. Interbeds of clay shale, as seen in the Hawarden core and in outcrops, represent small pulses of clastic input. Units consisting of chalks and shaly chalks according to Hattin (1975) represent deposition of largely pelagic sediment in a quieter, far off-shore portion of the shelf, below effective wave base.

Carlile Shale

The Carlile Shale caps the Cretaceous sequence in Iowa. The deposit represents renewed influx of prodelta mud into the area. Deposition of the Carlile was probably under normal marine salinities as evidenced by the fairly diverse fauna. Poor preservation and extensive removal of this unit by post-Cretaceous erosion makes more detailed analysis not feasible in this study area.

SUMMARY AND CONCLUSIONS

Stratigraphic and sedimentologic analyses of Cretaceous rocks found in surface exposures and in the subsurface of northwest Iowa have revealed a sequence of depositional environments from continental fluvial deposits of the Dakota Formation to sedimentation in a shallow epicontinental sea represented by the Graneros Shale, Greenhorn Limestone and Carlile Shale. Subsurface information was in the form of geologic core and well cuttings, with most wells having natural gamma-ray logs. Interpretations of the lower two-thirds of the Dakota Formation were based completely upon subsurface data because of a lack of surface exposures. All pertinent outcrops were measured and described in detail. This included the upper Dakota through the Greenhorn, with the Carlile exposed in one small outcrop, which did not show contact relationship.

The lower Dakota was deposited on the pre-Cretaceous erosional surface developed on Paleozoic bedrock. The lower Dakota is characterized by: 1) multilateral sandstone geometry; 2) coarse-grained nature of the sandstone; and 3) predominantly coarsening-upward sequences with fining-upward sequences becoming more common towards the top. Environmental interpretations suggest initial deposition by braided to coarse-grained meandering streams at times when fluvial gradients were highest. With erosion of the source area and subsequent deposition on the alluvial plain, gradients decreased, and coarse-grained meanderbelts were dominant in the upper part of the lower Dakota. Interbeds of clay and silt are interpreted to be channel fills and floodplain deposits.

With continued deposition, gradients became further reduced, causing a transition into fine-grained meanderbelt deposits of the upper Dakota. These deposits were dominanted by clay and silt of the floodbasin. Sandstone units are typically fining-upward with a vertical sequence of sedimentary structures that shows an upward decrease in flow regimes. These features are especially well displayed in the Sergeant Bluff quarry. Lignites are common in the floodbasin deposits, suggesting a humid climate. Spores and pollen derived from one of these lignites at Sergeant Bluff indicate that the upper Dakota is of Cenomanian age and probably lower Cenomanian. This suggests that the lower Dakota may be Albian or older (see Ravn, this volume).

The effects of marine transgression are seen in the deposits of the uppermost Dakota, Graneros Shale and Greenhorn Limestone. The uppermost Dakota consists of a complex of marginal marine environments associated with the upper or "topset" deposits of a delta. Lack of good, continuous exposures or fossil evidence makes detailed environmental interpretations difficult.

The Graneros represents prodelta to shelf deposits of clay and silt. Abundance of marine organisms increases upward, suggesting a stabilization of salinity from brackish water at the base to normal marine at the top. This seemingly anomalous sequence of reversed and reduced sequence of shoreline deposits overlain by offshore mud deposits is caused by deltaic deposition into a transgressing seaway.

With further eustatic rise in sea level, the shoreline moved rapidly to the east, effectively cutting off the majority of siliciclastic influx. The result was pelagic sedimentation of mostly carbonate mud and skeletal grains producing the chalks and shaley chalks of the Greenhorn Limestone. Several small pulses of clastic input are evidenced by interbeds of calcareous clay shale.

The Greenhorn is overlain by prodelta muds of the Carlile Shale, recording a resumption of deltaic progradation into the area. The Carlile is poorly exposed in northwest Iowa and is the youngest known Cretaceous unit remaining after post-Cretaceous erosion.

ACKNOWLEDGEMENTS

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LITHOSTRATIGRAPHY AND SEDIMENTARY PETROLOGY OF THE SPLIT ROCK CREEK FORMATION, LATE CRETACEOUS, OF SOUTHEASTERN SOUTH DAKOTA

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ABSTRACT

The name Split Rock Creek Formation is proposed for a small (200 km^2) basin-filling deposit resting unconformably upon the Late Precambrian Sioux Quartzite in southeast South Dakota. The unit attains a maximum thickness of nearly 100 meters, and consists of a sequence of sandy diamictites and quartz sandstones overlain by laminated organic claystones which grade upward into interbedded opaline sediments and massive cherts. The formation occupies an east-west elongated basin which parallels the strike of the Sioux Quartzite, and locally rests upon mafic intrusive rocks. Deeply weathered intrusives and Sioux Quartzite metasediments served as source rocks for the diamictites, which were deposited as mudflows on basinward slopes of at least 15°. The laminated organic claystones contain abundant carbonaceous wood debris and teleost fish scales. They are transitional upward to organic-rich opaline sediments. Opaline sediments in the Split Rock Creek Formation occur as laminated and bioturbated spiculites. In both fabrics, siliceous sponge spicules of the class Demospongea comprise 30% of the rock volume. Opal occurs as biogenic opal-A, and opal-CT lepispheres. The interbedded massive cherts are intensely bioturbated spiculites with chalcedony occupying matrix and void-filling positions. Petrographic evidence and published experimental data on silica diagenesis suggest that the cherts are early diagenetic features, and their formation was initiated by geochemical factors related to bioturbation. Land plant debris and detritus from local Precambrian rocks are found throughout the Split Rock Creek Formation, indicating contemporaneous exposure of adjacent Precambrian terrane. Studies by Shurr (this volume) have shown that the Sioux Quartzite Ridge was a prominent physiographic feature on the eastern margin of the Late Cretaceous Western Interior seaway. The Split Rock Creek Formation was deposited in a sheltered marine-influenced embayment surrounded by Precambrian highlands near the crest of the ridge. It was deposited as a shallow water facies equivalent of an Upper Cretaceous marine unit, probably the Niobrara Formation, during progressive inundation of the Sioux Quartzite Ridge.

INTRODUCTION

Scattered occurrences of sedimentary rocks covering the Precambrian Sioux Quartzite in Minnehaha County, South Dakota, have been reported since Upham (1885) first noted two outcrops of "chalk rock". Various authors have published widely divergent interpretations of the origin and age relations of these lithologically distinctive rocks (see article by Bretz in this guidebook). The name "Pathfinder Formation" was informally applied to these deposits by Rothrock (1958), based on studies of subsurface cores from the Northern States Power Company Pathfinder steam plant site east of Sioux Falls.

In this paper, the name Split Rock Creek Formation is proposed for these areally restricted rocks, after exposures of the unit along cutbanks of Split Rock Creek in Minnehaha County, South Dakota. While the biostratigraphic correlation of the Split Rock Creek Formation is still not precisely known, faunal evidence and regional relationships indicate that it was deposited during Late Cretaceous time.

The Split Rock Creek Formation is composed of diverse lithologies, including quartz sandstones, sandy diamictites, carbonaceous claystones, calcium bentonites, massive bedded cherts, and opaline spiculites.

PREVIOUS WORK

The history of geologic investigations in the area of the Split Rock Creek Formation is summarized by Bretz elsewhere in this guidebook, and the details will not be repeated here. Two previous workers, Rothrock (1958), and Stach (1970) made significant contributions to the understanding of these deposits, and created a framework for future studies.

Rothrock (1958) recognized that the diverse assemblage of sedimentary rocks of the area are part of a single depositional package, for which he informally proposed the name "Pathfinder Formation". Rothrock also recognized that sponge spicules are important faunal elements in the unit, and proposed an informal lithostratigraphy for the unit ("upper clay member", "black rock member", and "lower clay member"), which he reported as having a maximum thickness of 104 feet (32 m).

Stach (1970) reported on the general geology and x-ray mineralogy of the Split Rock Creek Formation. He was the first worker to note the presence of calcium bentonites in the Split Rock Creek Formation, and reported that cristobalite, the zeolite clinoptilolite-heulandite and expandable clays are major constituents of the opaline rocks of the unit. As with previous workers (Baldwin, 1949; Steece, 1959), Stach, (1970) interpreted the opaline rocks of the Split Rock Creek Formation as an altered volcanic ash.

REGIONAL SETTING

The Split Rock Creek Formation is an areally restricted deposit, covering approximately 80 square miles (207 km^2) in southeastern South Dakota. It was deposited in a local topographic depression on the Precambrian rocks of the Sioux Quartzite Ridge, a prominent positive physiographic feature throughout Cretaceous sedimentation along the eastern margin of the Western Interior seaway (see papers by Bunker and Shurr, this volume). Test drilling and subsurface mapping by Derric Iles of the South Dakota Geological Survey shows that the depression is elongate along an east-west axis (figure 1), and appears to be an eastward draining valley incised along the strike of the Sioux Quartzite.

AGE OF THE SPLIT ROCK CREEK FORMATION

The age of the Split Rock Creek Formation has been poorly understood since the rocks were discovered. Cretaceous and Cenozoic ages have been proposed by various authors (see Bretz, this volume). Early workers correlated the opaline spiculites of the Split Rock Creek Formation with the Niobrara Formation (Bain, 1895; Beyer, 1896; Todd, 1899; Darton, 1909), although Rothrock and Newcomb (1926) clearly demonstrated that the two units are lithologically and chemically distinct. Although the strata of the Split Rock Creek Formation are fossiliferous, the identified macrofossils have not precisely bracketed its age, and micropaleontological studies have only recently been jointly undertaken by the Iowa and South Dakota Geological Surveys.

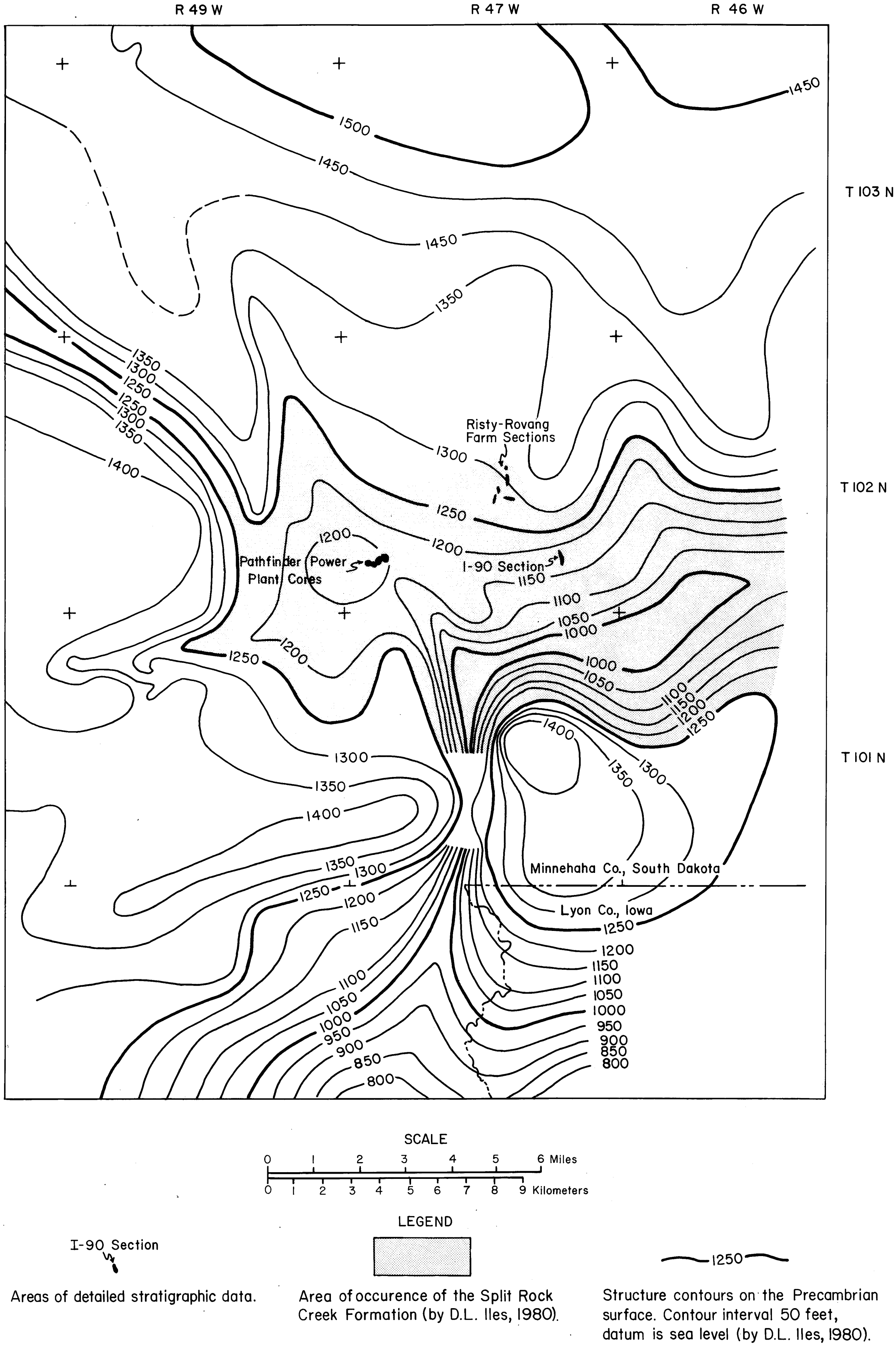

Figure 1. Distribution of the Split Rock Creek Formation, and structure contours on the Precambrian surface, Minnehaha Co., South Dakota.

At present, the age of the Split Rock Creek Formation can only be inferred by faunal evidence and regional relations. Important faunal evidence includes:

1) The presence of sequoia twig molds (range from Late Jurassic to recent, Arnold, 1947, p. 321) provides a maximum age.

2) The presence of teleost fish scales (probable range from Late Jurassic to recent, Romer, 1966) supports the maximum age reported above.

3) The presence of sponge spicules, radiolarians, and gastropods (Rothrock, 1958), foraminifera (Steece, 1959), fish bones and scales, pelecypods, and crustaceans (Stach, 1970) indicate deposition in a marine environment.

The only documented post-Paleozoic marine transgressions in this area occurred in the Late Cretaceous, thus suggesting the time of deposition of the Split Rock Creek Formation.

Samples of the Split Rock Creek Formation have been processed for palynomorphs, but have not produced any grains to date. In addition to abundant carbonaceous debris, the processed samples have yielded organic cuticles from planispiral foraminifera (R. L. Ravn, Iowa Geological Survey, personal communication), indicating marine influence.

A speculative overview of regional stratigraphic relationships suggests that earlier correlations of the Split Rock Creek Formation with the Niobrara Formation may have, in part, been correct. Subsurface data in southeastern South Dakota has shown that the Niobrara Formation rests unconformably on the Sioux Quartzite along the crest of the Sioux Quartzite Ridge (see Shurr, this volume). This relationship has also been reported along the eastern end of the ridge in Minnesota (Austin, 1970). The Niobrara Formation is exposed along Beaver Creek in Lincoln County, South Dakota (field trip stop number 7) some 20 miles (32 km) south of the southernmost known exposure of opaline spiculites in the Split Rock Creek Formation (I-90 section, field trip stop 8). Although separated by a local ridge of Sioux Quartzite, both exposures crop out at elevations between 1300 and 1350 feet (396 - 410 m) above sea level. Structural mapping (see Bunker, this volume) indicates little, if any structural relief on the Cretaceous rocks between these locations, suggesting a lateral stratigraphic equivalence.

The opaline spiculites of the Split Rock Creek Formation may be shoreline equivalents of the Niobrara Formation, deposited in a cul-de-sac protected by highlands of the Sioux Quartzite. Cavaroc and Ferm (1968) have reported the occurrence of cherty spiculites in a similar depositional setting from the Middle Pennsylvanian Allegheny Formation in Ohio and West Virginia. They interpreted the spiculites as having been deposited during maximum transgressive episodes in local cul-de-sacs receiving little or no detrital sediment.

LITHOSTRATIGRAPHY

The lithostratigraphy of the Split Rock Creek Formation is defined with a limited data base. Only three exposures of more than a few meters in thickness are known, and only two of them display contacts between lithologic units. Three cores of the Split Rock Creek Formation were taken during foundation studies at the Northern States Power Company Pathfinder plant. These cores are the only detailed subsurface samples of the unit, and are stored at the South Dakota Geological Survey. Data from drill cutting samples, both from commercially drilled wells and test drilling by the South Dakota Geological Survey, have been used to map the configuration of the Precambrian surface of the area, and to grossly define the areal geometry of the Split Rock Creek Formation.

Pathfinder Plant Cores

The principal subsurface data on the Split Rock Creek Formation comes from three cores acquired during foundation studies for the Pathfinder Steam Plant during the summer of 1957. The cores, all within section 30, T. 102 N., R. 48 W., Minnehaha County, South Dakota, are spaced less than 0.25 miles (0.4 km) apart in an east-west direction (figure 2).

This section, composed of four distinct units, lies upon the Sioux Quartzite, which has an erosional relief of 25 feet (8 m). The basal unit, a friable medium to coarse sandstone known only from discarded cuttings might be the lateral equivalent of a pisolitic sandy claystone (paleosol?) in borehole #3. Both these units grade upward into a grey laminated claystone which contains medium to coarse sand in the bottom half and has wood and teleost fish debris scattered throughout. Within the middle of the claystone, in borehole #3, is a 5 inch (2 cm) thick black organic clay which has yielded organic cuticles of planispiral foraminifera (Robert Ravn, pers. comm.).

Overlying and gradational to the laminated claystone are light grey to black organic opaline spiculites. These were previously termed the Black Rock Member by Rothrock (1958). The lower spiculite is conspicuously laminated, porous, and occasionally silicified. The lighter colored upper spiculite is moderately to intensely bioturbated and heavily silicified. Sponge spicules are visible in hand specimen in both units. The extreme upper part of this unit is also exposed in outcrop at an elevation of 1300 feet (395 m) along the Big Sioux River (SW-SW-SW, sec. 30, T. 102 N., R. 48 W.).

A calcium bentonite occurs near the base of the bioturbated spiculite in borehole #1, but is absent in boreholes #2 and #3 because of poor recovery. Secondary void-filling carbonates, of diagenetic origin, are a minor lithology in the upper part of the bioturbated spiculites in borehole #1.

Not illustrated on the cross-section (figure 2) is Rothrock's (1958) 30 feet (9 m) thick upper clay member. This unit was not recovered in the core and is known only vaguely from brief descriptions of discarded cuttings.

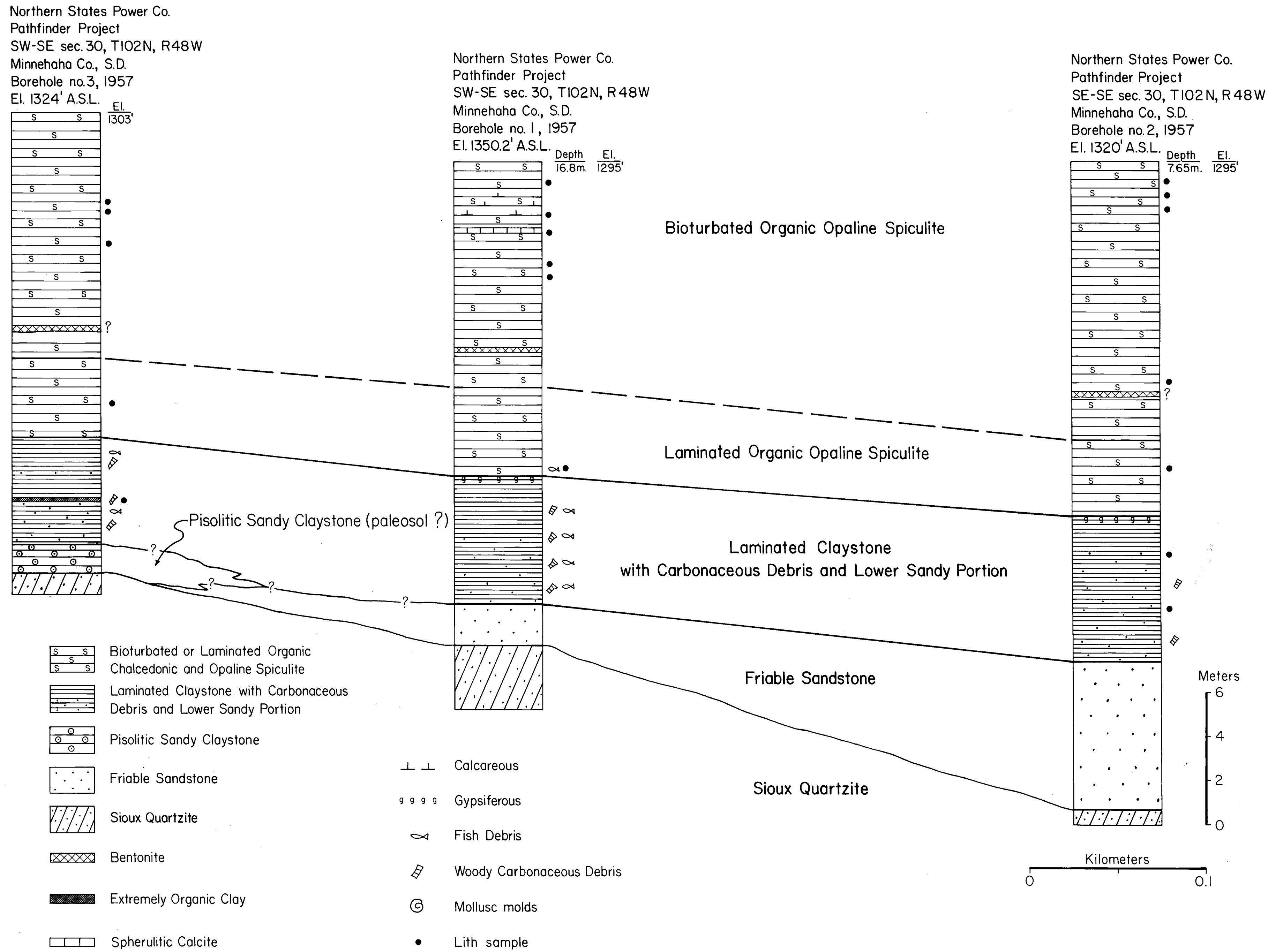

Figure 2. Stratigraphy of the Pathfinder Steam Plant foundation study cores.

I-90 Section

The I-90 Section (NE-NE-SW, sec. 26, T. 102N., R. 48W., Minnehaha County, South Dakota, see description for stop 8) consists of a 2.6 foot (0.8 m) thick section to the north of I-90 and a 18.5 foot (5.6 m) thick section 395 feet (120 m) to the south of I-90. Both sections are exposed on a west-facing cutbank along Split Rock Creek. The principal lithology present is a light grey to white, iron stained and variably cherty laminated to intensely bioturbated opaline spiculite (figure 3).

The upper 9 feet (2.7 m) of the south section is exposed in the outcrop and the lower 9.5 feet (2.9 m) is from a 1 inch core. The cored interval is a laminated opaline spiculite with occasional silicified (cherty) burrows and zones of iron staining. A 1.2 inch (3 cm) thick olive green bentonite is present midway through the core. The outcrop portion of the south section is thinly to massively bedded, and contains iron liesegang staining at irregular intervals. Chert occurs as discrete tubes (averaging 1 cm in diameter) in the core and the basal half of the outcrop, but is the dominant rock type in the upper half of the exposure. The cherty section exhibits massive to contorted to wavy bedding, which gives the outcrop a distinctly vuggy appearance.

The lower portion of the north section is a variably cherty opaline spiculite, which is sharply overlain by a noncalcareous light grey to yellow-orange clay. This is tentatively identified as the upper clay member of Rothrock (1958).

Risty Farm Section

The Risty Farm Section (SW-SE, sec. 14; and NW-NE, sec. 22, T. 109N., R. 48W., Minnehaha County, South Dakota) is a west-facing cutbank along Split Rock Creek exposing the Precambrian-Cretaceous contact along the northern edge of the depositional basin of the Split Rock Creek Formation (see figures 4 and 5). Four detailed measured sections along a 340 foot (104 m) north-south transect (figure 6) expose a maximum thickness of 23 feet (7 m) of Split Rock Creek Formation. The erosional unconformity beneath the unit dips as steeply as 15° to the south, and erosional relief greater than 17 feet (5 m) can be seen within the transect. The Risty Farm Section occurs along an apparently vertical contact between two Precambrian rock units. The topographically higher Sioux Quartzite, and the Corson Diabase, which is intrusive into the Sioux Quartzite, are both exposed near the Risty Farm Section (see description for stop 10). Along the entire transect of the section, however, only the Corson Diabase is exposed beneath the Split Rock Creek Formation.

Two major distinct lithologic units are exposed in the Risty Farm Section. The lowermost unit is a sandy diamictite up to 4 feet (1.3 m) thick. It consists of very fine to coarse quartz and weathered feldspar sand grains in a yellow brown clay matrix. Irregular wavy partings occur at vertical spacings from 0.4 to 1.2 inches (1 to 3 cm) in some locations. At the base of this unit at the north section (figure 6) is a thin (7 cm) bed containing flat pebble clasts of weathered argillite up to 2 inches (5 cm) long. Within the diamictite, larger clasts of weathered quartzite can be found, up to 7 inches (18 cm) in long dimension. These clasts are found where

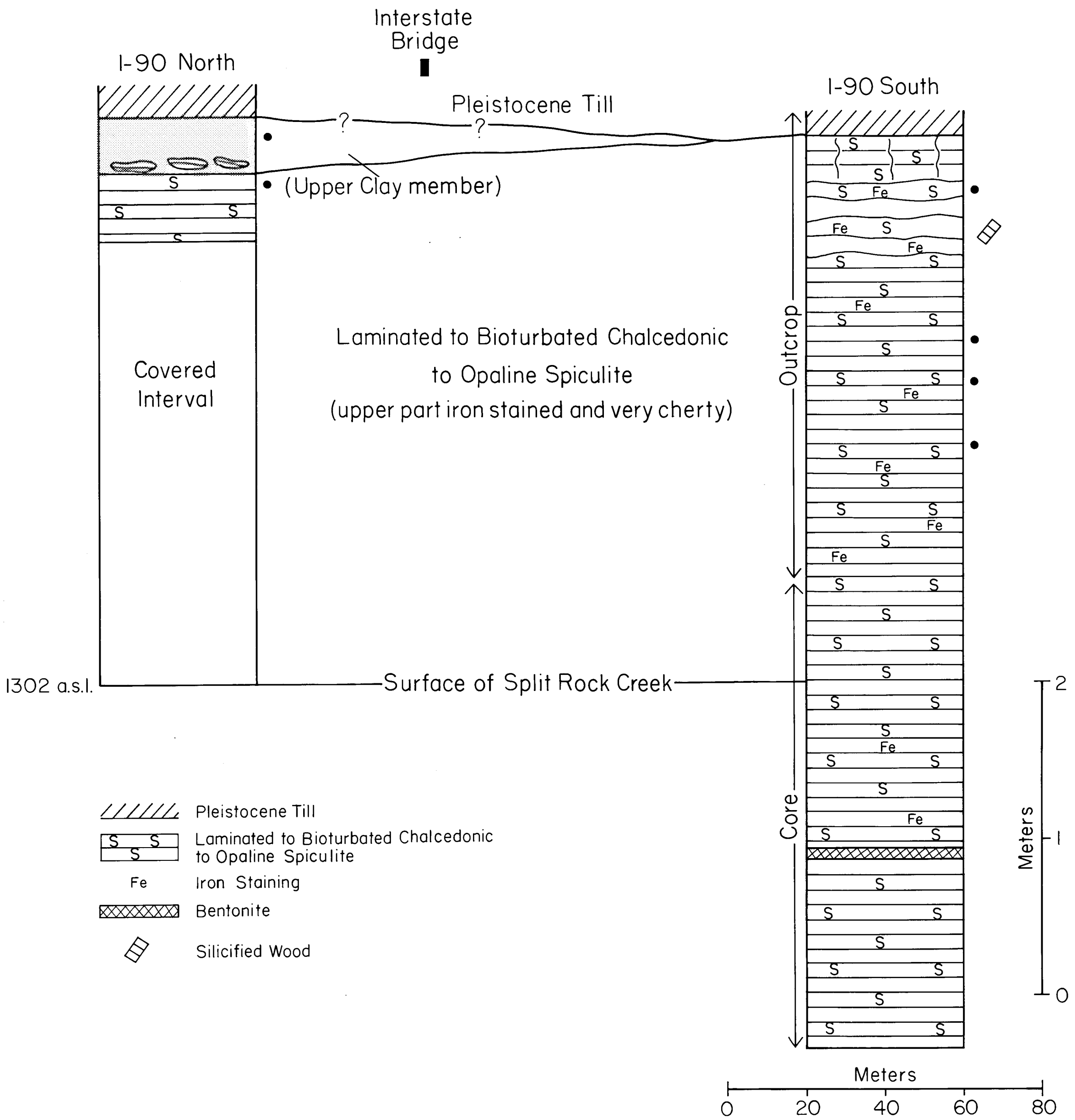

Figure 3. Stratigraphy of the I-90 Section. Symbols same as those shown in figure 2.

the diamictite rests on the Corson Diabase, and suggest minimum distances of transport for the clasts of several hundred feet (see stop 10 description). Several stone lines, composed of clasts of weathered quartzite, argillite, and diabase, are found further down the paleoslope to the south, in Risty Farm Sections A and B (figure 6).

Above the diamictite is 21 feet (6 m) of white, porcelaneous, opaline spiculite. The contact between these two units parallels the configuration of the unconformity beneath the Split Rock Creek Formation, but bedding becomes horizontal toward the upper part of the section (see section C,

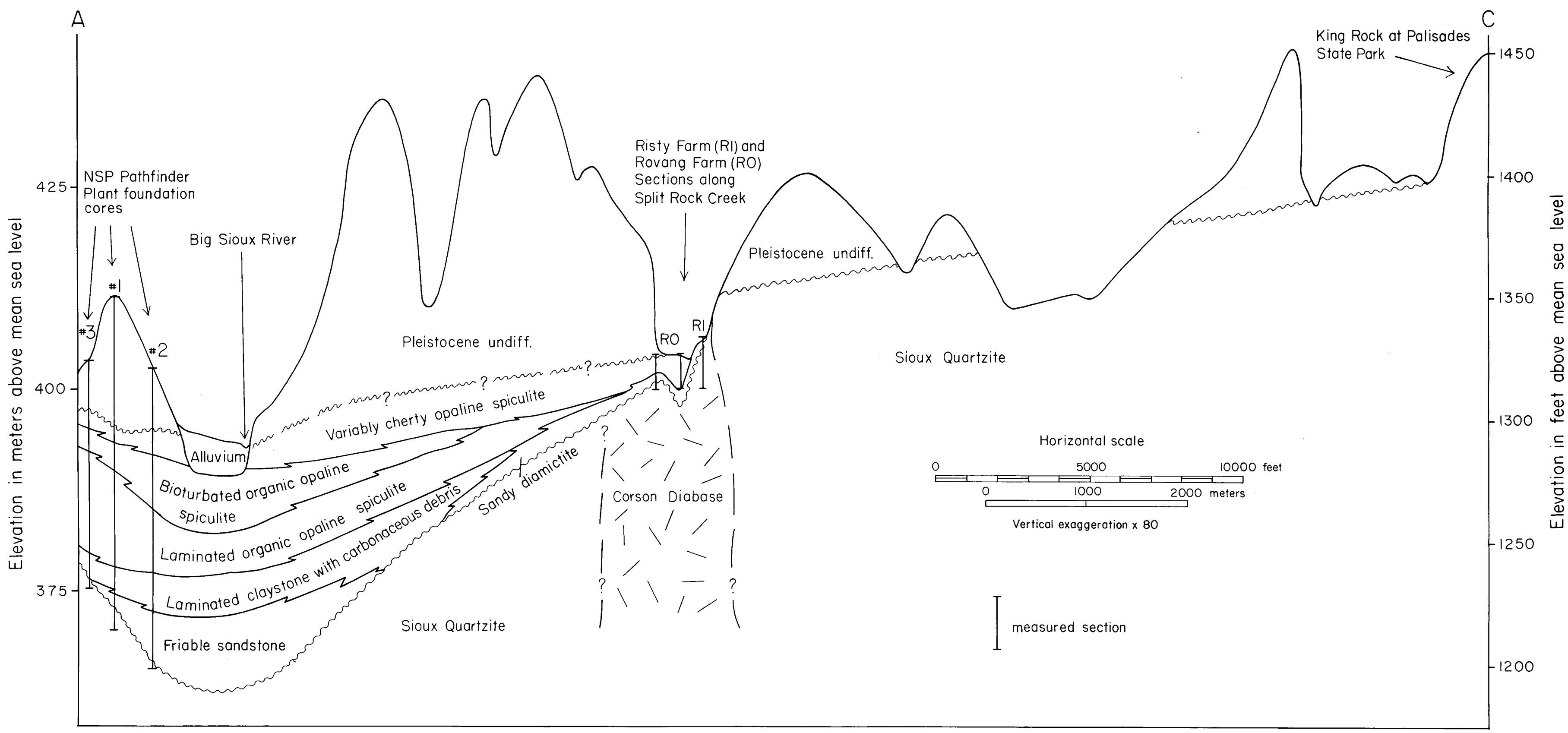

Figure 4. Northeast-southwest cross-section through the basin of the Split Rock Creek Formation, from Palisades State Park to the Pathfinder Steam Plant cores. Line of section is shown in figure 5. Surface of Precambrian rocks is modified from subsurface mapping in progress by D. Iles.

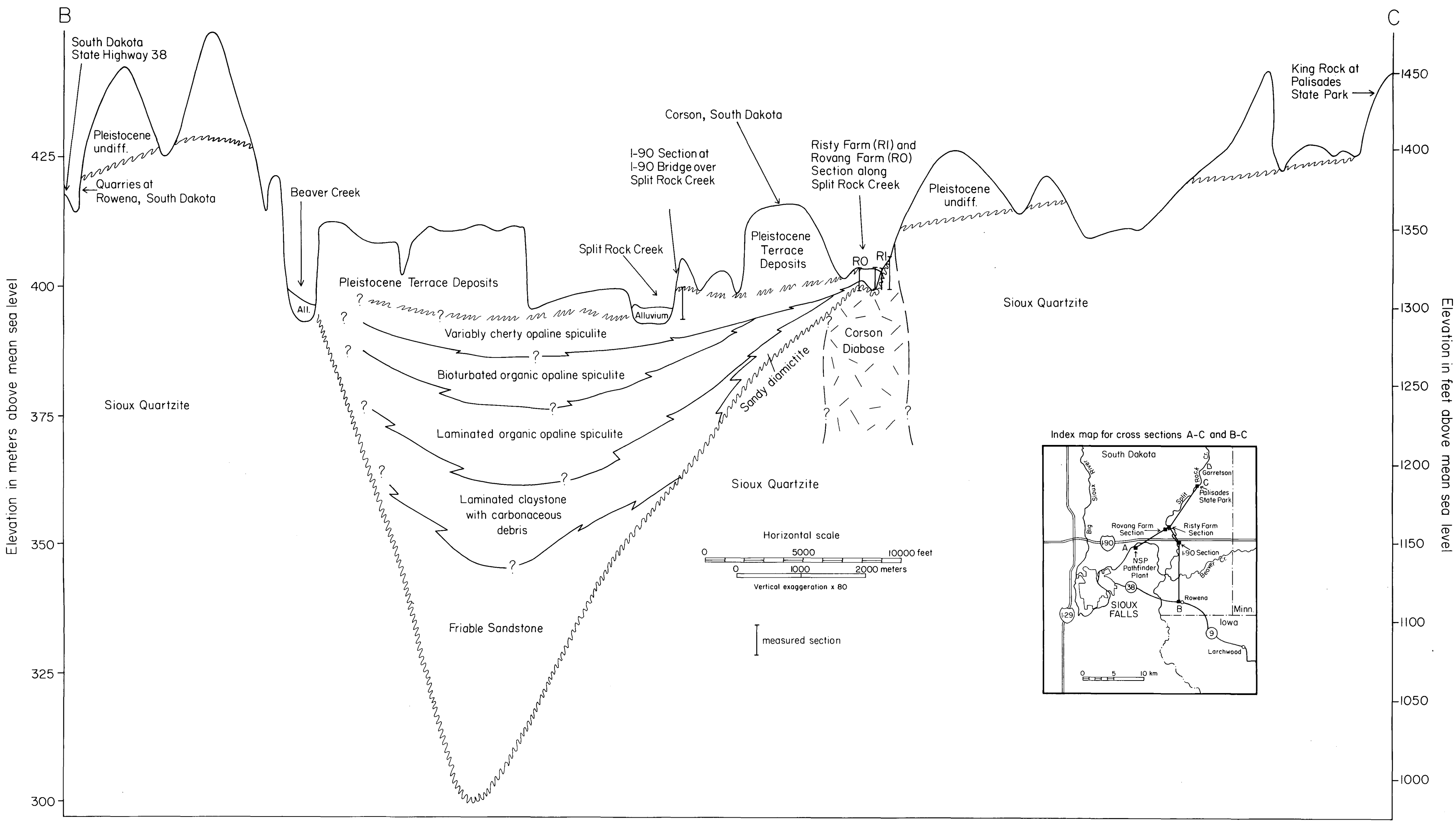

Figure 5. North-south cross-section through the basin of the Split Rock Creek Formation, from Palisades State park to Rowena, South Dakota.

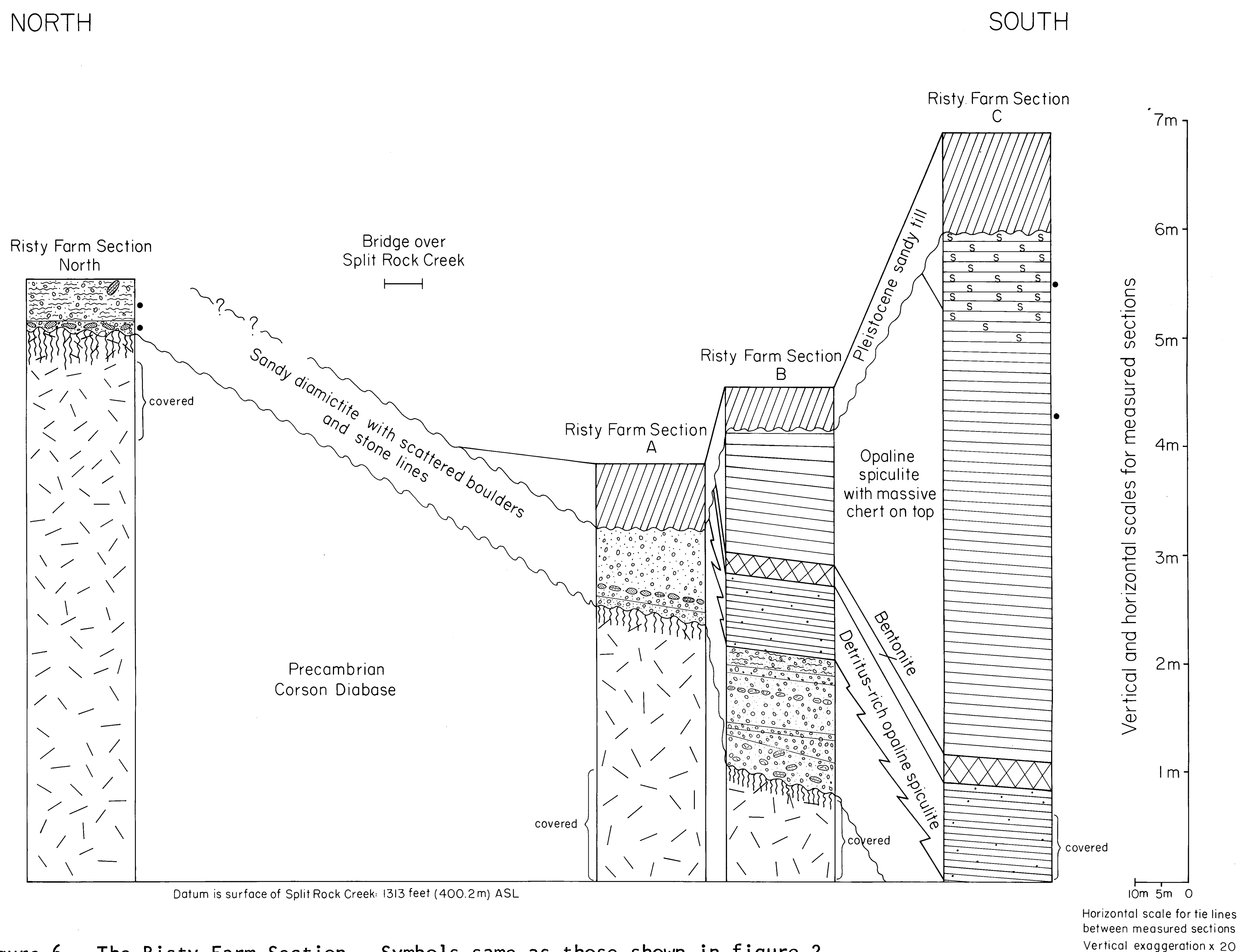

Figure 6. The Risty Farm Section. Symbols same as those shown in figure 2.

figure 6). Detrital quartz sand grains are abundant in the first meter above the contact with the diamictite, but decrease in abundance upward. A calcium bentonite, from 7-9.5 inches (18 - 24 cm) thick, occurs 2.2 feet (0.67 m) above the base of the opaline spiculite. The upper surface of the bentonite is irregular, with approximately 2 inches (5 cm) of relief. The uppermost meter of section C is a massive chert unit, petrographically a chalcedonized opaline spiculite, which has been erosionally truncated from the rest of the section.

Rovang Farm Section

The Rovang Farm Section (SE-NE-NW and NE-SE-NW, sec. 22, T. 102N., R. 48W., Minnehaha County, South Dakota) is an east-facing cut bank on Split Rock Creek that exposes a similar stratigraphic sequence to the Risty Farm Section, located 700 feet (213 m) to the northeast. Over 6 feet (1.8 m) of relief on the Cretaceous-Precambrian contact can be seen at the Rovang Farm Section (figure 7). Unlike the Risty Farm Section, this erosional surface does not dip in one consistent direction, but gently undulates over the length of the exposure. The regional southward dip of this surface, however, is indicated by an outcrop of cherty white opaline spiculite along the creek bed 600 feet (183 m) downstream to the south. The Rovang Farm Section has not been measured in the same detail as the Risty Farm Section, so the effect of erosional relief on the Corson Diabase on individual stratigraphic units exposed here has not been documented (figure 7).

As in the Risty Farm Section, the Rovang Farm Section consists of two major lithologic units, a basal sandy diamictite and a white, porcelaneous opaline spiculite. The diamictite is 2.4 feet (0.7 m) thick, and consists of very fine to very coarse quartz and weathered feldspar sand grains in a tan olive green clay matrix.

The lowermost meter of opaline spiculite at the Rovang Farm Section contains detrital quartz grains which decrease in abundance upward. A significant variation from the Risty Farm Section is seen, as two calcium bentonites are found within the 7 feet (2.1 m) of opaline spiculite exposed at Rovang Farm. Correlation of these bentonites (figure 7) with the single bentonite observed at Risty Farm is uncertain. The upper, thicker bentonite is burrowed and filled by opaline spiculite. These 0.4 inch (1 cm) thick burrows range up to 6 inches (15 cm) in length.

An interesting assemblage of macrofossils has been found in the opaline spiculite at the Rovang Farm Section. Plant leaf and stem molds are found with regularity at this location. Brian Witzke of the Iowa Geological Survey has collected and identified a sequoia twig mold from the spiculite here (Plate I, A). Molds of molluscs and fish debris are frequently observed in these rocks.

SEDIMENTARY PETROLOGY

The origin of the Split Rock Creek Formation has been enigmatic for many years, largely because of the assemblage of unusual lithologies within the unit. Since many of these rock types are not widely known, especially in this region, a brief discussion of their petrology is necessary for further interpretation.

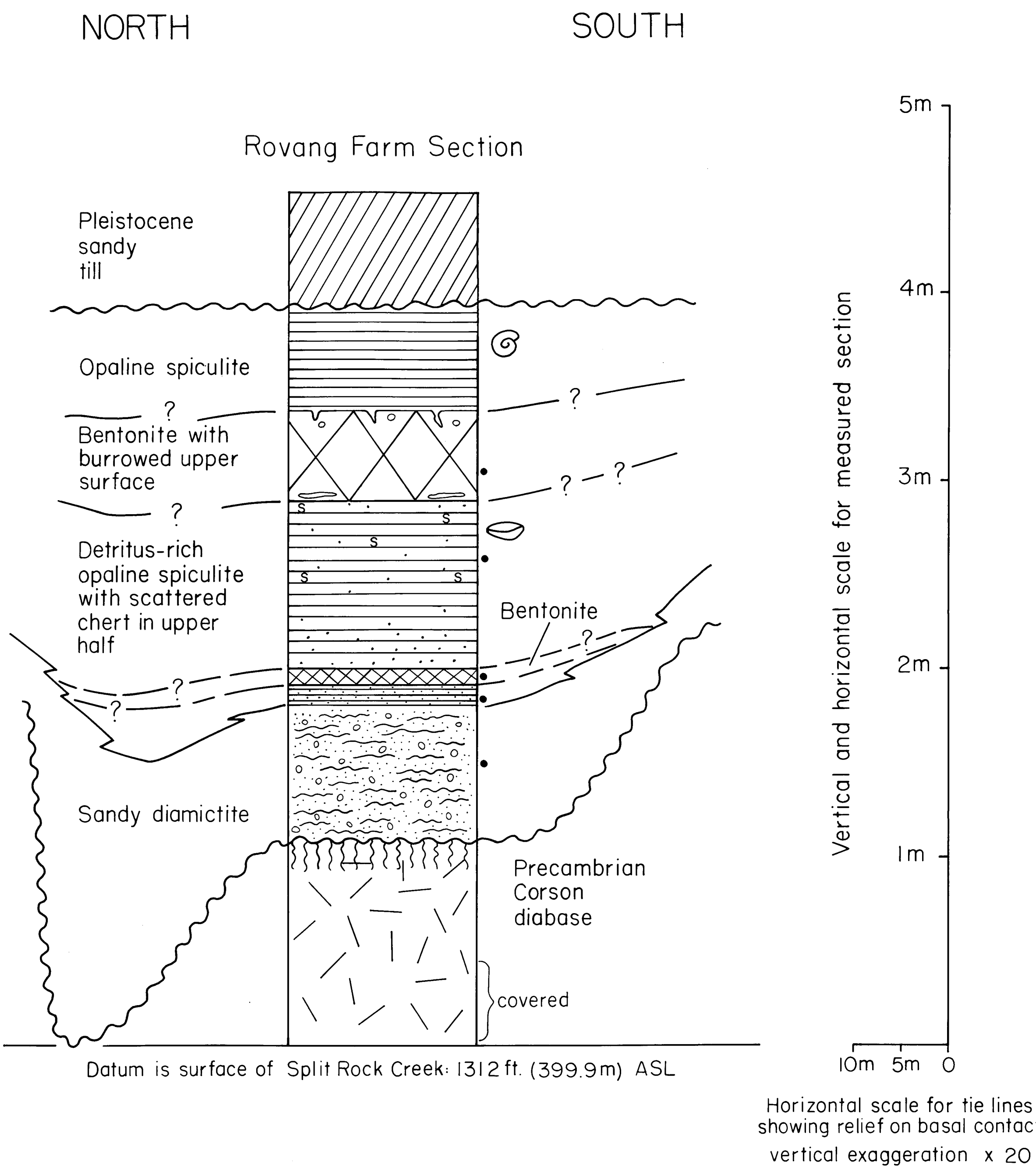

Figure 7. The Rovang Farm Section. Symbols same as those shown in figure 2.

Basal Coarse Clastics

Friable sandstones and sandy diamictites occur at the base of the Split Rock Creek Formation. The friable sandstones are known only from the Pathfinder Plant cores, and no samples of these rocks were recovered during the drilling. Although they have never been examined, reports of their pink color (local drillers refer to them as "quartzite wash"), the highly weathered nature of the pink Sioux Quartzite from the cores, and the presence of abundant pink quartz sand grains in the overlying claystones strongly suggests that these sandstones were locally derived from the weathered Sioux Quartzite.

The sandy diamictites are exposed where the Split Rock Creek Formation rests on the Corson Diabase. These rocks consist of angular to subangular detrital grains of quartz, plagioclase, and opaque minerals floating in a matrix of isotropic homogeneous clay (Plate I, B). Detrital grains range from 50 μm to 2 mm in diameter, and do not display any grading. Lithic fragments of quartzite, argillite, and diabase up to 7 inches (18 cm) in long dimension have been found floating within the diamicite. The clay matrix occupies 40 to 70% of the volume of the rock; weathered plagioclase detritus, 15 to 30%; quartz detritus, 14%; and opaque mineral detritus 5%. Stach, (1970) reported that the clay fraction from the "sandstones" at the Risty Farm Section consists of expandable clays, illite, and small amounts of clinoptilolite. He noted the predominance of ilmenite in the heavy mineral suite, suggesting the identity of the opaque mineral detritus observed petrographically.

Laminated Claystone

This dark grey laminated clay was not examined petrographically, but can be characterized nonetheless. The lower portion contains scattered medium to coarse quartz sand grains. X-ray analysis of a sample from borehole #1 shows a mixed layer montmorillonite - illite clay. Carbonaceous wood debris and teleost fish scales and debris are common. The unit is relatively impermeable and forms an effective aquiclude between water bearing porous to fractured spiculites above and porous sands below (Britzius, 1957).

Opal Terminology

The opal terminology used in this paper is that of Jones and Segnit (1971). The general term "opal" is subdivided to opal-A and opal-CT, depending upon the x-ray diffraction pattern of the material. Opal-A is amorphous biogenic silica and is isotropic in thin section. In opal-A, the d(101) α-cristobalite peak (at $2\theta = 22°$) is a broad, low curve. Opal-CT is essentially a poorly ordered cristobalite, is faintly birefringent in thin section, and occurs as small bladed spheres (lepispheres) 5 to 50 μm in diameter (Kastner, et. al., 1977). The d(101) α-cristobalite peak for opal-CT is more sharply defined than in opal-A, but still much broader than well crystallized α-cristobalite.

Organic Opaline Spiculites

The organic opaline spiculites which have been described exhibit two different textures, laminated and bioturbated. The relative amount of different framework constituents (primarily sponge spicules) within the two fabrics were initially very similar, but syn- to early post-depositional fabric modification (from laminated to burrowed) was responsible for preferential solution or preservation of the original spicules.

In hand specimen, the laminated organic opaline spiculites are a relatively uniform dark grey color, but in thin section under plane-polarized light, a prominent interlayering of dark brown and lighter brown laminae is visible (Plate I, C). Laminae thickness varies from 0.5 mm to 5 mm. The dark brown layers consist of isotropic to faintly birefringent matrix with extremely thin wavy stringers of organic material.

Dispersed throughout this dark brown isotropic matrix are oval to circular voids averaging 50 to 60 μm in diameter. These voids have the same diameter and shape as well-preserved sponge spicules within stratigraphically higher portions of the Split Rock Creek Fm. The voids are interpreted to be molds of dissolved sponge spicules. As already noted, most spicules molds are oval to circular, the result of an oblique to transverse cut through the mold, but elongate molds, produced by a longitudinal cut are also present; the molds are oriented parallel to subparallel to bedding.

The lighter colored laminae exist as such because a much higher ratio of spicule molds to isotropic-organic matrix is present within them (Plate I, C). Oval to circular void space molds occupy approximately 30% of the light colored laminae. Both the light and dark laminae contain scattered detrital medium to coarse, angular quartz silt grains. Phosphatic fish debris is also present in very small amounts.

Utilizing high magnification, opal-CT lepispheres can be seen rimming some of the oval to circular spicule molds. Although enough SEM work has not been done to verify it, the occurrence of lepispheres occupying void rim positions suggests that the majority of the isotropic to faintly birefringent matrix consists of fine crystalline ($\leq$ 10 μm) lepispheric opal-CT. Kastner, et. al., (1977) have illustrated lepispheres ranging in diameter from 5 to 50 μm.

The overlying moderately to intensely bioturbated organic opaline spiculites present a drastic textural contrast to the laminated organic spiculites (Plate I, D). Bioturbation within these rocks not only altered the original laminated fabric, but also was the principal process responsible for initiating subsequent diagenetic mineralization.

Upon even cursory microscopic examination, several characteristics differentiate the bioturbated from laminated spiculites:

1) Extensive chalcedonization of matrix and spicules (Plate I, E).

2) Common occurrence of well to partially preserved opaline sponge spicules (Plate I, E).

3) Development of well formed opal-CT lepispheres (Plate I, F).

4) Routine presence of fecal pellets (Plate I, D).

Depending upon the intensity of bioturbation, the fabric can range from being relatively homogenous to obviously burrowed. Discrete burrows, where preserved, are composed dominantly of spherulitic length-fast (and subordinate length-slow) chalcedony, and are surrounded by a combination of organic rich lepispheres and sponge spicules. Subordinate components within the chalcedonized burrows include opal-CT lepispheres, fecal pellets and detrital quartz silt. Combined SEM photomicrographs of lepispheres and x-ray diffraction studies demonstrate the presence of opal-CT (Plate

I, F). Fecal pellets and quartz silt are also common minor components of the material that surrounds the chalcedonized burrows.

More homogenous bioturbated textures consist of a framework of packed spicules and quartz silt grains with subordinate fecal pellets in a matrix of lepispheric opal and spherulitic chalcedony (Plate I, E). The matrix of this fabric can grade from being lepisphere dominated to chalcedony-dominated. Within this fabric spicules occur in four basic modes (Plate II, A and B):

1) unaltered isotropic biogenic opal (opal-A).

2) lepisphere or chalcedony filled central canal with unaltered walls.

3) lepisphere filled central canal with chalcedony walls.

4) oval to circular spherulitic chalcedony areas rimmed by lepispheric opal-CT.

Spicules average 50-60 μm in diameter and opal-CT lepispheres average 10-20 μm in diameter. The bioturbated rocks consist of approximately 30% spicules. This is the same percentage as the spicule-rich laminae within the laminated organic spiculites.

Besides occupying various spicule and matrix positions, chalcedony exists as botryoidal void rim cement (Plate II, C). In contrast to the length-fast nature of most other chalcedony, the botryoidal chalcedony is length-slow and probably represents a change in pore fluid chemistry during later stages of diagenesis (Carver, 1980).

Fecal pellets are ellipsoidal in cross section, dark brown under plane polarized light, and are randomly distrubuted. They range in size from 100 to 800 μm, (0.1-0.8 mm), are isotropic, and are composed of tightly packed opal-CT lepispheres. Phosphatic fish debris comprises approximately 1% of the total rock. Minor portions of the bioturbated spiculites in borehole #1 contain poikilotopic ferroan and non-ferroan calcite which occupies matrix and spicule positions similar to that of chalcedony. Ghost spicule structure is apparent within some poikilotopic areas. Investigation of the chalcedony-calcite diagenesis has not as yet been undertaken.

Opaline Spiculites

The opaline spiculites which outcrop at the I-90, Risty Farm and Rovang Farm Sections are petrographically very similar to the organic opaline spiculites at the power plant. The principal difference between them is the lower concentration of organic material in the opaline spiculites. This accounts for their rather unusual white to light grey color in weathered outcrop.

The opaline spiculites are characterized by textures that range from laminated to intensely bioturbated (Plate II, D). As in the organic spiculites, burrows are represented by an abundance of spherulitic chalcedony occupying spicule and matrix positions. The cherty portions of the outcrop are the most intensely bioturbated spiculites. Their main component is chalcedony, but opal-CT lepispheres are also common. Sponge spicules, as in the organic spiculites, are present as unaltered biogenic opal, and combinations of lepispheres and chalcedony and spherulitic chalcedony.

The portions of the opaline spiculites that do not appear cherty in hand specimen display faint laminations in thin section (Plate II, E). Laminations are illustrated by subparallel alignment of spicules and very fine organic and chalcedony stringers. Laminations are abruptly truncated and deformed at the borders of chalcedonized burrows (Plate II, E). Spicules and quartz silt are the framework grains, and isotropic to faintly birefringent opal-CT lepispheres constitute the matrix material. Clinoptilolite and expandable clays have also been reported from the laminated opaline spiculites (Stach, 1970).

Of particular interest is the stratigraphic relationship between laminated and bioturbated opaline spiculites. The two lithologies are found interbedded and laterally equivalent to one another in outcrop. At I-90, the intensely bioturbated chalcedony cherts overlie moderately bioturbated to laminated spiculites.

Well-preserved burrows have been recovered from the extensively chalcedonized I-90 exposure (Plate II, F). Identification of silicified wood fragments with preserved cellular structure from the I-90 section has been confirmed by Jeff Schabilion, Univ. of Iowa, Dept. of Botany (pers. comm., 1980). One well preserved sequoia twig impression was found by Brian Witzke of I.G.S. within the laminated opaline spiculites at the Rovang Farm Section (Plate I, A).

DEPOSITIONAL ENVIRONMENTS

Detailed biostratigraphic studies (chiefly micropaleontological) must be completed before a fully acceptable synopsis of the depositional history of the Split Rock Creek Formation can be written. Correlation of the Split Rock Creek Formation with rocks of the standard reference section of the Cretaceous Western Interior must be documented to fit the unit into a regional scheme. Given this present limitation, several general statements can be made.

The Split Rock Creek Formation, a small local basin-filling deposit, is similar to many platform sedimentary sequences. The lithologic succession is a gradational progression from coarse to fine clastic sediments, culminated by sediment-starved biogenic deposition. This general sequence is typical of many Phanerozoic marine transgressions in the mid-continent region. In most of these sequences, biogenic carbonate deposition predominates, but in the case of the Split Rock Creek Formation, biogenic silica deposition occurred in a cul-de-sac on the shoreline margin of the Sioux Quartzite Ridge during a Late Cretaceous marine transgression (see Shurr, this volume). Similarity of elevations suggests that the opaline spiculites of the Split Rock Creek Formation may correlate with the Niobrara Formation. If true, this would mean that biogenic silica (sponge spicules) deposition along a protected sediment-starved shoreline was contemporaneous with widespread pelagic carbonate (coccoliths, etc.) deposition in the Western Interior seaway. This relationship is very similar to the depositional setting envisioned for shoreline siliceous spiculites by Cavaroc and Ferm (1968, p. 269).

The environment of the depositional basin must have been rather unique in order to accommodate large sponge populations. Modern sponges which secrete siliceous spicules belong to the Classes Hexactinellida and Demospongea. Tetraxon spicules indicative of Class Demospongea are common elements in the Split Rock Creek spiculites. Present day demosponges inhabit shallow waters of normal marine salinity experiencing low wave activity and minor quantities of detrital influx. Sponge colonies also occur frequently near the mouths of rivers, probably because of the greater concentration of dissolved silica present in these waters (de Laubenfels, 1957, p. 771; Blatt, et. al., 1972, p. 538). Demosponges consisting of spicules bound together with organic spongin disintegrate readily upon death; this, in addition to grazing by fish and molluscs explains the lack of preserved sponges and the occurrence of only discrete spicules within the laminated porcellanites. Inhabitance of shallow marine waters by siliceous sponges has been documented by others for numerous periods in geologic time (Bergquist, 1978; Finks, 1960, 1970; Finks et. al., 1961; Rigby, 1969; Storr, 1976; Wiedenmayer, 1977).

Regional stratigraphic relationships (see Shurr, this volume), the presence of abundant land plant debris, and the presence of detrital quartz in the opaline spiculites all indicate that the Precambrian rocks along the crest of the Sioux Quartzite Ridge were exposed during the deposition of the Split Rock Creek Formation. The deep weathering of these subaerially exposed Precambrian rocks during Cretaceous sedimentation (Austin, 1970; Parham, 1972; Stach, 1970) and the presence of interbedded bentonites suggest likely sources of dissolved silica that would facilitate the proliferation of silica-secreting sponges in a small marine-influenced embayment.

The Split Rock Creek Formation attains a maximum known thickness of approximately 300 feet (91 m, figure 5), and deposition within the local basin was probably contemporaneous with one or more stratigraphic units of the Late Cretaceous Western Interior seaway. The geology of the strata beneath the opaline spiculites is known only through the Risty Farm and Rovang Farm Sections, and the Pathfinder Plant cores. All these sites indicate dramatic sedimentologic and stratigraphic control by the erosional topography developed on the Precambrian rocks. The basal diamictites at the Risty and Rovang Farm Sections appear to be mudflows, deposited on basinward slopes of up to 15°. Their textures and sedimentary structures are similar to those of modern lobate sediment flows described by Lawson (1979, p. 49-65). These rocks and the other clastic units of the Split Rock Creek Formation are worthy of further examination, as the stratigraphy of the entire unit has important regional implications.

COMMENTS ON THE ORIGIN AND DIAGENESIS OF THE OPALINE SPICULITES

When this project was initially undertaken, the authors did not expect to discover the occurrence of shallow marine biogenic opaline sedimentary rocks in southeastern South Dakota. The announcement of their presence may come as a surprise to many. These Late Cretaceous deposits are some of the oldest opaline rocks still in existence (Blatt, et. al., 1972, p. 539), and their field relations have important implications concerning several current controversies on the origin and diagenesis of siliceous sediments.

Volcanogenic-Biogenic Controversy

As has been the case with other deposits of biogenic siliceous sediments (Hein, et. al., 1978; Riech and von Rad, 1978; Carver, 1980), opaline rocks of the Split Rock Creek Formation have been interpreted as volcanic ashes (Baldwin, 1949; Steece, 1959; Stach, 1970). Stach (1970) supported his interpretation by noting the presence of cristobalite, clinoptilolite, and expandable clays in these rocks. Although discrete bentonites do occur within the Split Rock Creek Formation, petrographic examination has failed to provide any supportive evidence for volcanic origin (ghosts of glass shards, euhedral zircons, etc.) of the opaline rocks. Abundant evidence for a biogenic origin has been found. Cristobalite, specifically opal-CT lepispheres in these rocks, has been shown to be a common constituent in biogenic silica deposits (Kastner, et al, 1977; Hein, et al, 1978; Carver, 1980). The presence of the zeolite clinoptilolite cannot be considered definitive evidence for volcanic origin, as Hein, et al., (1978), and Reich and von Rad, (1979), have reported that it is a common by-product of the transformation of biogenic opal-A to lepispheric opal-CT in Cenozoic diatomaceous sediments.

Deep-Shallow Water Controversy

The paleobathymetry of biogenic siliceous sediments has been controversial for some time. The most well known biogenic siliceous deposits are the pelagic diatomaceous and radiolarian sediments of modern and ancient deep sea floors. The presence of sponge spicules, common elements in siliceous sediments, frequently has been used to infer deep water sedimentation (300 m - 1,000 m; de Laubenfels, 1957). Cavaroc and Ferm (1968) interpreted siliceous spiculites as shallow marine shoreline deposits. More recently, Carver (1980) interpreted Tertiary spicule-bearing opaline rocks of the Atlantic coastal plain as shallow marine deposits. Regional stratigraphic relations, the abundance of land plant debris, and the presence of coarse detritus indicate that the opaline spiculites of the Split Rock Creek Formation were deposited in shallow marine water, probably in a protected shoreline.

Diagenesis of Opaline Rocks

The "diagenetic maturation sequence" of opaline rocks from biogenic opal-A to opal-CT lepispheres to chalcedony and microquartz, has been outlined in detail by Kastner, et al. (1977). The controls of temperature and depth of burial on the diagenetic maturation of opaline sediments have been well documented (Jones and Segnit, 1971; Murata and Nakata, 1974; Mitzutani, 1977; Hein et al., 1978).

In the Split Rock Creek Formation, however, opaline rocks are interstratified with chalcedonic cherts. X-ray diffractograms of the opaline spiculites display broad, diffuse peaks at $2\theta = 22°$, a characteristic of opal-CT which has not been restructured by either deep burial or exposure to elevated temperatures (Murata and Larson, 1975). Silica diagenesis in the Split Rock Creek Formation must be explained by factors other than burial or heating. Petrographic examination has shown that burrowing controls the location of most of the chalcedony in the siliceous rocks of the Split Rock Creek Formation.

Kastner, et al., (1977, p. 1052-1057) described geochemical factors which control the diagenesis of opal-A. They reported that the presence of magnesium in solutions of high alkalinity (i.e., marine waters) facilitates the maturation of opaline sediments, whereas clay minerals, particularly expandable clays, act as inhibitors. Expandable clays compete for free magnesium, which occupies inter-layer sites. Stach (1970) reported the presence of expandable clays in the laminated opaline spiculites of the Split Rock Creek Formation.

These relationships suggest a hypothesis which may explain the gross patterns of diagenesis in the opaline spiculites. The preferential chalcedonization of the burrowed rocks can be explained by their increased exposure to magnesium-rich marine water, because of their high porosity, and compositional changes in the soft sediments within the burrows. Burrows in the bioturbated organic opaline spiculites are conspicuously depleted of organic matter, which suggests that the silicified burrows may have been depleted of chemical inhibitors to silica diagenesis as well.

This mechanism implies that the chalcedonic cherts were formed during early diagenesis, in the presence of marine pore fluids. Petrographic evidence supports this contention. Sponge spicules and land plant fossils are better preserved in the burrowed chalcedonic rocks than the adjacent laminated opaline rocks, where they tend to be preserved as moldic porosity. This difference in preservation suggests that the chalcedonic cherts were formed prior to the nearly complete dissolution of all spicules and fossil plants. The longevity of the opaline rocks of the Split Rock Creek Formation is probably related to the presence of disseminated expandable clays which have inhibited diagenesis, and early flushing of magnesium-rich pore fluids resulting from subaerial exposure at the close of Late Cretaceous marine sedimentation on the Sioux Quartzite Ridge. More petrographic work is needed to understand the details of diagenesis in this unit. The Split Rock Creek Formation deserves recognition and further attention as a field laboratory for the study of geochemical controls on the diagenesis of biogenic silica deposits.

ACKNOWLEDGEMENTS

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PLATE I

(A) Sequoia twig impression in laminated opaline spiculite at Rovang Farm Section. Scale bar = 1 cm. (B) Matrix material from diamictite, Rovang Farm Section. Silt to sand size quartz and ilmenite (?) detritus floating in a matrix of homogeneous isotropic clay. Light grains are quartz and opaque grains are probably ilmenite. Tonal variations in the matrix are caused by differential plucking of large grains during the processing of the thin sections. Larger weathered plagioclase grains and lithic fragments are also important constituents of the rock. Plane polarized light; scale bar = 500 μm. (C) Laminated organic opaline spiculite. Most clear areas are voids. Dark laminae are organic rich and isotropic. Plane polarized light; scale bar = 2 mm. (D) Bioturbated organic opaline spiculite. Burrows are dominated by chalcedony (c) and surrounded by lepispheric organic matrix (l). Fecal pellets (f). Voids (v) within isotropic organic matrix are from plucking and dissolution of sponge spicules. Plane polarized light; scale bar = 2 mm. (E) Sponge spicules (s) within lepispheric opal-CT (o) to chalcedony (c) matrix. Plane polarized light; scale bar = 250 μm. (F) Opal-CT lepispheres. Scanning electron micrograph of packed lepispheric matrix. Some lepispheres line a pore. Bioturbated organic opaline spiculites. Scale bar = 100 μm.

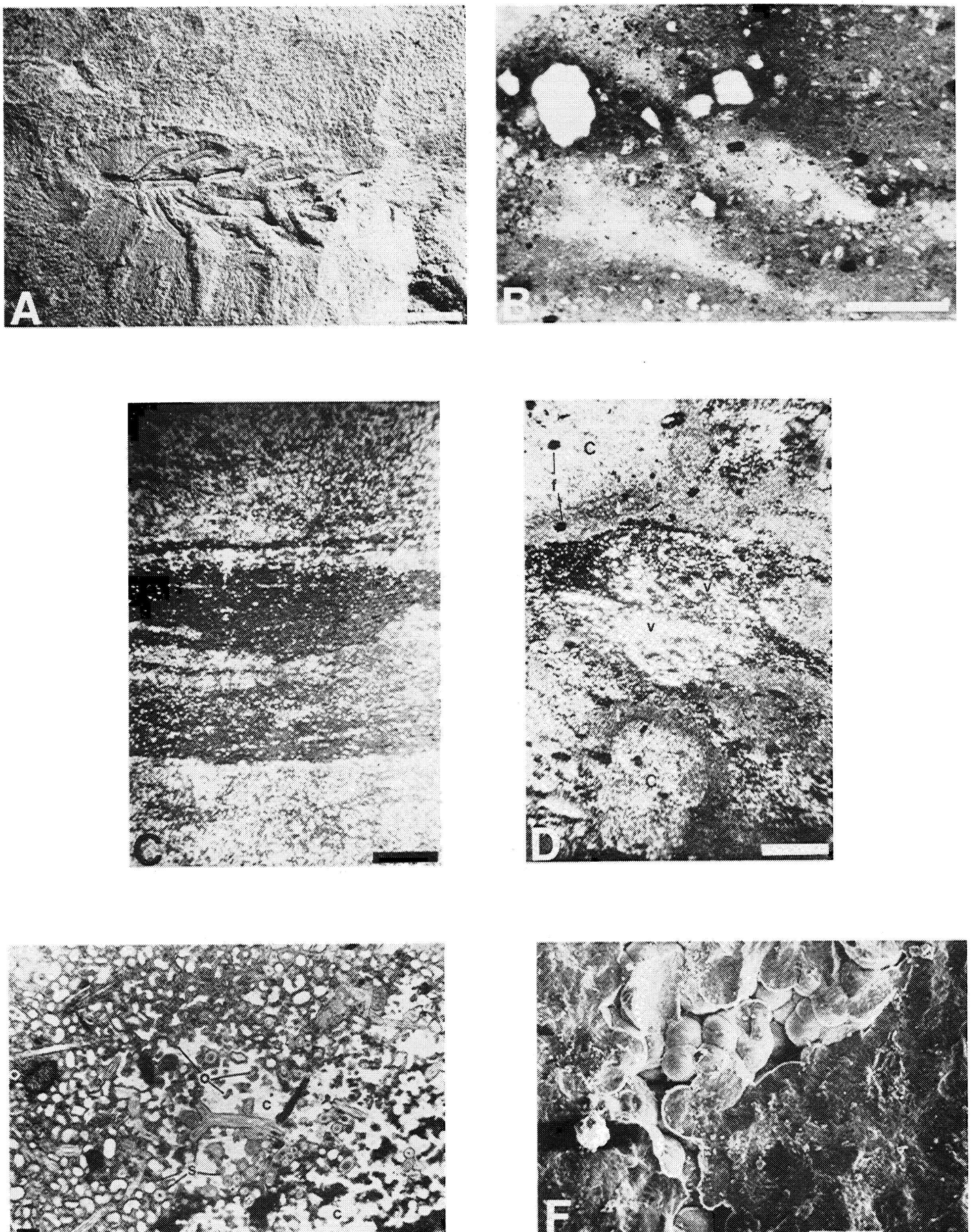
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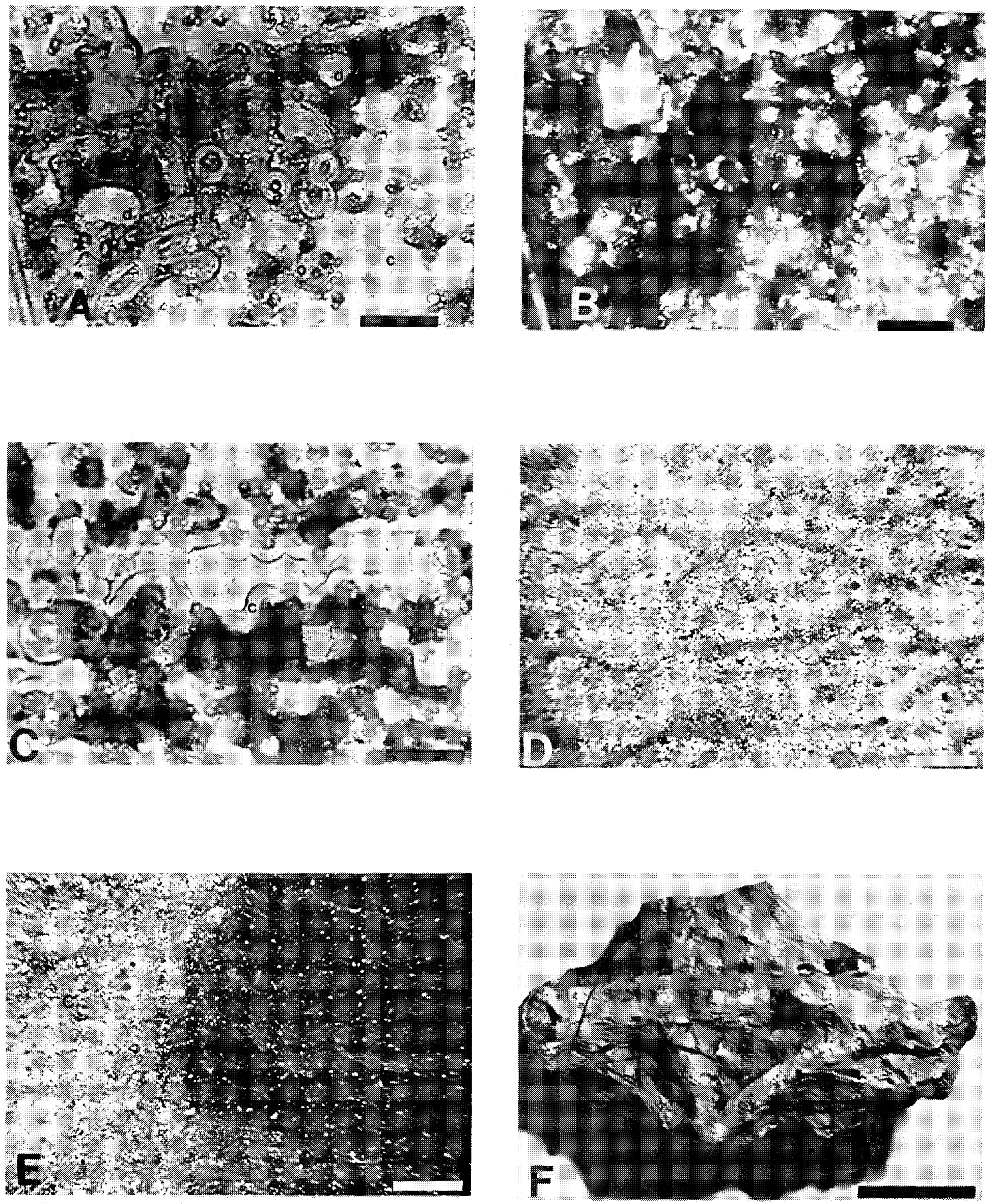
PLATE II

(A, B), Various modes of spicule occurrence within the bioturbated organic opaline spiculites. (a) Original opaline spicule with chalcedony filled central canal. (b) Spicule with lepisphere center and chalcedony wall. (d) Spicule void filled with spherulitic chalcedony. Matrix varies from opal-CT lepispheres (o) to chalcedony (c). (A), plane polarized; (B), cross polarized; scale bar = 125 μm. (C), Botryoidal length-slow chalcedony (c) rimming void within bioturbated organic opaline spiculite. Plane polarized light; scale bar = 125 μm. (D), Bioturbated opaline spiculite. Microscopic view of chert from I-90 Section. Most light areas are chalcedony while darker arcuate laminae contain abundant opal-CT lepispheres. Plane polarized light; scale bar = 2 mm. (E), Slightly bioturbated laminated opaline spiculite from I-90 Section. Faint birefringent laminae are abruptly terminated by large chalcedonized burrow (c). Although not visible at this power spicules are unoriented and have retained original opaline character much better within the burrow than in laminated phase where spicules are subparallel to bedding and present as molds. (F), Chalcedonized burrows from I-90 Section. Burrows have weathered into relief from the surrounding laminated spiculite.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CRETACEOUS VERTEBRATE FOSSILS OF IOWA AND NEARBY AREAS OF NEBRASKA, SOUTH DAKOTA, AND MINNESOTA

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ABSTRACT

Vertebrate fossils have been noted within all Cretaceous formations in the area. Teleost fish bones and scales are the most conspicuous and abundant vertebrate fossils within the marine shale and marl intervals. The occurrence of dinosaur remains in the lower Dakota Formation is consistent with previously interpreted terrestrial-fluvial depositional environments. The overlying marine units in the upper Dakota through Pierre Shale sequence have yielded an abundance of disarticulated teleost fish remains, and rare articulated fish fossils have been found within the Greenhorn Formation. Teeth of fish- and mollusk-eating sharks are also noted. Marine reptile remains, including mosasaur, plesiosaur, and giant turtles, have been rarely encountered in the area. The Cretaceous vertebrate faunas along the eastern margin of the Interior Seaway are generally comparable with better known faunas further west, especially the Niobrara of Kansas.

INTRODUCTION

Compared to the quantity of information published on the Cretaceous vertebrate faunas of the Great Plains and American West, the Cretaceous vertebrates of the eastern region of the Interior Seaway have received little attention. The area included in this summary report encompasses Iowa and portions of Nebraska, South Dakota, and Minnesota or essentially the Cretaceous outcrop areas along the middle reaches of the Missouri River (from the Great Bend region downstream along the Iowa-Nebraska border), the Big Sioux River Valley, and the Minnesota River Valley region (figure 1). Illustrated specimens (Plates 1 and 2) with catalog numbers prefixed by SUI are reposited at the Univeristy of Iowa, Department of Geology.

HISTORICAL BACKGROUND

Some of the early investigators and explorers of the Cretaceous geology in the study area observed vertebrate fossils in various stratigraphic intervals, and an excellent review of the early history of investigations is found in Tester (1931). Nicollet's report of 1841 (published 1843a) notes fish scales in strata now included in the Greenhorn Limestone of the Dixon Co., Nebraska region (p. 35), and fish scales and fish, shark, and "crocodile" vertebrae are noted from probable Niobrara or Pierre strata in the Great Bend area of the Missouri (p. 35, 170). Nicollet (1843b) reiterated his earlier observations of Cretaceous strata along the Missouri River in present-day Dixon and Dakota Cos., Nebraska. Hall and Meek (1856) divided the Cretaceous of the Missouri River region into five stratigraphic divisions; Division 3 is a "marl" with oysters and fish scales noted. Meek and Hayden (1862, p. 419) formally designated Division 3 the Niobrara Division, a marl and chalky unit containing, among other things, "large scales and other remains of fishes." Some stratigraphic confusion is evident in Meek and Hayden's report since their Niobrara Division was extended to include strata in the vicinity of the Big Sioux River where most exposed marls and chalks are now referred to the older Greenhorn Limestone. Later workers (e.g. Calvin, 1894) in Iowa incorrectly included Greenhorn rocks within the Niobrara Division.

St. John (*in* White, 1870, v. 1, p. 292, 294, v. 2, p. 196-199) identified fish remains and scales in strata now assigned to the upper Dakota and Graneros Formations, and an "abundance of fish remains", including teleosts and shark teeth and vertebrae, was noted in Greenhorn strata in Woodbury Co., Iowa. Leidy (1873) described mosasaur remains from Niobrara strata along the Missouri River near the Santee Agency, and Meek (1876, p. xxv-xxxi) observed fish remains in Graneros, Greenhorn, and Niobrara strata of the study area. Workers in the late 1800s continued to note fish and shark remains in Cretaceous strata of western Iowa (Calvin, 1893a, 1893b, 1894; Bain, 1895, 1896), although no systematic descriptions were ever undertaken. Twentieth century workers have made additional discoveries of Cretaceous vertebrates in the study area, and their contributions are noted in the following section.

STRATIGRAPHIC OCCURRENCES

Vertebrate fossils have been noted in all Cretaceous formations represented in the study area. Table 1 summarizes the general stratigraphic distribution

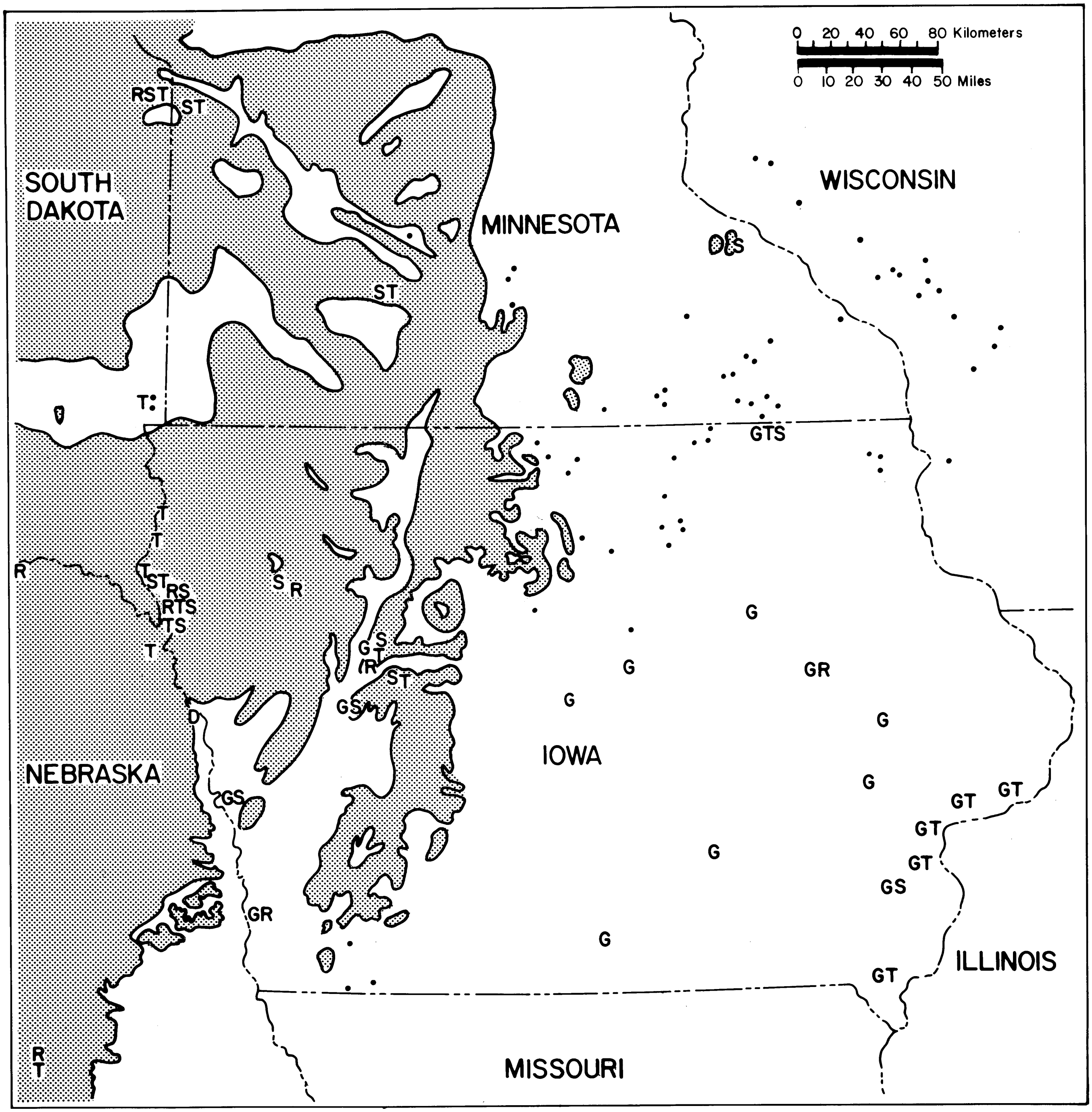

Figure 1. Map of study area illustrating the distribution of vertebrate fossils discussed in text. Patterned area is present-day distribution of Cretaceous rocks (after Sloan, 1964; Ludvigson and Bunker, 1979; geologic maps of Iowa, South Dakota, and Nebraska), and dots are known Cretaceous outliers (from Andrews, 1958; Sloan, 1964; geologic map of Iowa). T--teleost fish, S--sharks, R--marine reptiles (plesiosaurs, mosasaurs, turtles), D--dinosaurs, G--Cretaceous fossils noted in Pleistocene glacial deposits and gravels.

TABLE 1. LIST OF VERTEBRATE FOSSILS

	D	Gs	Gn	C	N	W	MO	P
Class Chondrichthyes								
Order Selachii								
undetermined shark teeth			x			x		x
Ptychodus spp.			x				x	x
Squalicorax falcatus			x				x	
Scapanorhynchus sp.			x					x
Lamna appendiculata			x					x
Lamna sulcata			x					x
Isurus mantelli			x				x	x
Isurus angustidens?								x
Odontaspis sp.			x			x		
Squatirhina sp.						x		
Synechodus sp.						x		
Order Chimaeriformes								
Myledaphus sp.						x		
Class Osteichthyes								
Subclass Actinopterygii								
Infraclass Holostei								
Pycnodus sp.?						x		
Protosphyraena sp.			x					
Infraclass Teleostei								
undetermined teleost scales	x	x	x	x	x	x	x	x
Superorder Elopomorpha								
Apsopelix sp.?			x					
elopiform scales	x	x	x					
Superorder Clupeomorpha								
clupeoid vertebrae							x	
Superorder Osteoglossiformes								
Ichthyodectes sp.							x	x
Xiphactinus sp.		x						
osteoglossiform scales/teeth	x	x	x				x	x
Bananogmius sp.			x					
Superorder Antherinomorpha								
antheriniform scales?	x							

Table 1. Con't.

	D	Gs	Gn	C	N	W	MO	P
Superorder Protacanthopterygii								
protacanthopterygian scales?		x	x			x		
Superorder Acanthopterygii								
acanthopterygian scales?			x					
Class Reptilia								
Subclass Anapsida								
Order Chelonia								
undetermined turtle vertebrae	x							
Desmatochelys lowii		x					x	
Subclass Lepidosauria								
Order Squamata								
mosasaur bones/teeth					x			x
Subclass Archosauria								
Order Crocodilia								
crocodilian remains	x					x		
Order Ornithischia								
ornithopod dinosaur	x							
Subclass Euryaspida								
Order Sauropterygia								
plesiosaur remains		x					x	
undetermined marine reptile remains		x					x	x

D--Dakota Fm.; Gs--Graneros Shale; Gn--Greenhorn Limestone; C--Carlile Shale; N--Niobrara Fm.; W--Windrow Fm., marine deposits; MO--Milbank-Ortonville granite district Cretaceous rocks of probable Carlile age; P--Cretaceous vertebrate fossils in Pleistocene gravels.

of vertebrate fossils, and additional information on specific occurrences is outlined below. Reconstructive sketches of the larger Cretaceous vertebrate animals noted in the study area are shown in figure 2.

Dakota

The oldest Cretaceous formation in the study area is the Dakota Formation of probable Albian and early Cenomanian age. The lower portion of the Dakota is a non-marine fluvial-related sequence of sandstones and clay rocks, and a few rare vertebrate fossils have been noted. The distal end of a left femur of an ornithopod dinosaur (Plate 2, figures 16-19) was discovered in Burt Co., Nebraska near the Missouri River south of Decatur in Dakota sandstones yielding leaf impressions. Additional dinosaur bone scraps were recovered north and west of Decatur (Barbour, 1931). Galton and Jensen (1978) studied the femur fragment from Burt Co., and they concluded that it is probably from a hadrosaurian, although possible relationships with *Iguanodon* could not be ruled out. This femur fragment is quite large and probably came from an animal whose body length was around 10 m (Galton and Jensen, 1978). No additional dinosaur material has yet been noted in the Dakota Formation of the study area. The potential for recovering additional dinosaur material in the Dakota outcrop belt of eastern Nebraska and western Iowa undoubtedly exists, although the lack of expansive Dakota exposures hinders the search. A partial skeleton of an ankylosaur (*Silvisaurus*) was collected in the Dakota Formation of Ottawa Co., north-central Kansas just south of the study area (Eaton, 1960), and crocodilian remains are noted in the Dakota of Kansas (Franks, 1975, p. 503). Bird tracks are also observed in the Dakota of Kansas (Williston, 1898a).

The upper portion of the Dakota Formation in the Big Sioux Valley outcrop area is transitional with the overlying marine Graneros Shale, and intertonguing deltaic deposits and marine mudstones are noted (Ludvigson and Bunker, 1979). Marine shales in the upper Dakota have yielded large fish teeth, possibly from predatory ichthyodectids (Plate 1, figure 33), and fish bones and scales in dark mudstones are locally abundant at many outcrops in the study area. Stanton (1922, p. 256) recorded fish and turtle vertebrae and the tooth of a crocodile from the upper Dakota near Jackson, Dakota Co., Nebraska, and Tester (1931, p. 237) noted fish bones in upper Dakota sandstones at Riverside, Iowa. Additionally, dense, crystalline, micaceous limestone lenses are noted in the upper Dakota of Iowa and northeastern Nebraska (e.g. Field Trip Stops 1 and 5) and were probably formed in interdistributary embayments. These limestones often contain an abundance of fragmentary fish fossils easily recovered in formic acid residues; vertebrae, teeth, maxillary and mandibular fragments, cranial elements and other bones, and scales are all assignable to teleost fish, although further taxonomic studies remain to be completed. The most abundant scales are from elopiform fish, although osteoglossomorph and possible antheriniform fish scales are also noted.

Graneros

The Graneros Shale in the study area is characterized by gray calcareous off-shore marine shales. The base of the Graneros is usually chosen within

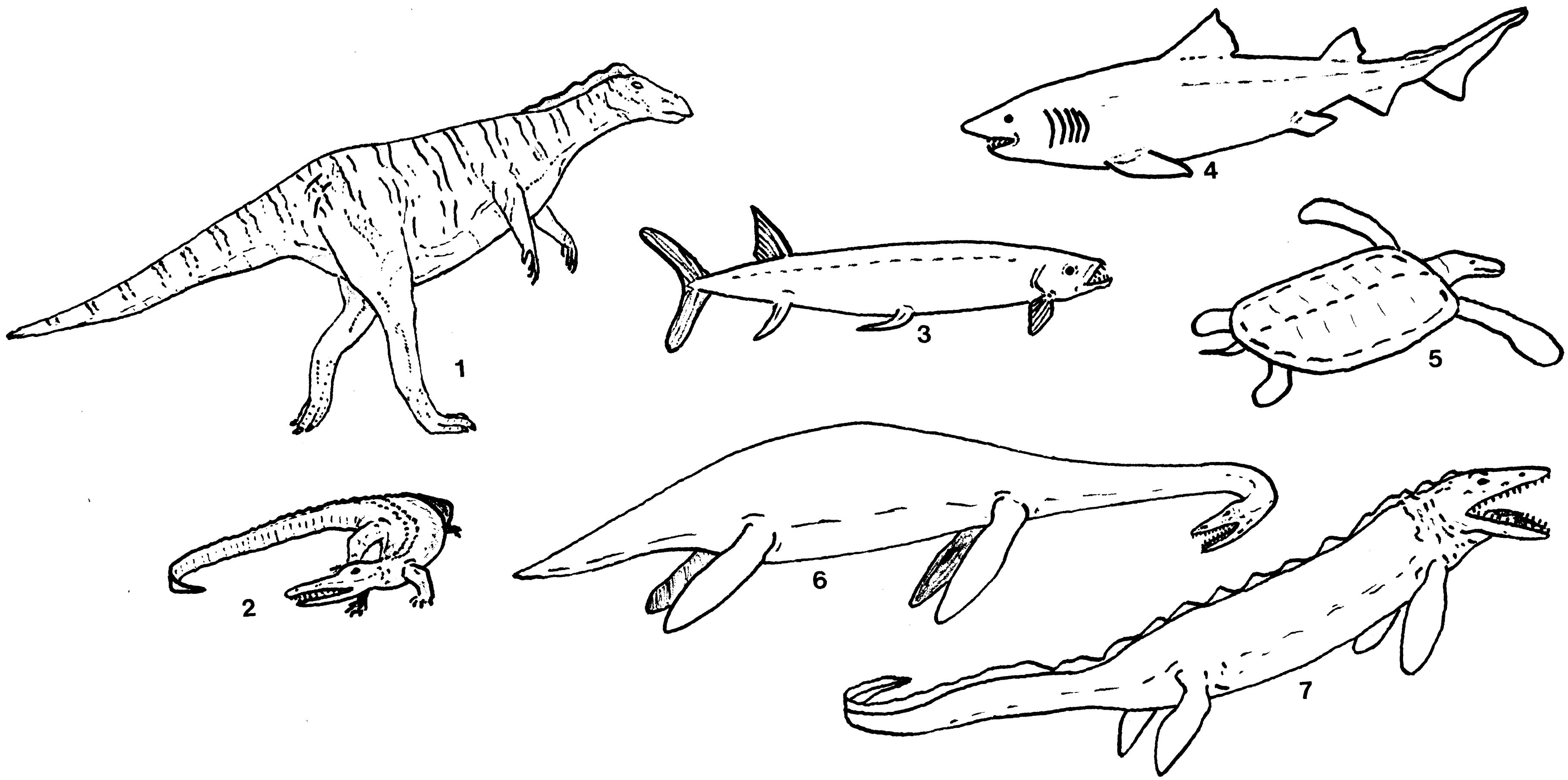

Figure 2. Sketches of larger Cretaceous vertebrate animals noted in the study area (approximately to scale). 1. ornithopod dinosaur (Dakota Fm.), 2. crocodilian (Dakota, Windrow Fms.) 3. large ichthyodectid fish (Graneros, Greenhorn Fms.), 4. large galeoid shark (Greenhorn, Windrow Fms.), 5. giant sea turtle (Graneros Fm.), 6. plesiosaur (Graneros Fm.), 7. mosasaur (Niobrara, Pierre Fms.).

the Dakota-Graneros shale sequence at the level where the shales become calcareous. These shales contain few benthic fossils (scattered *Inoceramus* are the most conspicuous), although teleost fish remains are noted at some horizons within the Graneros in great abundance. The dark gray Graneros shales contain unoxidized organic material, and, in combination with the general scarcity of burrows and benthic fossils, low to, at times, negative Eh benthic depositional conditions are inferred. The abundant fish remains in parts of the Graneros probably accumulated as dead elements of the pelagic fish fauna became disarticulated in near-surface waters by predators and through decay and then settled to the bottom. Additionally, some fish bones and scales are noted within coprolitic masses. Fish scales are also noted in carbonate concretions in the upper part of the Graneros at Riverside, Iowa. The Graneros fish scale/bone beds in Iowa are analogous to similar accumulations in other deposits such as the Lower Cretaceous Mowry and Aspen shales of the Rocky Mountain region.

Each superorder of teleost fish can be distinguished by distinctive scale types (Cockerell, 1919), although further taxonomic subdivision based on scales alone is usually not advisable. The majority of identifiable Graneros fish scales belong to the osteoglossomorph fish (Plate 1, figures 38-45). Exceptionally large osteoglossomorph scales, some in excess of 5 cm., are reasonably assigned to representatives of the ichthyodectids, a family of large predatory fish. Similar large scales have been noted associated with the ichthyodectid *Xiphactinus*; these scales were termed *Cladocyclus* by Leidy (1873). A large dentary of *Xiphactinus* was recovered from the Graneros Shale near Fairbury in southeastern Nebraska (Stewart, 1900, p. 293). The Graneros Shale at Riverside, Iowa has yielded a slab containing large bony fin-spines (Plate 2, figure 3 and 4), and these closely resemble spines of ichthyodectids like *Xiphactinus*. Stewart, (1900, p. 284) suggested that ichthyodectid spines "formed powerful weapons of defense." Additional teleost scales in the Graneros Shale of Iowa are tentatively assigned to the elopiform fish, and some smooth forms resemble scales of protacanthopterygian fish.

Marine reptile remains are also noted in the Graneros Shale in the study area. A series of marine reptile vertebrae was collected from a cistern excavation through the Graneros during the late 1800s in sec. 35, T90, R48, Plymouth Co., Iowa along the field trip route (Calvin, 1893b, p. 156). These vertebrae are presently on display at the Sioux City Public Museum (Plate 2, figures 5 and 6); 73 vertebrae, most with the processes broken off, measure 3.8 m (12.5 ft) in total length on the display board. The centrum of the largest vertebra is 87 mm wide. After examining photographs of the vertebrae on display, Jim Martin (1980, personal communication) was kind enough to supply the following diagnostic comments: "The long series of vertebrae appear to have flat centra, transverse processes, haemal processes, and neural arches similar to those of a plesiosaur. The appearance of the base of the vertebra does cast some doubt on the presence of haemal arches, although I would have to see them to be sure." Additionally, a large marine reptile vertebra (Plate 2, figures 7 and 8) was collected by Paul Williams near an exposure of Graneros Shale in sec. 14, T90, R48, Plymouth Co., Iowa. A partial skeleton of the large marine turtle, *Desmatochelys lowii*, was collected in 1893 from the Graneros Shale near Fairbury in southeastern Nebraska (Williston, 1898c).

Greenhorn

The Greenhorn Limestone overlies the Graneros in the study area and consists primarily of shaley, chalky limestones, often with abundant specimens of the bivalve, *Inoceramus*. The Greenhorn contains a great abundance of pelagic forams and coccoliths, and it is no surprise that an abundant representation of the pelagic teleost fish and shark fauna is also preserved in the formation. Teleost fish bones and scales are scattered to very abundant throughout much of the formation, and articulated fish remains can be encountered at some localities. Two nearly complete fish fossils are known from the Greenhorn in Iowa (Plate 2, figures 1 and 2). The specimen from Stone State Park (Field Trip Stop 4) is closely comparable to Woodward's (1907, p. 106) illustration of *Anogmius* (= *Bananogmius*) from the Niobrara of Kansas. Greenhorn outcrops at Riverside, Iowa have yielded as yet unidentified articulated cranial elements and unscattered scale sections from individual fish. Extensive searching in the numerous Greenhorn outcrops of western Iowa and eastern Nebraska was not undertaken for this study, although the author believes that good potential exists for recovering additional articulated fish remains in the Greenhorn. Additional collections would be important in clarifying the evolution of the upper Cenomanian - lower Turonian teleosts in North America. Fish scales in the Greenhorn are similar to those in the Graneros; osteoglossomorph (including large ichthyodectid), elopiform, and possible protacanthopterygian and acanthopterygian scales are noted.

Shark teeth are occassionally encountered in the Greenhorn, but never in great abundance. The classification of detached shark teeth remains a somewhat subjective procedure, although studies of connected series of teeth (e.g. Williston, 1900; Woodward, 1902-1912) have clarified the taxonomic relationships of many Cretaceous shark tooth types. The Greenhorn Limestone of Plymouth Co., Iowa has yielded the bulk of shark teeth in the study area where the specimens range from light tan to black in color (varying contrasts on Plate 1 illustrate variations in color). All specimens are closely comparable to well-known Upper Cretaceous cosmopolitan forms. Teeth from predatory fish-eating galeoid sharks are the most abundant shark teeth in the Greenhorn, and characteristic forms are referrable to *Squalicorax*, *Scapanorhynchus*, *Lamna*, and *Isurus* (Plate 1, figures 1-30). The ptychodontid sharks possessed hundreds of low-crowned teeth arranged in parallel rows similar to modern rays, and such a battery of teeth was well suited for crushing the shells of mollusks like *Inoceramus*. St. John (*in* White, 1870, p. 198) and Calvin (1893a, p. 8, 1893b, p. 150, 1894, p. 146) reported the ptychodontid, *Ptychodus*, from the Greenhorn of northwestern Iowa. No marine reptiles have yet been noted in the Greenhorn Limestone in the study area.

Carlile, Niobrara, Pierre

The Carlile Shale, a silty gray shale, overlies the Greenhorn and is usually poorly fossiliferous, although fish scales are noted (Hattin, 1980, personal communication). Condra (1908, p. 12) records "many fish scales" in Carlile strata in northeastern Nebraska. The Niobrara Formation has not yet been noted in Iowa because of post-Cretaceous erosion, but scattered outcrops are present in parts of eastern Nebraska and South Dakota. The occurrences of Niobrara vertebrate fossils in the study area pale in comparison to the world-renowned and abundant vertebrate fossils of the Niobrara chalks and

PLATE 1

1 - 7 *Squalicorax falcatus* shark teeth, Greenhorn Ls., each tooth shown in outer (above) and inner (below) views. 1-5. SUI 13111, Plymouth Co., Ia; 6, 7. SUI 13179, sec. 19, T91, R48, Plymouth Co., Ia. (all x 1).

8 - 13 *Scapanorhynchus* sp. shark teeth, Greenhorn Ls., each tooth shown in outer (left) and inner (right) views except fig. 9 shown in outer and side (right) view. 8. SUI 13113, Plymouth Co., Ia.; 9. SUI 13135, Plymouth Co., Ia.; 10-13. SUI 13134, Plymouth Co., Ia. (all x 1).

14 - 20 *Lamna appendiculata* shark teeth, Greenhorn Ls., 14-18 shown in outer (above) and inner (below) views. 14-18. SUI 13114, Plymouth Co., Ia.; 19. SUI uncat., Grant City, Sac Co., Ia.; 20. SUI 13132, Plymouth Co., Ia. (all x 1).

21 *Lamna sulcata* shark tooth, Greenhorn Ls., SUI 13132, Plymouth Co., Ia. (x 1).

22 - 28 *Isurus mantelli* shark teeth, Greenhorn Ls., (except 25), each tooth shown in outer (above) and inner (below) views except fig. 25. 22-24. SUI 13115, Plymouth Co., Ia.; 25. SUI 45114, from gravels near Lake View, Sac Co., Ia.; 26. SUI 13137 Plymouth Co., Ia.; 27. SUI 13133, Plymouth Co., Ia; 28. sec. 8, T90, R46, Hinton, Plymouth Co., Ia. (Art Bettis collection). (all x 1).

29 *Isurus angustidens?* shark tooth, gravels near Missouri Valley, Harrison Co., Ia., SUI uncat. outer (left) and inner (right) views. (x 1).

31, 32 *Ptychodus polygyrus* tooth from a mollusk-eating shark, gravels near Lake View, Sac Co., Ia., SUI 45110, 31. side view, 32. crown view. (x 1).

33 Fish tooth (probably from a large ichthyodectid), upper Dakota Fm., Iowa Geol. Survey core drilled near Hawarden, Sioux Co., Ia., depth 216.9 ft., SUI uncat. (x 1).

34 Fish tooth (aff. *Protosphyraena)*, Greenhorn Ls., Plymouth Co., Ia., SUI 13128. (x 1).

35 - 37 Fish vertebrae (ichthyodectid aff. *Ichthyodectes)*, gravels near Lake View, Sac Co., Ia., SUI 45109, 35. side view, 36. posterior view, 37. side view. (all x 1).

38 - 45 Teleost fish scales, Graneros Shale, Riverside, Woodbury Co., Ia., SUI uncat., 38-40, 42. undetermined teleost scales (probably from ichthyodectids); 41, 43-45. teleost scales (large ichthyodectids). (38-42, 44 x 2; 43, x 1.5; 45, x 1.2).

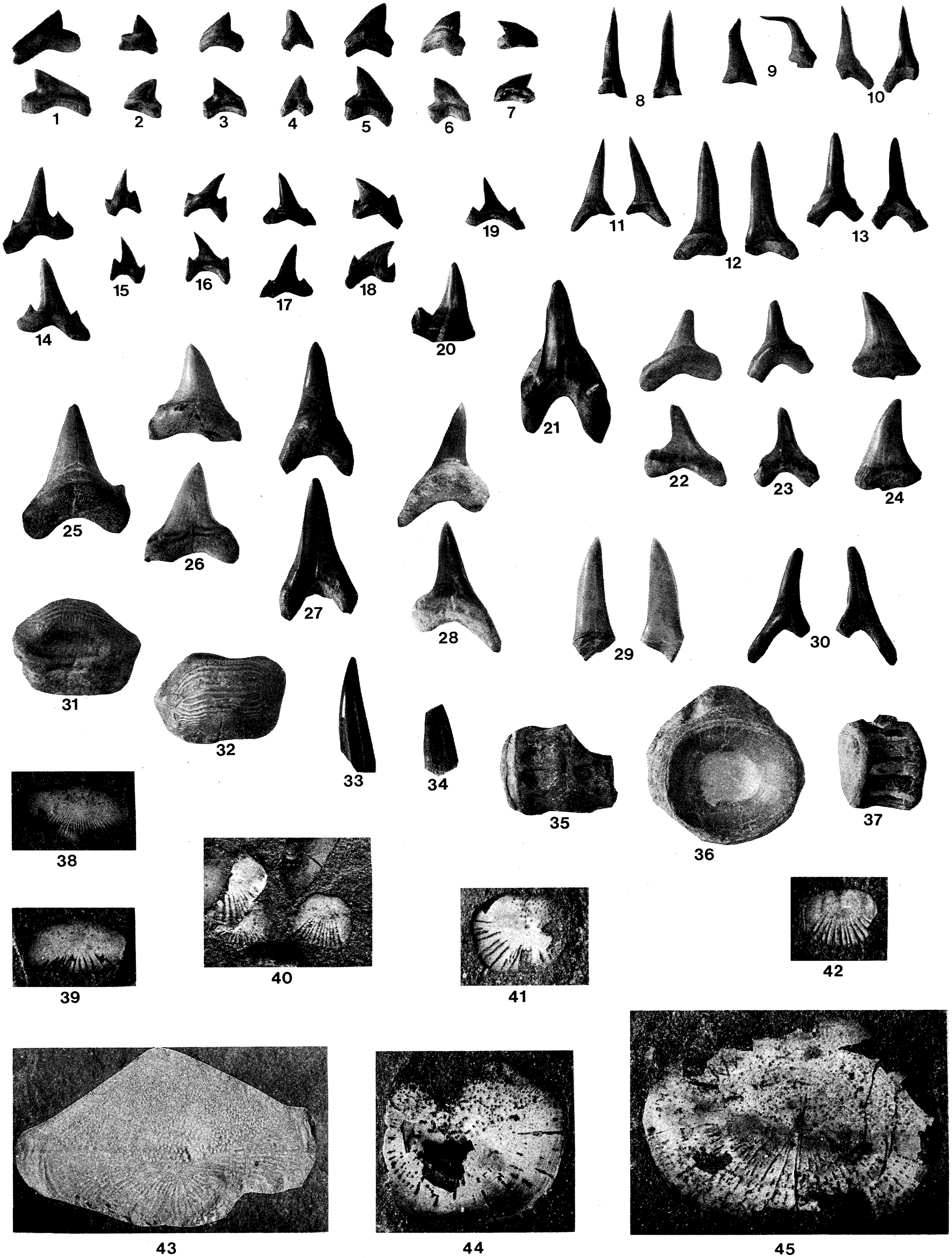
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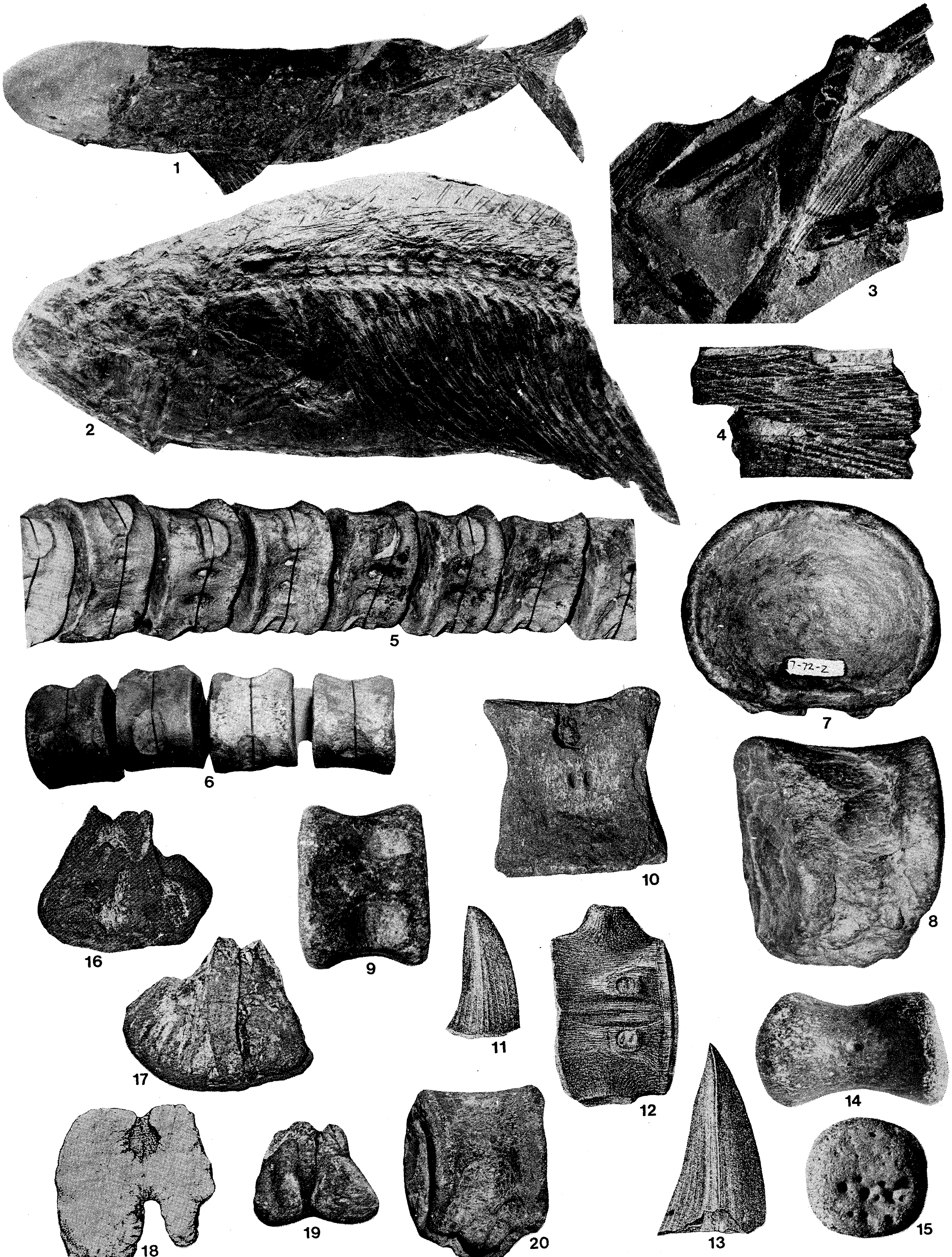
PLATE 2

Figure	
1	Teleost fish (nearly complete, head missing), aff. *Apsopelix* (probably an elopomorph), Greenhorn Ls., Westfield, Plymouth Co., Ia., on display at Sanford Museum, Cherokee, Ia. (x 0.5).
2	Teleost fish, *Bananogmius* (osteoglossomorph), Greenhorn Ls., Stone State Park, Woodbury Co., Ia., on display at Sioux City Public Museum. (x 0.25).
3, 4	Fish spines, ichthyodectid, Graneros Sh., Riverside, Woodbury Co., Ia., SUI uncat., 3. spines in shale slab (x 0.5), 4. broken spine showing surface detail (x 1).
5, 6	Plesiosaur vertebrae, Graneros Sh., sec. 35, T90, R48, Plymouth Co., on display at Sioux City Public Museum (vertebrae held onto display board with wire, visible on photos), 5. central portion of vertebral column, oblique view of lower surface (x 0.25), 6. four tail vertebrae, side view (x 0.25).
7, 8	Marine reptile vertebra, Graneros Sh., NW sec. 14, T90, R48, Plymouth Co., Ia., specimen at Sanford Museum, Cherokee, Ia., 7. posterior view, 8. side view (x 0.25).
9	Marine reptile vertebra, gravels near Lake View, Sac Co., Ia., SUI 45111, bottom view (x 0.85).
10	Marine reptile vertebra (specimen is probably crushed), gravels near Vail, Crawford Co., Ia., specimen at Sanford Museum, Cherokee, Ia. (x 0.3).
11 - 13	Mosasaur, Niobrara Fm., near Santee, Knox Co., Nebr., specimens listed at Swarthmore College Museum (illustrations from Leidy, 1873). 11, 13. mosasaur teeth (x 0.65); 12. mosasaur caudal vertebra, bottom view (x 0.35).
14, 15	Marine reptile bone, gravel pit near Vinton, SW sec. 20, T85, R10, Benton Co., Ia., SUI 33071. 14. side view, 15. anterior view (both x 0.85).
16 - 19	Ornithopod dinosaur bone, probably a hadrosaur, distal end of left femur, Dakota Fm., 2 mi. south of Decatur, Burt Co., Nebr., reposited at Nebraska State Museum (figs. 16-18 from Galton and Jensen, 1978, with permission; fig. 19 from Barbour, 1931, with permission Nebr. St. Mus.). 16. lateral view, 17. medial view, 18. distal view, 19. posterior view (16-18 x 0.1; 19 x 0.065).
20	Marine reptile vertebra, side view, gravels near Cherokee, Pilot Twp., Cherokee Co., Ia., specimen at Sanford Museum, Cherokee, Ia. (x 0.35).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marls in central and western Kansas (e.g. Cope, 1875; Williston, 1898a, 1898b, 1898c, 1900; Stewart, 1900). Fish scales and bones are noted in the Niobrara of the study area (Bretz, this volume) and Leidy (1873, p. 279) described mosasaur teeth and a vertebra from probable Niobrara deposits near Santee, Nebraska (Plate 2, figure 11-13). Some exposures of Pierre Shale are noted in the western part of the study area where fish scales have been observed. Condra (1908, p. 16) notes shark teeth and mosasaur remains in the Pierre Shale of northeastern Nebraska, and chalky beds within the Pierre of Knox Co., Nebraska have yielded "72 vertebrae, the paddle bones, and pieces of ribs of a very large mosasaur" and "crocodile bones".

Minnesota

The deposition of Cretaceous sediments within the study area in southern Minnesota and adjacent parts of eastern South Dakota was greatly influenced by topographic features on the Precambrian surface, especially the Sioux Quartzite Ridge (Shurr, this volume). The sequence of Cretaceous formations and rock types noted in Iowa and Nebraska is modified in the Minnesota area by the onlap and offlap of Cretaceous marine and nearshore environments onto a predominant Precambrian terrane. During eustatic changes in sea level the marine Cretaceous units successively overlap the eastern shoreline areas and topographically higher regions probably achieving maximum inundation during the Niobrara transgression. Eastward in Minnesota the Cretaceous rocks include non-marine fluvial and lacustrine, coastal plain, and marine mudstone deposits assigned to the Windrow Formation (Sloan, 1964). The Windrow in southeastern Minnesota and northeastern Iowa is characterized by iron-rich rocks, including iron-cemented sandstones and conglomerates, possibly deposited in river channels. Cretaceous marine vertebrate fossils are noted at several localities in the soutern Minnesota area. The Milbank-Ortonville granite district of west-central Minnesota and adjacent northeastern South Dakota exposes a thin layer of reworked sediments, including conglomerates, sandstones, and shales, resting directly on Precambrian granites (Sloan, 1964, p. 15), in places with abundant vertebrate fossils; "shark's teeth and small teleost vertebrae are sufficiently abundant in some places . . . to make . . . up to about 5%" of the rock (Zangerl and Richardson, 1960, p. 8). Additionally, ichthyodectid fish, possible plesiosaur and mosasaur, and large marine turtle remains have also been noted (ibid.). The marine portion of the Windrow Formation in Brown Co., south-central Minnesota has yielded shark vertebrae in silty sandstones (Sloan, 1964, p. 22), and teleost fish, galeoid and heterodontoid shark, chimaera, and crocodile remains are noted in coarse-grained sandstones (Estes *in* Sloan, 1964, p. 25). The marine Cretaceous rocks in Brown Co. are apparently Niobrara correlates (Sloan, 1964). The easternmost occurrence of marine Cretaceous deposits known along the entire extent of the Interior Seaway is in Goodhue Co., southeastern Minnesota where a shark tooth was found in-place in a clay pit (Sloan, 1964, p. 19; Austin, 1972). Although outside of the study area, an abundant marine vertebrate fauna in the Coleraine Formation of northeastern Minnesota (Sloan, 1964; Erickson, 1970) is noteworthy because of close similarities with the vertebrate faunas of southern Minnesota and Iowa. At least one of the Late Cretaceous marine transgressions (especially Niobrara) onlapped in an easternly direction at least as far as southeastern and northeastern Minnesota, where outliers of marine Cretaceous rocks are still preserved.

Split Rock Creek, Pleistocene

Teleost fish scales are noted in Upper Cretaceous siliceous deposits of the Split Rock Creek Formation (probable Niobrara correlate) on the Sioux Quartzite Ridge in southeastern South Dakota (Ludvigson, et al., this volume). A variety of Cretaceous fossils have been recovered within Pleistocene glacial till and outwash and channel gravel deposits in Iowa, and their known distribution is illustrated in figure 1. White (1870, v. 1, p. 98; 1873; 1888), Wilson (1888), Keyes (1892), Udden (1899), and Tester (1927) reported Cretaceous fossils within the glacial drift at various locations across Iowa, and teleost fish bones/scales/teeth and shark teeth are noted. Cretaceous vertebrates have been encountered in Pleistocene and early post-Wisconsin gravels in western Iowa, and shark teeth (Plate 1, figures 25, 29, 31 and 32), fish vertebrae (Plate 1, figures 35-37), and marine reptile remains (Plate 2, figures 9, 10 and 20) are noted. Additionally, a marine reptile bone has been recovered from gravels in eastern Iowa (Plate 2, figures 14 and 15).

CONCLUDING REMARKS

Lower Dakota vertebrate fossils are rare, although noted dinosaur remains are compatible with previously inferred terrestrial-fluvial environments. Transitional marine environments represented in the upper Dakota Formation, including a complex of deltaic, interdistributary, and nearshore marine environments, were populated, in places, by a great abundance of teleost fish, and crocodiles are also noted. Fully marine offshore mudstone environments represented by the Graneros Shale preserved large marine reptiles (plesiosaurs, turtles) and a variety of teleost fish remains, including giant predatory ichthyodectids, which inhabited the surface waters. Fish-eating galeoid sharks, mollusk-eating ptychodontid sharks, and a variety and abunance of teleost fish characterize the pelagic vertebrate fauna of the Greenhorn chalks and marls. The marine vertebrate faunas of the Carlile, Niobrara, Pierre, and Windrow Formations in the study area are also predominated by teleosts and sharks, and marine reptiles are only rarely noted. The Graneros-Greenhorn shark and teleost fish fauna includes forms that compare closely with other known Late Cretaceous marine vertebrate faunas, especially the British chalks (Woodward, 1902-1912), Niobrara chalk of Kansas (Stewart, 1900; Williston, 1900), and Gulf Coast chalks (Applegate, 1970).

The Cretaceous was a time marked by tremendous evolutionary diversification of the teleost fish, and the new groups of teleosts and galeoid sharks assumed prominence as the most successful higher level trophic elements in the pelagic realm. The highest level marine predators in the Cretaceous seas, the mosasaurs and plesiosaurs, did not survive the end of the Cretaceous. The marine vertebrate faunas of all stratigraphic units considered in the study area reflect the great importance of teleost fish as pelagic elements in the Cretaceous Interior Seaway, and further studies and discoveries are needed to clarify the evolutionary and ecologic relationships of the abundant vertebrate animals that inhabited the eastern portion of that seaway.

ACKNOWLEDGMENTS

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Preliminary Observations on the Palynology of Upper Dakota Formation Lignites in Northwest Iowa and Northeast Nebraska

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The age of the Dakota Formation in its type area (northeast Nebraska and adjacent sections of South Dakota and Iowa) has been a matter of debate for many years. Examination of the palynomorphs from Dakota Formation lignites and lignitic shales in the area has proved to be a useful tool for biostratigraphic correlation. Several of these units, both in outcrop and from recent Iowa Geological Survey cores, have been processed for palynomorphs in conjunction with other studies of Dakota sediments. Certain samples, particularly lignites exposed at Sergeant Bluff and Stone Park near Sioux City, Iowa, yielded rich, diverse assemblages of spores and pollen. The present report represents an introductory note to a continuing formal study of Dakota Formation palynostratigraphy in the type region.

Early assessments of the age of the type Dakota were based on the study of plant fossils, especially dicotyledonous leaf compressions. These were interpreted as ranging from Triassic to Miocene in age, and controversy raged among numerous paleobotanists for several years until the Cretaceous age of the sediments was agreed upon in 1866 (Tester, 1931). Debate continued well into the 20th century on whether the Dakota should be considered Lower or Upper Cretaceous. Frequently the biostratigraphic comparisons were hampered by the use of fossils obtained from "Dakota" strata far removed from the type area. Among the more important assessments of the age of the Dakota were those of Berry (1920), who compared a "true Dakota" flora with that of the Woodbine Formation in Texas (now considered Cenomanian), and Lee (1927), who recognized strata spanning the Lower-Upper Cretaceous boundary in the "Dakota Group" of the Rocky Mountains.

Plate 1. Pollen and spores from the upper Dakota lignites

FIGURE

1. *Stereisporites antiquasporites* (Wilson and Webster) Dettmann 1963; Sergeant Bluff lignite, 575X.

2. *Gleicheniidites confossus* Hedlund 1966; Stone Park lignite, 575X.

3. *Appendicisporites auritus* Agasie 1969; Sergeant Bluff lignite, 330X.

4. *Trilobosporites purverulentus* (Verbitskaya) Dettmann 1963; Sergeant Bluff lignite. 575X.

5. *Perotrilites pannuceus* Brenner 1963; Sergeant Bluff lignite, 575X.

6. *Ephedripites ambiguus* Hedlund 1966; Sergeant Bluff lignite, 575X.

7. *Camarozonosporites dakotaensis* Agasie 1969; Sergeant Bluff lignite, 575X.

8. *Appendicisporites potomacensis* Brenner 1963; Stone Park lignite, scanning electron photomicrograph, 650X.

9. *Triporoletes laevigatus* (Pocock) Playford 1971; Sergeant Bluff lignite, scanning electron photomicrograph, 650X.

10. *Pinuspollenites* sp.; Sergeant Bluff lignite, 575X.

11. *Cicatricosisporites hallei* Delcourt and Sprumont 1955; Sergeant Bluff lignite, 575X.

12. *Appendicisporites tricornitatus* Weyland and Greifeld 1953; Stone Park lignite, scanning electron photomicrograph, 650X.

13. *Retitricolpites* sp.; Stone park lignite, 575X.

14. *Liliacidites dividuus* (Pierce) Brenner 1963; Sergeant Bluff lignite, 575X.

15. *Artiopollis indivisus* Agasie 1969; Sergeant Bluff lignite, 575X.

16. *Cicatricosisporites dorogensis* Potonie and Gelletich 1933; Sergeant Bluff lignite, 575X.

17. *Stephanocolpites tectorius* Hedlund 1966; Sergeant Bluff lignite, 575X.

18. *Balmeisporites glenelgensis* Cookson and Dettmann 1959; Sergeant Bluff lignite, 330X.

19. *Arcellites disciformis* Miner 1935; Sergeant Bluff lignite, 150X.

20. *Schizosporis reticulatus* Cookson and Dettmann 1959; Sergeant Bluff lignite, 330X.

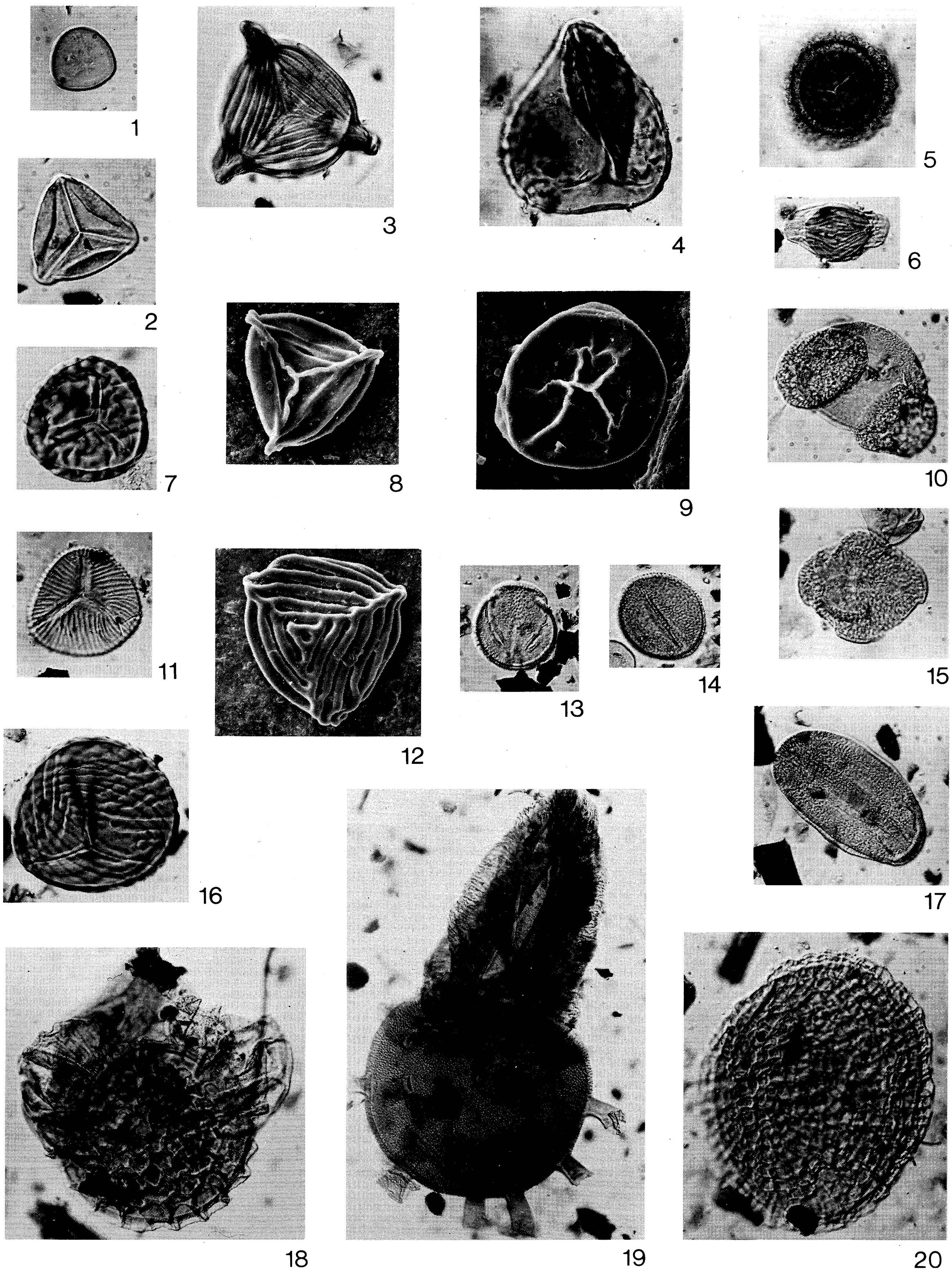

Plate 1. Pollen and spores from the upper Dakota lignites.

Schemel (1950) examined megaspores and other larger plant microfossils from a lignite exposed in Plymouth County, Iowa, but he did not describe microspores or pollen. Hall (1963) described megaspores and a few species of microspores from a lignitic clay exposed south of Sioux City. Hall suggested possible correlation of his clay zone with Schemel's lignite, but was uncertain. Both these units occur near the top of the Dakota in their respective areas, and they may correlate with either the Sergeant Bluff or Stone Park lignites. Of the samples examined in the present study, the Sergeant Bluff lignite produced the most diverse assemblage of palynomorph taxa useful for biostratigraphic comparison with previously published works. The miospore (less than 200 microns) size fraction of the palynological residue contained abundant numbers of numerous species of the striate fern-related genera *Appendicisporites* and *Cicatricosisporites*, which along with spores related to other ferns, lycopods and bryophytes, dominated the population. Typical of these spores are *Gleicheniidites* spp., *Cyathidites* spp., *Deltoidospora hallii* Miner 1935, *Osmundacites wellmanii* Couper 1953, *Camarozonosporites dakotaensis* Agasie 1969, *Lycopodiumsporites crassimacerius* Hedlund 1966, *Laevigatosporites ovatus* Wilson and Webster 1946, *Perotrilites pannuceus* Brenner 1963, *Verrucatosporites* spp., and *Stereisporites antiquasporites* (Wilson and Webster) Dettmann 1963.

Gymnospermous and angiospermous pollen grains were much less abundant than were the spores, but a considerable variety of pollen types were observed in the Sergeant Bluff lignite. Included among these were *Rugubivesiculites rugosus* Pierce 1961, *Phyllocladidites microreticulatus* Brenner 1963; *Pinuspollenites* spp., *Ephedripites virginiaensis* Brenner 1963; *E. ambiguus* Hedlund 1966, *Stephanocolpites tectorius* Hedlund 1966, *Liliacidites dividuus* (Pierce) Brenner 1963; *Monosulcites* spp., *Rousea georgensis* (Brenner) Dettmann 1973, *Artiopollis indivisus* Agasie 1969 and various *Tricolpites* spp.

The Sergeant Bluff lignite also yielded a variety of well preserved large palynomorphs, including the megaspores *Balmeisporites glenelgensis* Cookson and Dettmann 1959 and *Arcellites disciformis* Miner 1935, as well as the problematical palynomorphs *Schizosporis reticulatus* Cookson and Dettmann 1959 and *Schizophacus majusculus* (Hedlund) Pierce 1976.

The angiospermous pollen types present in the Sergeant Bluff and Stone Park lignites include only the more primitive monosulcate and tricolpate morphologies; more advanced tricolporate and triporate grains which are found in the upper Cenomanian and younger Cretaceous strata were not observed. Additionally, the rare presence of spores such as *Trilobosporites purverulentus* (Verbitskaya) Dettmann 1963 and *Triporoletes laevigatus* (Pocock) Playford 1971, reported by previous investigators from Albian and older strata, suggest an age for the lignites of lowermost Cenomanian. The most similar North American assemblages reported are those of Hedlund (1966) from the Cenomanian Woodbine Formation of Oklahoma and Agasie (1969) from Dakota strata in Arizona. As the Sergeant Bluff and Stone Park lignites (as well as the other lignitic zones investigated) occur near the top of the Dakota, significant possibility exists that lower portions of the Dakota may be pre-Cenomanian in age. Unfortunately, the sediments below the lignitic zones in the type area consist principally of sandstones from which no palynomorphs have yet been obtained.

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Geology of the Sioux Falls, South Dakota Area

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INTRODUCTION

The Sioux Falls, South Dakota area has held the interest of naturalists and geologists since the early 1800's because of the good exposures of Sioux Quartzite and associated rocks. This paper will develop the history of geologic work in the area and summarize the important aspects of the rock units and their geologic history.

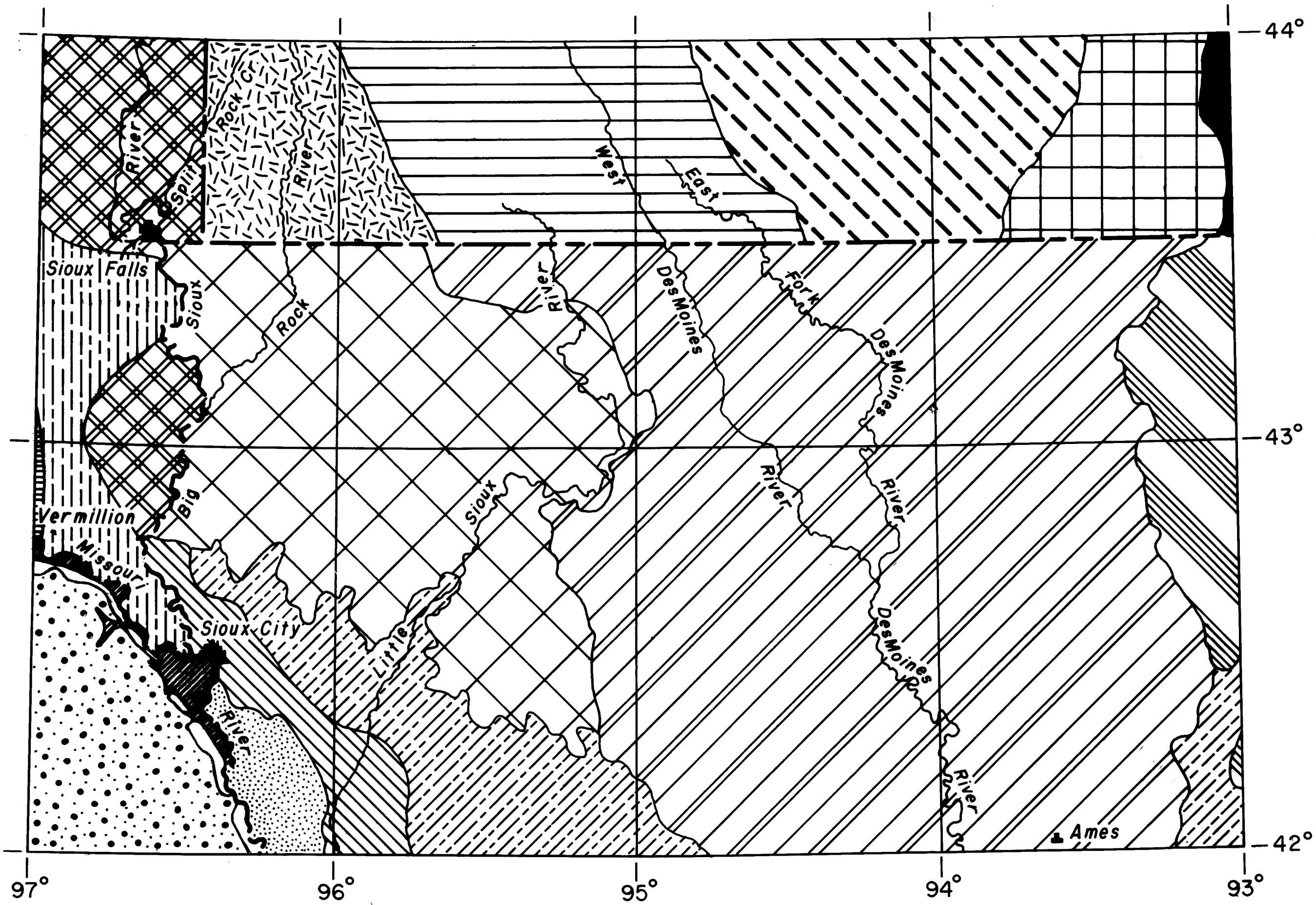
GEOGRAPHIC AND PHYSIOGRAPHIC SETTING

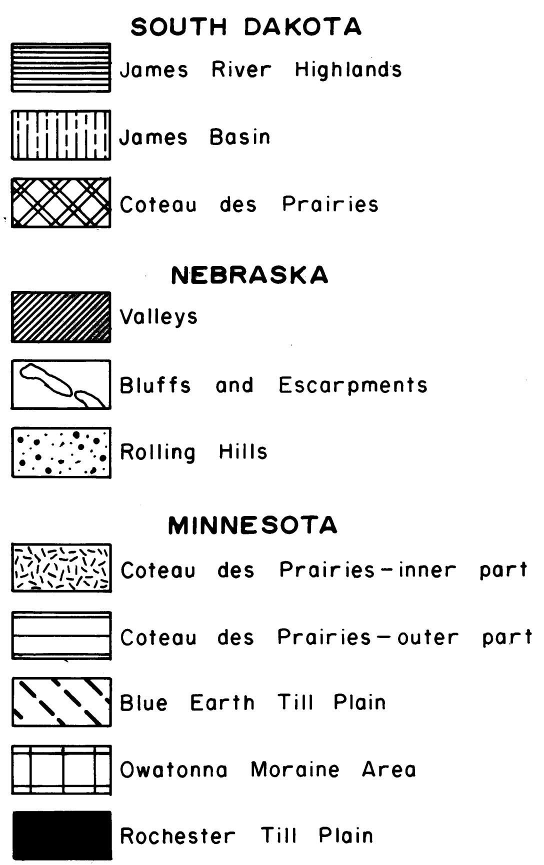
The Sioux Falls portion of the field trip occurs to the east and northeast of Sioux Falls, in the southeastern corner of Minnehaha County (figure 1). Sioux Falls, the largest city in the State (population approximately 100,000) is the county seat and is an important medical, agricultural, and business center.

The field trip area lies entirely in the Coteau des Prairies (Mountains of the Plains) Division of the Central Lowland Province (figure 1). The principal drainage is the Big Sioux River and its tributaries, which drain the Coteau des Prairies. The tributary of interest in the field trip area is Split Rock Creek. This creek, along with the Big Sioux River, is responsible for the outcrops to be investigated on this portion of the field trip.

The physiography of the area is largely the result of the actions of the Pleistocene ice sheets which invaded the area.

Split Rock Creek and Sioux Falls figure prominently in O. E. Rolvaag's classic on early pioneer life in South Dakota, GIANTS IN THE EARTH (1927, and various editions since).





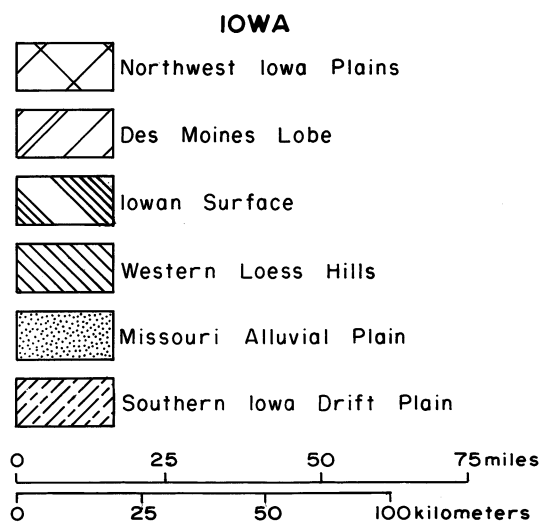


Figure 1. Major geographic and physiographic features of the field trip area (from Nebraska Conservation and Survey Division 1973; Prior, 1976; South Dakota Geological Survey, 1973; and Wright, 1972).

GEOLOGIC SETTING

The bedrock units, from oldest to youngest, that will be observed on this part of the trip are the Sioux Quartzite, the Cordon Diabase and associated Corson "slate," the newly named Split Rock Creek Formation (see Ludvigson et al., this volume) and the Pleistocene deposits.

Sioux Quartzite

Although a few white men had briefly mentioned and visited the Sioux Quartzite pipestone quarries (near modern day Pipestone, Minnesota) before him, George Catlin, the American artist who painted Indian life, was the first to bring the area to general attention. Catlin collected some of the pipestone and gave it to Dr. C. T. Jackson of Boston who studied it and named it catlinite in Catlin's honor (Jackson, 1839).

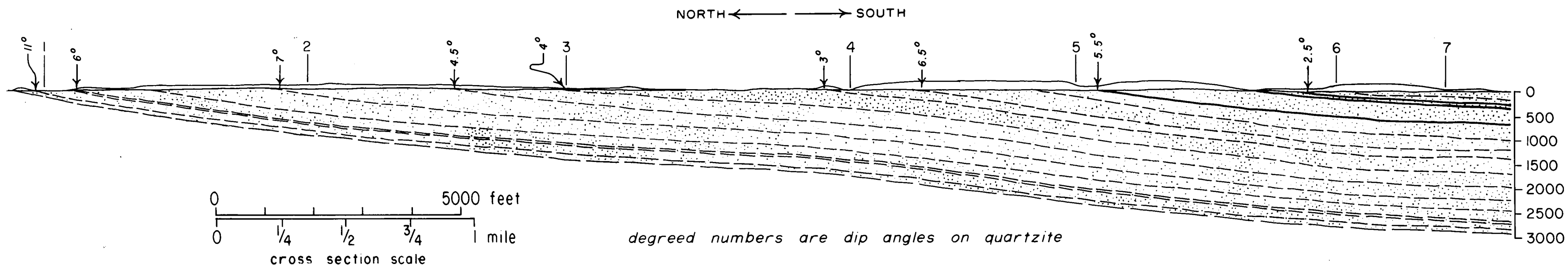
Less than two years after Catlin's first visit, Catlin's friend Joseph LaFramboise led the first truly scientific expedition to the pipestone quarry. This was the Nicollet-Fremont Expeditions of 1838 and 1839, which spent from June 30 - July 6, 1838 at the pipestone quarry. Although the pipestone was quarried and traded before this, it quickly became an important trade item with white men after this expedition and is still quarried for religious and commercial purposes to this day.

Archeological studies suggest that the first quarrying was done at Pipestone by people of the Oneota Aspect about 1600-1650 A.D. These people were later known as the Iowa and Oto tribes. The migration of the Sioux tribes into the area initiated the most widespread use of the catlinite (Murray, 1965, p. 11, 15, 17-18).

Recent interest has developed in the Sioux Quartzite as a uranium prospect, because of similarities to the Athabasca unconformity type uranium deposits in Canada, which have yielded some commercial uranium deposits. Several companies are developing exploration and leasing programs in eastern South Dakota with hopes of finding commercial deposits of uranium.

The Sioux Quartzite is an extremely well indurated, silica-cemented, fine to medium grained, usually pink sedimentary rock (orthoquartzite) which breaks across quartz grains. It contains minor beds of conglomerate and argillaceous materials, variously known as shale, pipestone, catlinite, mudstone and slate. The three conglomerate zones have coarse-grained particles up to 13 inches (33 cm) in diameter set in a quartz sand and gravel matrix. The larger particles consist of vein quartz, chert, jasper, cherty iron-formation, quartzite, mudstone and felsite. The fine-grained beds range from argillaceous quartzite, to nearly pure claystone. Sedimentary structures include ripple marks, torrential cross bedding, cut and fill stratification and mud cracks. The quartzite has been extensively fractured into joint sets near the surface because of a series of open folds. It forms a ridge running east-west from New Ulm, Minnesota to the Pierre, South Dakota areas variously known as the Sioux Ridge, Sioux Uplift, or Siouxia (part of the Transcontinental Arch).

Thickness estimates vary considerably but Baldwin (1950) measured about 2,700 feet (823 m) of section at Palisades (figure 2) and it was drilled for 3,797 feet (1,157 m) at an oil test near Wagner, South Dakota. Baldwin (1950)



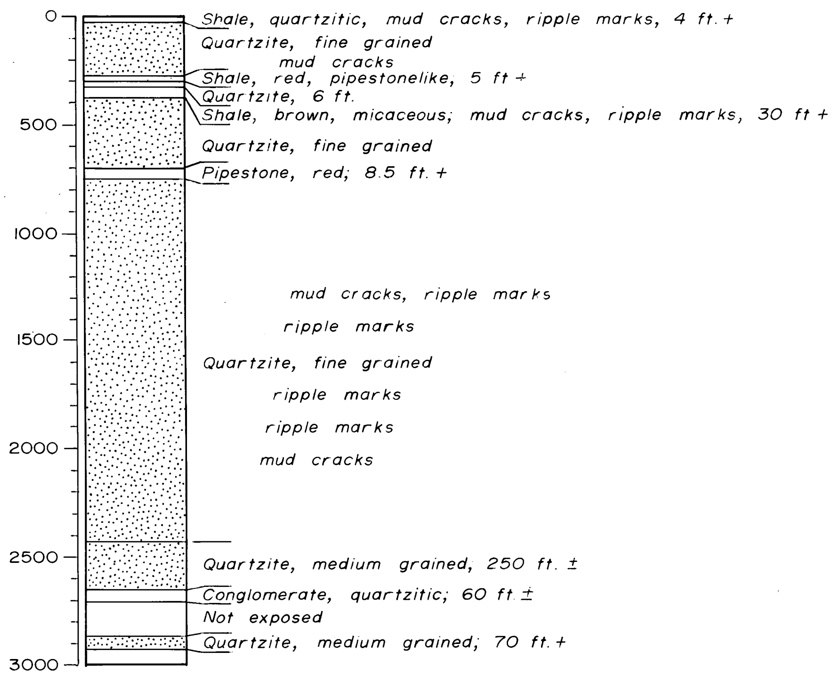
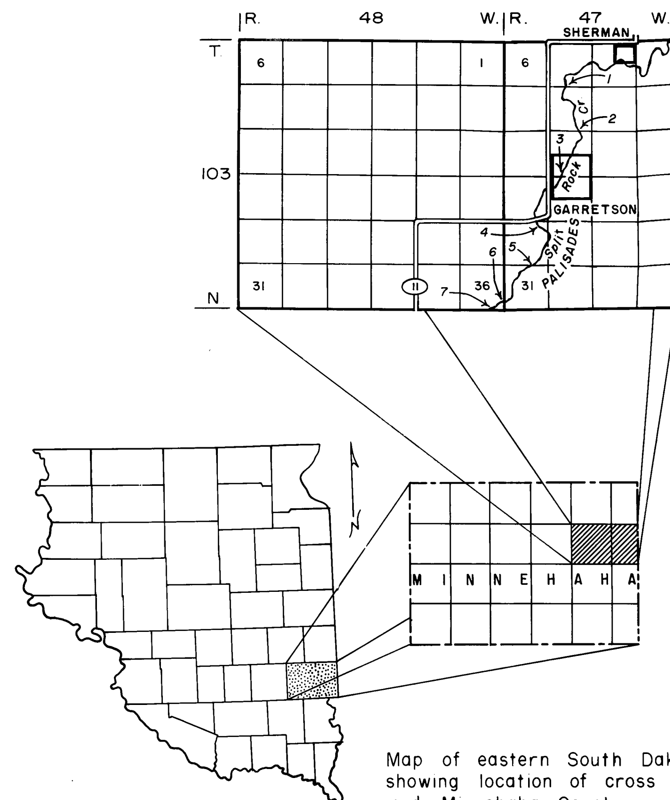


Figure 2. Generalized cross section and columnar section of the Sioux Quartzite in the Palisades State Park area at Stop 9 *(from Baldwin, 1949)*.



Map of eastern South Dakota showing location of cross section and Minnehaha County.

estimated a minimum thickness of 7,920 feet (2,414 m) for the quartzite in the Rock County, Minnesota structural basin. (For more detail, refer to Baldwin 1949, 1950 and Austin, 1972a).

The early expeditions and accounts were concerned mainly with geography and map making; geological observations were of minor importance, and attention to the Sioux Quartzite focused on the pipestone quarries. Today, the accounts are mostly of historical interest. Interested field trip participants are referred to Hayden, 1867; White, 1869; Winchell, 1884; p. 1-110; Murray, 1965; and Bray and Bray, 1976.

White (1870) named the Sioux Quartzite from exposures near the Big Sioux River in extreme northwestern Iowa and assigned it to the Azoic System and tentatively to the Huronian Group.

From 1872 to 1888, studies of the Sioux Quartzite were largely done by the Minnesota Geological and Natural History Survey (Winchell, 1872, 1878, 1882, 1884, 1885, and Upham, 1885, 1888) and by the U.S. Geological Survey (Irving and Van Hise, 1884; Irving, 1885); they were concerned primarily with basic field observations of the exposures, petrographic studies, economic uses of the rock, and structural and building properties. Winchell (1885) reported fossils from the unit at Pipestone, but now they are not considered to be organic remains.

Studies from the early 1890's to the late 1940's (Todd, 1894, 1900, 1903a,b; Keyes, 1895; Beyer, 1896; Hall, 1899; Wilder, 1899; Todd and Hall, 1903; Bendrat and Spencer, 1904; Sardeson, 1908; Darton, 1909; Van Hise and Leith, 1909; Rothrock and Newcomb, 1926; Lugn, 1934; Berg, 1937, 1938; Rothrock and Otton, 1947; and Baldwin, 1949) dealt with field observations and mapping, economic uses and properties, mineralogic and petrographic studies, and water resource capabilities. Beyer (1896) was the first to investigate in detail the quartzite and its relationships to the igneous and sedimentary rocks associated with it, which led him to assign the unit to the Huronian.

Berg's (1937, 1938) mineralogic, chemical and weathering study of the Sioux Quartzite near Pipestone reported sericite, pyrophyllite, diaspore, red hematite, specularite, pyrite and possible rutile from the catlinite beds and, in the quartzite beds, in addition to the above minerals, quartz, chalcedony and zircon. He mentioned three cementing material types: diaspore-quartz; diaspore-pyrophyllite-quartz; and phrophyllite-quartz.

Baldwin (1949) did a detailed stratigraphic and structural study of the Sioux Quartzite exposures at the Palisades (figure 2); this work was part of a larger study (Baldwin, 1950), which was the first to integrate regional stratigraphy and structure. Grout and others (1951) tentatively placed the Sioux Quartzite between the Animikie and Keweenawan in their stratigraphic study of the Minnesota Precambrian.

Barkley (1952, 1953), Flint (1955), Dienhart (1958), and Rothrock (1958) provided descriptions of the Sioux Quartzite in studies of water supplies, Pleistocene geology, and nuclear plant site geology and water supplies, respectively.

Goldich and others (1959) determined a K-Ar age on pipestone from the quarries at Pipestone. They obtained a minimum age (because of tectonic stresses) of 1.2 b.y. They suggested that the unit was deposited in post-Animikian time and that the date indicated deposition in Early or early Middle Keweenawan time. They felt that the tectonic features were developed during Duluth Gabbro emplacement.

Steece (1959a,b) mapped the Sioux Quartzite in the Hartford and Sioux Falls quadrangles and provided a brief description of the unit. Miller (1961) made a detailed study of the Sioux Quartzite in the New Ulm area. Steece (1964, 1975) summarized the important characteristics of the unit.

Goldich and others (1961) suggested that the Sioux Quartzite was deposited in Late Precambrian (Early Keweenawan) time, as a platform-type sedimentary sequence, on crystalline basement rocks which date back to the Penokean and Algoman orogenies. The 1.2 b.y. date they reported in 1959 probably indicates the time of folding and mild metamorphism of the unit. They consider the igneous dikes reported by Sardeson (1908), which cut the quartzite in the New Ulm area, to be Middle Keweenawan.

Goldich and others (1966) and Lidiak and others (1966), in their studies of geochronology in the midcontinent area, fit Sioux Quartzite deposition into the sequence of Precambrian events. They reiterated the 1.2-1.7 b.y. age for the deposition of the Sioux and tentatively considered it to be younger than the Iowa plutonic complex (> 1.3 b.y.) and older than Middle Keweenawan.

Austin (1970) determined the weathering characteristics and products of the quartzite and associated units near New Ulm and postulated that the quartzite had been subjected to humid, tropical, well drained conditions which led to formation of a regolith of loose sand and kaolinite (quartzite wash). In Lower Upper Cretaceous (Cenomanian) time, this climate was replaced by temperate, poorly drained conditions which led primarily to illite and montmorillonite formation. Triplehorn (1971) questioned some of the clay mineral-paleoclimate interpretations and Austin (1971) clarified these questions and suggestions.

Austin, Grant, Ikola and Sims (1970) provided an up-to-date map of the Sioux Quartzite area of Minnesota. Sims and Morey (1972) summarized the important aspects of the Sioux Quartzite.

Lidiak (1971) determined the Rb-Sr age on the rhyolites interbedded with Sioux Quartzite from a well at Hull, Iowa to be 1.4 ± 0.05 b.y. (minimum age because of slight alteration). He concurred that the quartzite was deposited between 1.2 and 1.7 b.y.

The most recent work on the Sioux Quartzite and associated rocks is a report by Stach (1970). He studied the mineralogy (using x-ray diffraction) of the Sioux Quartzite and the associated igneous and sedimentary rocks.

Igneous Rocks

There are several occurrences of igneous rocks intruded into the quartzite. We will see the Corson Diabase and its relationships to the Sioux Quartzite (Corson "slate") and Split Rock Creek Formation at the third stop on the second day of the field trip. These igneous rocks have permitted the fitting of the Sioux Quartzite into the Precambrian time system.

Corson Diabase and Corson "slate"

Culver and Hobbs (1892) were the first to report the existence of the Corson Diabase and they provided the first field relationships and petrography. Culver suggested the diabase was an island in the Sioux sea, rather than an intrusive body. Hobbs, in the petrographic study, showed that the rock was a coarse-grained olivine diabase containing feldspar (probably labradorite), augite, hornblende, biotite, ilmenite, apatite, chlorite and magnetite, and a little pyrite. Beyer (1896) presented a detailed study of the mineralogy, petrography and alteration products of the Corson Diabase, and its association with the Sioux Quartzite and Split Rock Creek Formation. He reported the rock to contain ophitic texture and to be totally holocrystalline. Minerals included are labradorite and oligoclase feldspars, altered to sericite or kaolin, chlorite and probably zoisite; augite, altered to amphibole, biotite, and a chlorite and actinolite aggregate; olivine, altered to a chloritic or serpentinous material with magnetite and hornblende grains and biotite; biotite altered to chlorite; hornblende; apatite; magnetite; and some ilmenite (?) and sphene. He also described the "slates" in the area, but his definition of the term included not only the contact metamorphosed Corson "slate", but also the argillaceous beds in the quartzite. Bendrat and Spencer (1904) reported a very hard bluish black "slate" 90 feet (27 m) thick at a depth of 45 feet (14 m) in a well southwest of Sioux Falls. Their description does not suggest it is an argillaceous bed in the quartzite, so it may represent contact metamorphosed "slate"; however, it is some distance from known occurrences of igneous rocks. Keyes (1914) named the olvine diabase in Split Rock Creek the Corson Diabase, and mentions the Corson "slate" outcrop. He also reported that a talc-chlorite schist was encountered at a depth of 10 feet (3 m) in a well in extreme NE¼ sec. 27, T. 101 N., R. 49 W. and suggested that it may be the altered product of a diabase. Stach (1970) did the first x-ray diffraction work on the Corson Diabase and Corson "slate" and their relationships to the Sioux Quartzite and Split Rock Creek Formation. He described the Corson "slate" as a dark-gray, spotted, slaty argillite that most likely resulted from contact metamorphism of argillaceous beds in the Sioux Quartzite. Mineralogy of the unit is mostly quartz and muscovite(?) with feldspar and hematite; weathering products are smectite and kaolinite.

The Corson Diabase, which is deeply weathered at most outcrops, has a near granular to ophitic texture. The fresh diabase is black with a greenish-yellow tinge and has moderately to severely altered plagioclase (An_{55}) and relatively unaltered olivine and augite. The reverse situation is found in the weathered diabase where the mafics decompose and the plagioclase is relatively unaffected and stands out in relief. Mineralogic changes by weathering include the development of free iron oxides, a very poorly ordered smectite, and kaolinite with scattered ilmenite(?) grains. Deep weathering forms a hard, red earthy mass; chemical changes include a 14 percent reduction in silica, a 14 percent increase in iron content, a titanium content increase, and a decrease in CaO, MgO, K_2O, and Na_2O. Stach (personal communication, 1980) reports that a *minimum* date of 1.1 b.y. was reported by Tom Durst (formerly of Case Western Reserve) on apatite from the Corson diabase; apatite was used as the diabase is too intensely weathered to obtain a Rb-Sr date.

Other Occurrences of Igneous Rocks

Beyer (1893) was the first to report on the igneous rocks encountered in the well at Hull, Iowa. He described the first petrographic study and gave the well log description. He described the rock as a quartz-porphyry; phenocrysts include orthoclase and quartz. The groundmass is aphanitic, composed of a devitrified glass, and contains very small iron oxide particles. He suggested these igneous rocks could have formed in two ways, from Paleozoic (possibly Carboniferous) lava flows erupting on the sea bottom, or from Post-Carboniferous intrusives (sills). He preferred the latter case and based his Paleozoic age estimate on the presence of the sandstone in the well. Keyes (1893) described the Hull well igneous rock as a quartz-porphyry, with a micrograniti c ground mass with large clear crystals of quartz and feldspar scattered throughout. Wilder (1899) also presented the log of the Hull well. Quartz porphyry was first encountered at a depth of 755 feet (230 m). Six of these layers were encountered from a depth of 755 to 1220 feet (230 to 372 m), interbedded with Sioux Quartzite. Norton (1912) and Lugn (1934) also described this occurrence. Lidiak (1971) dated the quartz-porphyry (rhyolite) from the well at Hull, Iowa at 1.47 ± 0.05 b.y. Today, there is disagreement as to whether these layers are sills or flows, and the number of layers.

Todd (1903a) reported igneous rocks from a well at Alexandria, South Dakota. Todd and Hall (1903) report diabase from a depth of 506 feet (154 m) in a well in SW¼ sec. 25, T. 104 N., R. 59 W. and at 512 feet (156 m) in NW¼ of the same section in northwestern Hanson County, South Dakota. Todd (1904) described an igneous rock exposure in the SW¼ NW¼ sec. 11, T. 101 N., R. 49 W. He sent specimens to his colleagues Merrill and Wilson. Merrill and Todd considered it to be a gabbro, while Wilson considered it to be a diabase. They all agreed that it contained plagioclase, augite, and magnetite. Merrill also reported biotite, titanic iron and apatite. This occurrence was exposed in a quartzite quarry and is not visible today because of siltation and flooding. Todd also reported a green "eruptive" rock 49 feet (15 m) thick at a depth of 880 feet (268 m) in a well near Yankton and an olivine diabase at a depth of 500 feet (152 m) in a well near Dover, South Dakota.

Darton (1909) mentioned dikes in the vicinity of the Dells and near Garretson; igneous masses were reported in a well in southwestern Minnesota and possibly in a well in north-central Hanson County, South Dakota. Baldwin (1950) summarized the Corson Diabase, Todd's (1904) Sioux Falls gabbro, and Sardeson's (1908) New Ulm granite occurrences in relation to the Sioux Quartzite. Barkley (1952, 1953) mentioned several occurrences of granite in wells in the area of the Sioux Quartzite ridge and concluded these occurrences may represent dikes intruded into the quartzite, with the quartzite underlain by granitic basement. Some of these granite occurrences are believed to be erosional windows in the quartzite.

Split Rock Creek Formation

The sediments comprising this unit are the focus of this field trip because they constitute an enigmatic unit. The time and rock stratigraphic relationships are presently being studied (see Ludvigson, et. al., this volume). The unit is post diabase-pre-Pleistocene and has decidedly Western Interior

Cretaceous characteristics. Upham (1885) was the first to mention these beds. He reported two occurrences of "chalk rock". The first is undoubtedly a weathered argillaceous bed in the quartzite; the second is probably exposures of the Split Rock Creek rocks, which are at least eight feet (2.44 m) thick. He tentatively assigned to this unit a Cretaceous age. Bain (1895) reported 15 feet (4.57 m) of Niobrara Formation overlying the quartzite near Carson [sic], S.D.; these beds most certainly represent the Split Rock Creek Formation. Beyer (1896) described these rocks at several points along Split Rock Creek. He described the "chalk rock" as a dirty gray color when fresh but which whitens on weathering; it has a porous nature, contains cherty concretions, and is thin bedded where bedding has not been obscured by weathering. He considered it to belong to the Niobrara Formation as did Todd (1899) and Darton (1909). Rothrock and Newcomb (1926) provided the first detailed work on the unit. They gave locations for two outcrops of "chalk", one in the NE¼ sec. 22, T. 102 N., R. 48 W., and the other in the center, sec. 26, T. 102 N., R. 48 W. The first is a maximum of 15 feet (4.57 m) thick and outcrops for about 500 feet (152.4 m) along Split Rock Creek. They provided a measured section at the second outcrop (p. 12-13).

> "4 feet (1.22 m) Chert zone. Color gray to tan, prevailing color yellow. All calcareous matter has been replaced by chert or removed, leaving holes an inch or less in diameter and giving the rock a spongy appearance. Chert between the holes is very dense, having an opal-like appearance. The contact of this zone with that underlying forms a sharp line.
>
> ****
>
> 4 feet (1.22 m) "Chalky" rock. Light gray when fresh, weathers to white. Very porous, but pores very small. Scattered pipes of chert through it, more abundant in the upper six inches than farther down."

They also provided a chemical analysis of the rock and demonstrated that it is not Niobrara. The analysis showed (Rothrock and Newcomb, 1926, p. 13) that the values for the Niobrara chalk at Yankton and the Corson "chalk" are respectively: SiO_2, 6.22% and 80.5%; Al_2O_3, 3.56% and 6.56%; CaO, 48.25% and ?; MgO, 2.00% and ?; and CO_2, 36.23% and 0.0009%. Since there were no fossils found with which to correlate with other sedimentary units, they did not assign an age or rock unit relationship. Baldwin (1949) noted three lithologies in the Split Rock Creek, a light gray semi-plastic gritty clay with occasional iron-stained and black patches, a gray clay, and a white, siliceous, chalky-looking rock. From microscopic examination Baldwin interpreted this "chalk" to be a volcanic ash, which has a cherty zone in several outcrops. The chert is a compact, structureless, hard, light gray to white rock, marked by small holes and pits; its field relationships suggest it is a weathering product of the ash. Baldwin (1950) reported woody plant fragments, sponge spicules and possible Radiolaria in the Split Rock Creek; he considered it to be of possible Cenozoic age. Flint (1955) tentatively correlated the Split Rock Creek with the Tertiary Ogallala Formation. Dienhart (1958), in his Pathfinder power plant site report, gave the results of core hole and water well logs in the area. He classified the Split Rock Creek into shales and slates of Cretaceous age, which are called "black granite" or "black rock" by the local well drillers, and into sandstone, some of which is probably rocks of the Split Rock Creek and some of which is quartzite wash.

Rothrock (1958), in a study of the geology and water supplies in the vicinity of the Pathfinder steam plant, informally called these rocks the Pathfinder Formation and subdivided it into the Upper Clay Member, the Black Rock Member, and the Lower Clay Member, all of Cretaceous(?) age. The upper member is about 30 feet (9.14 m) thick and is a smooth greasy clay, which is bright yellow at the top, apparently because of weathering, with a very dark gray below this. The Black Rock Member is a series of shelly sandstones, limestones, and siltstones with clay partings; the black color is derived from carbonaceous matter. A maximum thickness of 56 feet (17.07 m) was reported from one of the core sites at the power plant. The upper part of the member was described as thinly bedded quartzite sandstone separated by thinly bedded black shale. Beneath this, porous sandstones and siltstones are the predominant rock types. The lower third of the member consists of sands and sandy clays, which grade into the Lower Clay Member. In core hole number one, he noted that three limestones were encountered, one near the top, and two in the lower third of the member; the upper one contains fish bones and the lower two are very sandy. The mottled bluish gray siltstones interbedded with the limestones in the member are of interest because of the fossils they contain; these have been identified as sponge spicules, tiny gastropods, and radiolarians. However, Rothrock concluded that the fossils are tetractinellid sponge spicules.

The Lower Clay Member is dark gray, very sandy in its upper portion, not as plastic as the Upper Clay Member, and has rather inconspicuous bedding. Rothrock (1958) tentatively assigned a Cretaceous age to the Pathfinder Formation (Split Rock Creek) and provided a geologic cross section of the Big Sioux Valley at the Pathfinder plant site and columnar sections of the Pathfinder from core holes and test wells.

Steece (1959b) mapped two exposures on the Sioux Falls quadrangle and considered the Split Rock Creek as Cretaceous(?) and Tertiary(?) rocks. He reported Cretaceous(?) foraminifera from a brown clay 20 feet (6.1 m) thick in a test hole in SW¼, SE¼, sec. 30, T. 102 N., R. 48 W. He noted that Rothrock (1958) and Baldwin (1949) report sponge spicules and Radiolaria, respectively, from this unit. Steece (1959b) tentatively referred to the Tertiary a two to six feet (0.61 to 1.83 m) thick weathered medium- to coarse-grained, noncalcareous, yellow sandstone containing pink grains of quartz and feldspar; it overlies weathered diabase and is overlain by two to four feet (0.61 to 1.22 m) of white compact flaggy volcanic ash(?).

Stach (1970) also studied the Split Rock Creek Formation. He tentatively correlates three feet (0.91 m) of clay in NW¼, NW¼, NW¼, SE¼, sec. 26. T. 102 N., R. 49 W. with the Upper Clay Member and describes it as a noncalcareous medium to dark gray clay, composed of well ordered smectite with no kaolinite or illite.

The Black Rock Member, which Stach calls the ash unit, is described by him as a very low density, "flaggy," moderately indurated unit. It is dark gray with thin lamellae of light gray sand when fresh, and weathers to a light gray. The weathered zone is one to three feet (0.30 to 0.91 m) thick and contains abundant chert nodules. The unit also contains a four to six inch (10 to 15 cm) thick bentonite, which is composed of extremely well ordered calcium-smectite. The ash bed is composed of amorphous material, quartz, and cristobalite with traces of clinoptilolite-heulandite and poorly ordered smectite. He notes remains of fish bones, bivalve molds(?) and a crustacean carapace(?) from this member.

The ash bed is underlain by silts and silty clays, also of the Black Rock Member, which are composed of quartz with varying amounts of opal-cristobalite and clinoptilolite-heulandite. Some samples are composed of nearly pure opal-cristobalite or clinoptilolite-heulandite, while other samples contain only minor amounts of these constituents. The clay fraction of this unit is usually poorly ordered smectite.

The Black Rock Member is underlain by reddish-brown and purple, loosely consolidated, fine to medium grained sandstones. The reddish-brown sandstone has fragments of weathered "slate" and highly weathered Sioux Quartzite. The clay fraction consists of poorly ordered smectite with minor amounts of clinoptilolite-heulandite; the clay fraction of the purple sandstone contains well ordered smectite with minor amounts of illite and clinoptilolite-heulandite. Both sandstones have a very heavy mineral fraction dominated by ilmenite, which is probably derived from the weathered diabase. The silts, silty clays, and sandstones possibly are units in the quartzite wash, which is a weathering deposit developed on the Sioux Quartzite (see the diamictite description in Ludvigson, et. al., this volume). The most recent work, which defines these rocks as the Split Rock Creek Formation is in Ludvigson, and others, in this volume.

PLEISTOCENE DEPOSITS

(by Merlin J. Tipton)

The drift in the Sioux Falls area has been mapped in the past as Kansan, Iowan, and Illinoian.

Leverett (1932) classified the drift in the interlobate area between the James and Des Moines lobes as Kansan. Flint (1955) reclassified Leverett's Kansan drift as Iowan based on the work of Smith and Riecken (1947).

Tipton (1958, 1959, 1960) and Steece and others (1960) found this Iowan drift south of Dell Rapids to be older than the Iowan drift north of the Dell Rapids area and reclassified this older drift in the area from Dell Rapids to Sioux City, Iowa as Illinoian. This was based on several lines of evidence, one of them being that the drift overlay the Pearlette ash at the Hartford site on Skunk Creek west of Sioux Falls. Two tills underlay the ash and were classified as Kansan and Nebraskan.

Boellstorff (1978) has dated the ash at Hartford as 0.7 m.y. and shown the three tills at Hartford to be the youngest three of six Pre-Wisconsinan tills. Boellstorff (1978) has also shown by fission-track dating that there are four "Pearlette" ashes dating 0.6, 0.7, 1.2 and 2.2 m.y. This will necessitate a reclassification of the Pre-Wisconsinan tills. The drift in the interlobate area north of Dell Rapids has been classified as Early Wisconsin by the South Dakota Geological Survey (1971). This infers the drift is something older than 20,000 y.b.p. and younger than 70,000 y.b.p. This 1971 map (figure 3) shows the Bemis moraine to be the oldest of the late Wisconsin events to occur in this area. From radiocarbon dates the Bemis moraine accumulated at about 14,000 y.b.p. The Altamont moraine accumulated about 12,500 y.b.p.

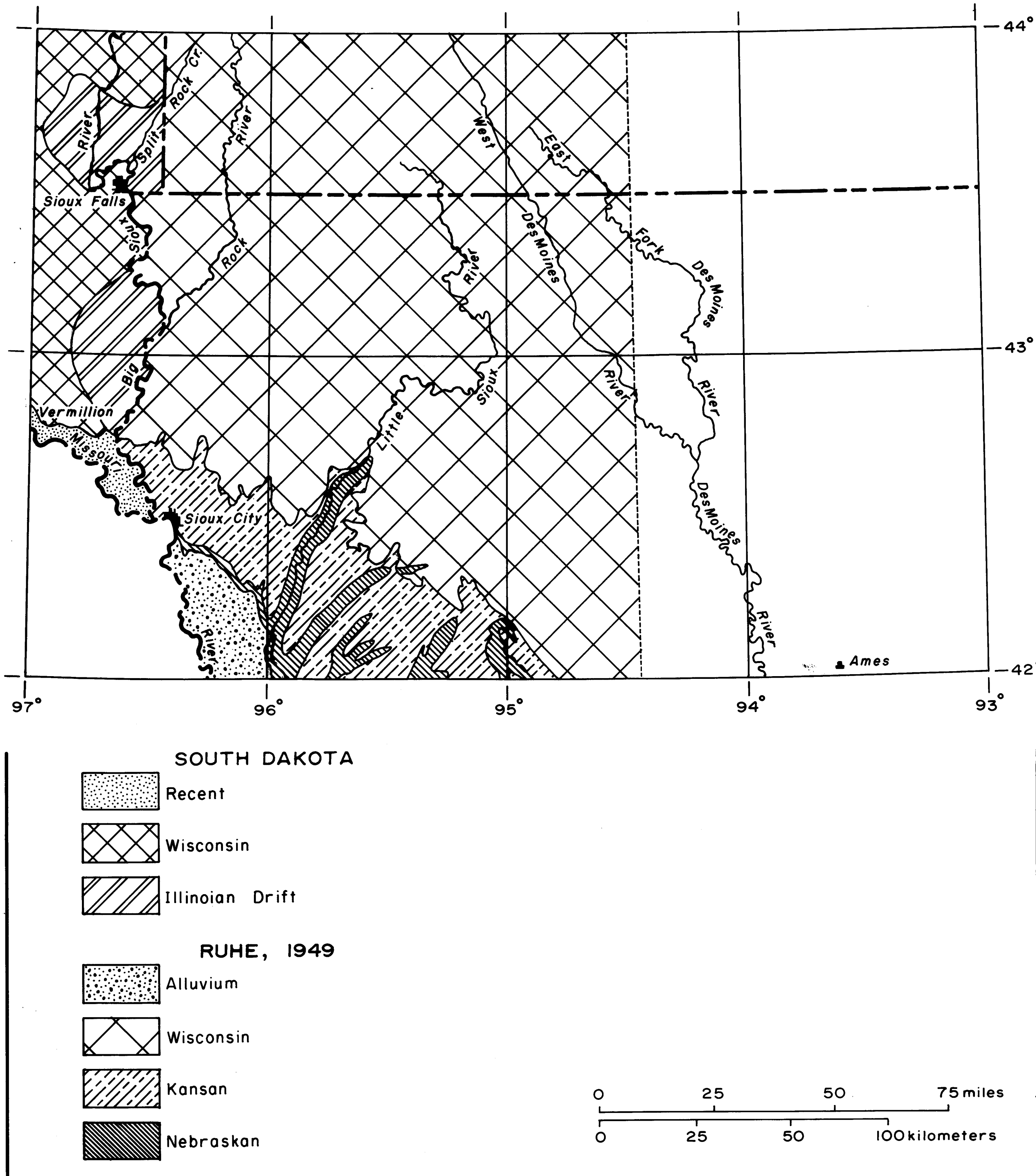


Figure 3. Generalized glacial map of the field trip area. *(from South Dakota Geological Survey, 1971; and Ruhe, 1949).*

These late Wisconsin tills have only scattered patches of loess on their surfaces but the older early Wisconsin and Pre-Wisconsin tills have continuous covers. The early Wisconsin tills north of the Dell Rapids area have a six- to eight-foot (1.83 to 2.44 m) cover of loess and the "Illinoian" tills to the south of the Dell Rapids area have more. In the area around Sioux Falls the loess on this Illinoian till is 12 to 15 feet (3.66 to 4.57 m) thick. To the south it becomes increasingly thicker, reaching a maximum in the Sioux City area where thicknesses of up to 100 feet (30.48 m) have been recorded.

GEOLOGIC HISTORY

The geologic history of this area extends back to Early Precambrian time, since it is on the Canadian Shield. Rocks of the Superior province (2.5 b.y. old or older) occur in northeastern South Dakota and in the Black Hills region and were affected by the widespread Algoman orogeny approximately 2.5 b.y. ago. There is disagreement as to whether these rocks of the Lake Superior area and in the Black Hills-Wyoming area were continuous across South Dakota. Differing interpretations of gravity and magnetic trends and basement rock samples have led to differing positions for the Superior, Churchill, and Peace River province boundaries within the State (e.g., Goldich and others, 1966; Muehlberger and others, 1967; Lidiak, 1971; Sims and Morey, 1972; and Schoon and McGregor, 1974). Subsequent tectonic and plutonic events have masked and/or altered the Early Precambrian rocks so that only with further samples and work will the disagreements be resolved.

Events recorded in the area in Middle Precambrian time (1.7-2.5 b.y. ago) were the deformation and consolidation of Middle Precambrian sedimentary rocks by the Penokean and Black Hills orogenies 1.6-1.8 b.y. ago (Goldich and others, 1966; Muehlberger and others, 1967).

Subsequent events in Late Precambrian time in the area include igneous activity in east-central South Dakota (1.6 b.y. ago; Goldich and others, 1966); granitic emplacement in south-central South Dakota and north-central Nebraska in the 1.43-1.49 b.y. range (Goldich and others, 1966); possible orogenic events at approximately 1.35 b.y. (Muehlberger and others, 1967); emplacement of gabbroic rocks in the plutonic complex (of Penokean origin) of northwestern Iowa at 1.3 b.y. or before (Lidiak and others, 1966); and deposition of the Sioux Quartzite between 1.2-1.7 b.y. ago. Lidiak (1971) dated rhyolite interbedded with quartz sandstone at Hull, Iowa at 1.47 b.y. and suggested the Sioux Quartzite is at least this old. The last major event of Precambrian time is the Keweenawan igneous activity at about 1.1 b.y., which manifests itself as the present day Midcontinent Gravity Anomaly. An unpublished minimum date of 1.1 b.y. was obtained on the Corson Diabase intrusive by Tom Durst and suggests that some Keweenawan activity may have extended beyond the main belt.

Paleozoic, and to a lesser extent Mesozoic, paleogeographic and sedimentation patterns in the area were controlled by the Transcontinental Arch, which separated the Williston and Forest City Basins from each other (see papers by Shurr, and by Bunker, this volume). Only during maximum transgressions did the highest portions of the arch become submerged and, even then, they were probably shoal areas with varying numbers of islands. Subsequent regressions eroded the transgressive deposits from the high areas of the arch. For a period by period analysis of Paleozoic, Mesozoic, and Cenozoic paleogeographic patterns, see the Rocky Mountain Association of Geologists Geologic Atlas of the Rocky Mountain Region (Mallory, 1972) and the references therein. (See also Bunker, this volume).

In general, major transgressions flooded the arch during the Early Paleozoic. By Late Paleozoic time (Pennsylvanian-Permian) and until Late Cretaceous time, the field trip area was generally an emergent area. Early Cretaceous residual deposits are known from the area (Austin, 1972b; Parham, 1972; Sloan, 1964).

In Late Cretaceous time, the Western Interior sea transgressed into the area, but the Transcontinental Arch and Sioux Ridge still locally controlled sedimentation (see Reeside, 1957; Weimer, 1978; and Shurr, this volume).

The area was largely positive and erosional during Cenozoic time except during the Pleistocene, when the Laurentide ice sheets deposited drift.

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CRETACEOUS STRATIGRAPHY AND SEDIMENTATION IN N.W. IOWA, N.E. NEBRASKA AND S.E. SOUTH DAKOTA

ROAD LOG AND STOP DESCRIPTIONS

R.L. Brenner[1], R.F. Bretz[3], B.J. Bunker[2], D.L. Iles[3],
G.A. Ludvigson[2], R.M. McKay[2], D.L. Whitley[1], and B. J. Witzke[2]

LOG - DAY 1

Mileage (Kilometers)	
0.0 (0.0)	Leave parking lot of Rodeway Inn, Sioux City, Iowa at 8:00 A.M.
0.2 (0.3)	Turn onto I-29 North (a detour) and drive to 1st Avenue Bridge.
1.1 (1.8)	Cross Missouri River into Nebraska, continue South on U.S. 77.
1.9 (3.1)	Junction of U.S. 77 and U.S. 20 in South Sioux City, Nebraska, continue on U.S. 77 (bear right).
10.1 (16.3)	Homer, Nebraska; turn left off U.S. 77 on to gravel road. Road traverses along the western edge of the Missouri River flood plain. Ridge to the right is held up by Cretaceous Greenhorn Limestone and capped with Pleistocene glacial sediments.
12.7 (20.4)	Turn right at cross-roads (towards Scout Camp) drive 1.1 miles (1.8 km) and park.

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13.8 (22.2) — STOP 1; J.B. Hoyt Gravestone section is located 0.3 miles (0.5 km) to the right down a dirt road in a farm house yard. Section consists of uppermost part of Dakota Fm, the Graneros, and the base of Greenhorn Fm. This stop is in the type area of the Dakota Formation.

17.5 (28.2) — Retrace route back to Homer, turn left on to U.S. 77, and then make the first right turn (onto John Street) in Homer, Nebraska. Continue to end of John Street and turn right on 5th Street onto athletic field.

18.0 (29.0) — STOP 2; Homer Athletic Field section. Sedimentary structures in the upper part of the Dakota Fm.

18.4 (29.6) — Return to U.S. 77 and turn left.

27.8 (44.7) — Junction of U.S. 77 and I-129; turn right (east) on I-129; cross Missouri River back into Iowa.

31.0 (49.9) — Junction of I-129 and I-29, turn right (south) on I-29.

34.9 (56.1) — Turn right on 8th Avenue, drive north to Ballou Tile and Brick Company Quarry.

35.6 (57.2) — STOP 3; Sargent Bluff Section. Turn into employee parking lot of Ballou Tile and Brick Company Quarry, park vehicle and walk 0.2 miles (0.2 km) into quarry. Dakota Formation mudrocks (basal portion of exposure) and sandstones (upper part) are exposed on quarry wall. This is the most extensive continuous exposure from which lateral and vertical sequences of lithologies and sedimentary structures can be observed. In addition plant fossils and pyrite concretions are abundant locally. Leave "quarry" turning left (south).

35.9 (57.7) — Turn right on 1st Avenue and return to I-29.

36.4 (58.6) — Turn right (north) on I-29.

46.1 (74.2) — Exit I-29 at Riverside-Rt. 12 Exit; proceed north on Rt. 12 through Riverside. Dakota sandstone poorly exposed in bluffs on right side of road.

48.5 (78.0)	Cross R.R. track, continue north on Rt. 12. Pit to right has good exposures of fossiliferous Greenhorn, Graneros and transition rocks into the Dakota, however it may not be accessible at time of trip. Nearly continuous outcrop of Dakota Sandstone on right side of road for next 15 miles (24 km).
50.0 (80.5)	STOP 4; Stone Park Section. Turn right through park entrance and proceed 0.3 miles (0.5 km) to Dakota Valley Picnic Area where LUNCH will be served. Outcrops of Dakota through Greenhorn formations are accessible south of park entrance on right (east) side of Rt. 12 and on the east side of the picnic ground.
50.6 (81.4)	Leave Stone Park turning right (north) on Rt. 12 Greenhorn Fm. holds up ridge on right side of road.
51.4 (82.7)	Partial skeleton of a marine reptile was excavated from the Graneros Shale near the farm to the right in the 1880's or early 1890's. It is now in the Sioux City Museum.
56.0 (90.1)	STOP 5; K-18 section on right side of road. Exposure of Dakota through Greenhorn, a good place to view the details of the Graneros-Greenhorn contact. Continue north on Rt. 12.
59.7 (96.1)	Relief on Cretaceous-Pleistocene contact on right side of road.
72.9 (117.3)	Akron, Iowa; continue north on Rt. 12.
79.7 (128.2)	Chatsworth, Iowa; continue north on Rt. 12.
82.1 (132.1)	STOP 6; Scotts Bottom Section. Carlile shale with secondary gypsum crystals found on exposed surfaces.
85.4 (137.4)	Hawarden, Iowa; continue north on Rt. 12.
85.9 (138.2)	Junction of Rt. 12 and 10; bear left (north) on Rt. 10.
89.7 (144.3)	Cross bridge over Big Sioux River into South Dakota; continue on Rt. 10.
91.7 (147.5)	Junction with Rt. 46, bear left (west) on Rt. 46 west.

99.0 (159.3)	Junction of Rt. 46 and Lincoln Co. road 131, turn right (north) on Co. road 131.
114.2 (183.7)	Junction of 131 and U.S. 18, turn right (east) on U.S. 18.
115.2 (185.4)	Turn left (north) on West Street (gravel road) on west edge of Canton, South Dakota.
117.2 (188.6)	Turn left (west) on gravel road.
118.5 (190.7)	STOP 7; outcrop of Niobrara calcareous shale in cutbank of Beaver Creek. Continue west on gravel road.
119.2 (191.8)	Turn left (south) on Rt. 11 (paved).
121.3 (195.2)	Junction with U.S. 18, turn right (west).
129.3 (208.0)	Junction with I-29, turn right (north) on I-29.
137.8 (221.7)	Junction with I-229, continue on I-29 north.
143.8 (231.4)	Exit 81 (South Dakota, Rt. 38) - Russell St. - Airport Exit - Exit I-29 turn right onto South Dakota 38 and Russell Street.
145.7 (234.4)	Turn right into Holiday Inn parking lot. End of Day 1.

LOG - DAY 2

Mileage (Kilometers)	
0.0 (0.0)	Leave Holiday Inn parking lot at 8:00 A.M.; proceed east on Russell Street.
0.4 (0.6)	Turn left (north) on Minnesota Avenue.
3.0 (4.8)	Turn right (east) on South Dakota 38A.

3.9 (6.3)	Turn left (north) on U.S. 77.
4.2 (6.8)	Turn on to I-90 east.
4.7 (7.6)	STOP 8; I-90 section. Outcrop of upper portion of Split Rock Creek Formation on the south side of road along Split Rock Creek. Continue east on I-90.
8.2 (13.2)	Exit 410; leave I-90, turn left (north) onto County Road
14.0 (22.5)	Turn left (west) onto gravel road.
15.0 (24.1)	Turn left (south), following signs to State Park.
15.1 (24.3)	Turn right onto blacktop road into Palisades State Park.
15.6 (25.1)	STOP 9; King Rock-Palisades State Park - high on the Sioux Quartzite Ridge.
16.6 (26.7)	Leave Park, turn left on gravel road.
17.8 (28.6)	Turn left; continue to Stop sign
18.0 (29.0)	Turn left onto South Dakota 11 (blacktop).
20.7 (33.3)	Junction, bear left and continue south on Rt. 11.
25.9 (41.7)	Turn right (west) onto gravel road.
26.3 (42.3)	STOP 10; Risty and Rovang Farm sections - Corson diabase and Precambrian argillite underlying Split Rock Creek Fm. diamictite and opaline spiculite. Turn around.
26.8 (43.1)	Return to Rt. 11 and turn right (south).
28.3 (45.5)	Turn right (west) onto I-90, return to Sioux Falls, South Dakota.
38.5 (62.0)	Junction of I-90 and I-29; turn south on I-29 and return to Sioux City, Iowa. Field trip ends in the parking lot of the Rodeway Inn.

END OF LOG

STOP DESCRIPTIONS

Figure 1 shows the approximate locations of each stop.

Stop 1. J.B. Hoyt Gravestone section: type area of the Dakota Formation (by B.J. Witzke and G.A. Ludvigson)

Meek and Hayden (1862, p. 419, 420) named the "Dakota Group" after the "hills back of the town of Dakota; also extensively developed in the surrounding country in Dakota county (Nebraska) below the mouth of Big Sioux River" where the "rock consists mainly of yellowish and reddish sandstones, in rather thick beds, interstratified, in places, with beds of yellow and ash-colored clays, and impure lignites." Stops 1 and 2 characterize the type area of the Dakota Formation, although no specific type locality has ever been designated. Stop 1, named after the solitary gravestone above the measured section, is on the property of Paul O'Connor, whose cooperation is acknowledged. This natural exposure of the upper Dakota is graphically illustrated in figure 2. The lower part of the exposed interval (figure 3) includes medium to dark gray mudstones with silt laminae and lenses of very fine grained sandstone and siltstone, and ironstone nodules; scattered to abundant plant debris is present. The overlying sandstone interval was noted by Tester (1931, p. 249) at this locality, although at that time the mudstones apparently were not exposed. The sandstones are predominantly very fine to fine grained, well-sorted, micaceous, and very platykurtic (Bowe, 1972). Friable, iron-cemented, and calcite-cemented zones are observed. Thin cross-bedded zones are present (Tester, 1931). Bowe (1972) analyzed the crossbed orientations at Stop 1, and calculated a mean azimuth of 280°, or approximately an east to west flow direction. A lens of calcite-grapeshot-cemented sandstone is present near the base of the overlying mudstone interval. Above the sandstones is a gray mudstone, mottled or interbedded with siltstones or very fine grained sandstones; gypsum crystals are present on weathered slopes. Several ironstone concretion layers are present. The next 10 meters are covered, and the section is resumed about 100 meters to the southeast. The uppermost exposed Dakota beds are medium to dark gray clay shales interlaminated with thin (0.3 to 3 cm) bentonite seams 1.5 to 1.6 meters above the base of the upper exposure. Sandstone and ironstone float is noted above these shales. X-ray diffraction patterns of the upper Dakota shales at Stop 1 reveal the presence of kaolinite mixed-layer clays, muscovite, and quartz (Bowe, 1972). The upper most exposed bed is a thin layer of dense, crystalline limestone with abundant fish scales; similar limestones are seen in the upper Dakota at Stop 5. Greenhorn Limestone float with *Inoceramus* can be seen along the slope below the gravestone.

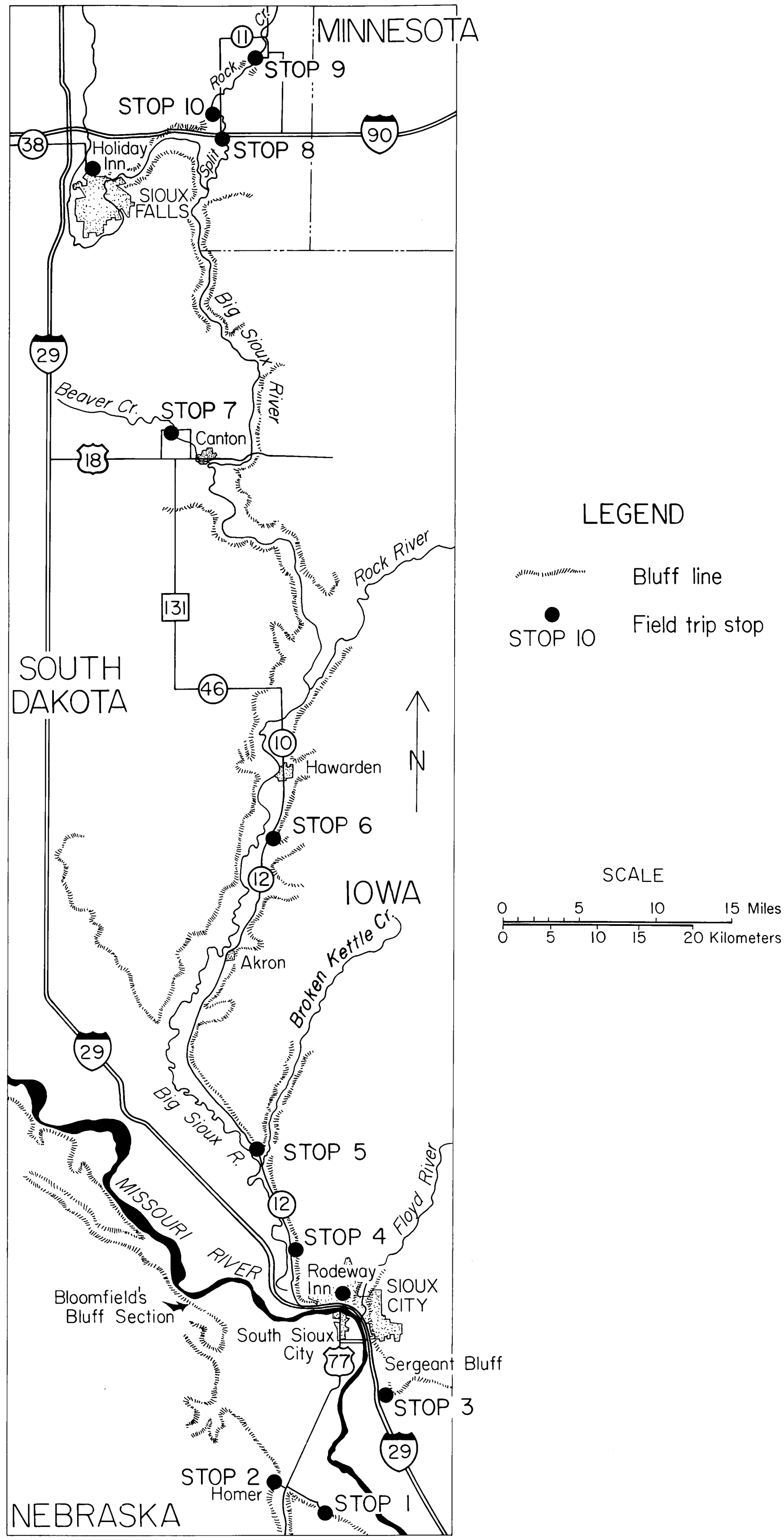

Figure 1. Map of field trip area showing approximate location of stops.

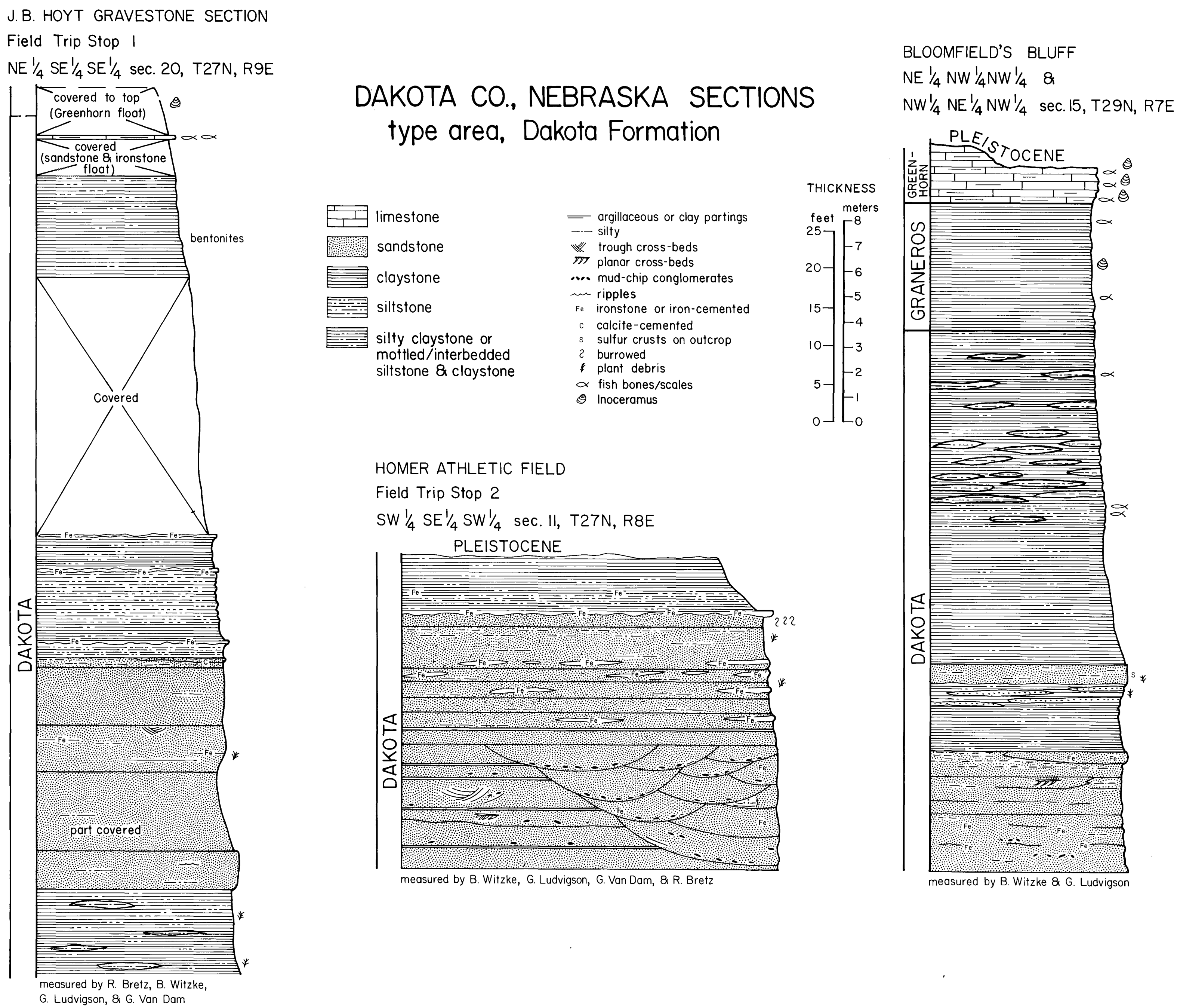

Figure 2. Measured sections of upper Dakota in type area, Dakota Co., Nebraska.

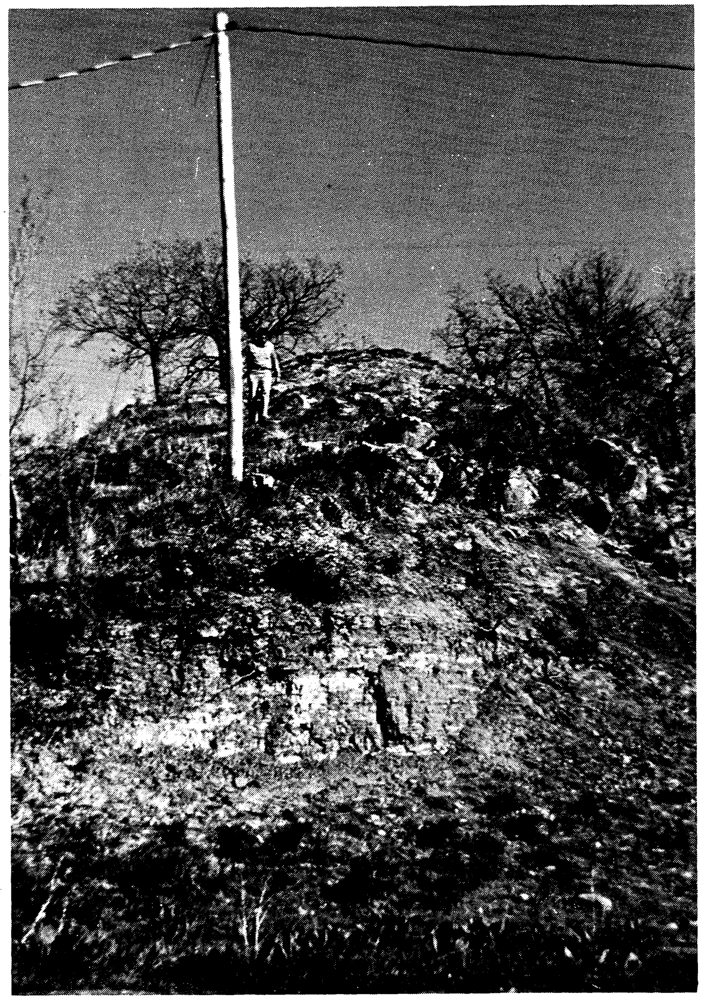

Figure 3. Lower part of J.B. Hoyt Gravestone sections showing sandstone lenses in silty mudstone. Southeast of Homer, Nebraska.

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STOP 2. Homer Athletic Field section: type area of the Dakota Formation (by B.J. Witzke and G.A. Ludvigson).

Prominent trough cross-bedded sandstones characterize the upper Dakota outcrops in the Homer area, and a major channel complex probably fed into this area from the east and northeast. The channel sandstones at Homer contrast with the upper Dakota sandstones that crop out to the north (e.g. Bloomfield's Bluff, figure 2) and south (Stop 1) in Dakota County, where horizontally-bedded sandstones with minor development of small-scale crossbeds are more characteristic. The main trough cross-bedded interval at Stop 2 cuts into an exposed 5 meter sequence of generally horizontally-bedded sandstone, with some planar crossbeds and troughs (largest trough 50 cm x 4 m), and thin interbeds of silty shale. The prominent trough cross-bedded interval is a very fine to fine grained, micaceous, well-sorted sandstone that is iron-cemented in places; the largest trough measures 2 m x 12 m. Shale chips (up to 5 cm), many which are iron-coated, are scattered to abundant in occurrence at the base of individual troughs. The large troughs can grade laterally into interbedded sandstones and claystones, although most troughs are truncated by other troughs. The overlying horizontally-bedded sandstones are interbedded with gray clay shales and siltstones, and several ironstone bands and scattered plant debris are observed. Immediately below a prominent 5 to 20 cm thick silty and sandy ironstone band is a burrowed friable sandstone; the diagonal (sub-vertical) burrows are up to 1 cm x 12 cm in size, and are iron-cemented. The overlying silty and sandy claystones and argillaceous siltstones are accessible at the north end of the exposure. Condra (1908, p. 10), describing outcrops at Homer, recorded 10 meters of sandy claystones between cross-bedded sandstones. Presently only about 2 meters of claystone can be seen at Stop 2. Rapid lateral variations between sandstones and claystones are expected within the upper Dakota channel complexes. The channel sandstones in the Homer area are informally termed part of the "Homer Channel" for this field trip.

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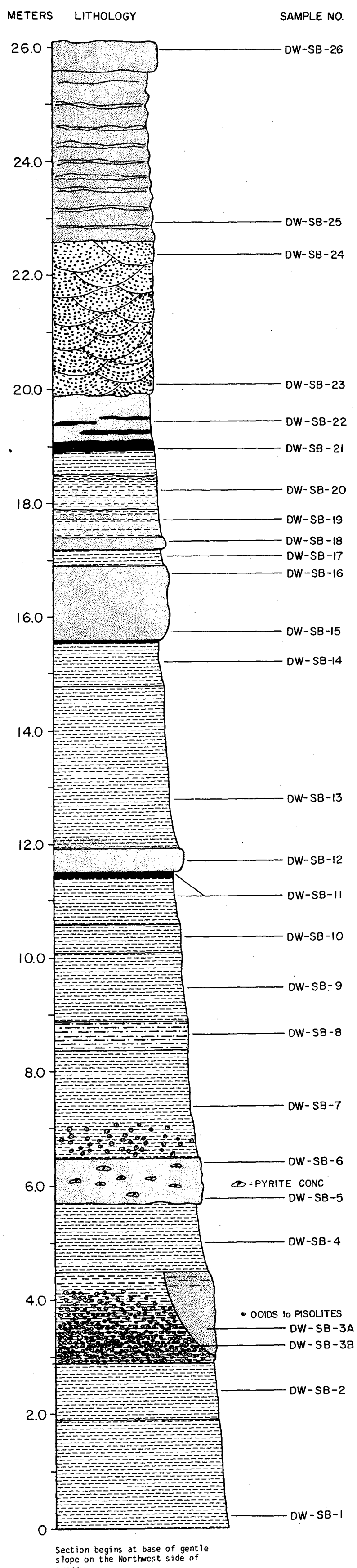
STOP 3. Sargeant Bluff Section (by R.L. Brenner and D.L. Whitley).

One of the best exposures of the Dakota Formation in the Field trip area is found in a clay shale quarry operated by Ballou Tile and Brick Company near Sargeant Bluff, Iowa. This exposure can be divided into two major units: 1) a lower dominantly mudrock unit; and 2) an upper dominantly sandstone unit (figures 4 and 5).

The lower dominantly mudrock unit consists of light to dark gray, silty claystones, clay shales, and siltstones. These sediments tend to show parallel bedding to ripple cross-laminations, suggesting quiet water deposition from suspension to deposition within the lower part of the lower flow regime. These sediments commonly contain woody plant material, which becomes increasingly abundant in the upper part of the unit, forming thin (0.2 meters or less) lignite beds. (For descriptions of these materials, see Ravn, this volume.) Siderite nodules, averaging about 1 mm in diameter, appear within mottled greenish gray and red claystone beds in the lower unit, and decrease in abundance within each bed. Several laminated to thin-bedded, ripple cross-laminated sandstone bodies with sharp basal contacts

SARGEANT BLUFF SECTION, BALLOU BRICK & TILE CLAY SHALE QUARRY

NE 1/4 SW 1/4 NE 1/4 Sec. 30 T88N R47W Woodbury Co., Iowa
Measured: 5/29/79 by Don Whitley



INTERVAL	DESCRIPTION
25.6 - 26.1 M	Sandstone, brown to orange brown, thin to medium bedded, predominantly fine grained quartz, subrounded, well cemented by calcite and some limonite, sharp basal contact.
22.6 - 25.6 M	Sandstone, buff, thin to medium bedded with shaley partings, ripple cross laminae in some beds, fine to medium grained quartz sand, subrounded to well rounded, coarser beds cemented by limonite, basal contact gradational.
19.9 - 22.6 M	Sandstone, buff stained yellow-brown in spots, shows large scale trough cross bedding, thick to medium bedded, predominantly fine to medium grained quartz with some mica and mafic minerals, subangular to subrounded, well sorted, coarser beds cemented by limonite and silica, otherwise poorly cemented by silica, becomes more massive to the south, sharp basal contact.
19.1 - 19.9 M	Interbedded sandstone and lignitic black shale, basal portion consists of lignitic black shale containing lenses of fine-grained sandstone, sandstone becomes more evenly bedded and finally dominates at top of unit, abundant root casts filled with sand, thin bedded to laminated becoming irregular due to bioturbation, some pyrite concretions in the lignitic black shale, gradational basal contact.
18.5 - 19.1 M	Carbonaceous black clay shale, thin-bedded grades upward to a lignite, clay shale contains numerous root casts, the lignite averages about .2 meters in thickness contains a high amount of woody organic debris and pyrite nodules or concretions, basal contact gradational.
17.9 - 18.5 M	Clay shale, brown to grey, fissile, contains some coaly (woody) fragments, some burrows or root casts, some thin, fine-grained sandstone interbeds, basal contact gradational.
17.4 - 17.9 M	Interbedded sandstone and shale, grey to buff, thinly laminated, highly disrupted due to bioturbation, some woody organic debris, sandstone is fine grained, basal contact gradational.
17.2 - 17.4 M	Sandstone, buff to orange-brown, laminated, small ripple cross-laminae, very fine grained quartz with some mica, some large root casts, sharp basal contact.
16.9 - 17.2 M	Carbonaceous clay shale, black, thin bedded, contains abundant coaly (woody) fragments, becomes lignitic toward top of unit, unit also contains some brown clay shale fragments, sharp basal contact.
15.6 - 16.9 M	Sandstone, light grey to buff, laminated to thin bedded, some ripple cross laminae, very fine grained, predominantly quartz with some mica and organic fragments, sharp basal contact.
14.8 - 15.6 M	Clay shale, dark grey to black, becomes increasingly more carbonaceous upward grading to a lignite at the top of the unit, thin irregular bedding due to bioturbation, sharp basal contact.
11.9 - 14.8 M	Clay shale, medium grey weathering light grey, thin irregular bedding, contains some woody organic fragments, basal contact gradational.
11.5 - 11.9 M	Sandstone, buff, thin bedded, very fine grained, predominantly quartz with some mica, well sorted, abundant concretionary sandstone cemented by limonite up to cobble size, some root casts or burrows, some woody organic fragments, sharp basal contact.
10.6 - 11.5 M	Clay shale, very dark grey to black, shows increasing woody organic matter upward to lignite at the top, some pyrite nodules in the more lignitic zone, sharp basal contact.
10.1 - 10.6 M	Clay shale, light greenish grey, fissile, contains abundant woody organic debris, sharp basal contact.
8.9 - 10.1 M	Clay shale, greenish grey, bedding indistinct, contains some woody organic debris, basal contact gradational.
8.4 - 8.9 M	Silty clay shale, light grey, fissile to thin bedded, contains abundant woody and resinous organic material, also small amount of pyrite, sharp basal contact.
6.5 - 8.4 M	Clay shale, medium grey, thin bedded, contains some siderite? pisolites in lower half of the unit, also contains some woody organic debris, some burrows or root casts, gradational basal contact.
5.7 - 6.5 M	Sandstone, light grey to buff, thin bedded, very fine grained, predominantly quartz with some mica, moderately well sorted, contains abundant small pyrite concretions up to 3 cm. in diameter, silica cement, some root casts or burrows, sharp basal contact.
4.5 - 5.7 M	Clay shale, medium grey weathering light grey, thin irregular bedding, some interbedded siltstone, contains abundant woody organic fragments, gradational basal contact.
2.9 - 4.5 M	"Pisolitic" clay shale, grey weathering reddish-brown to yellow-brown, thin to medium bedded, siderite? "Pisolites" from .5 mm to 2 mm in diameter varying in abundance from a minor constituent to the dominant constituent, pisolites surrounded by clay matrix, grades upward to clay shale, laterally the unit is channelled out and is replaced by a very fine grained sandstone grading upward to a siltstone, very light grey, thin bedded, contains abundant woody and resinous organic material, basal contact gradational.
1.9 - 2.9 M	Clay shale, grey with abundant reddish brown iron staining, indistinct bedding, contains abundant woody organic fragments, gradational basal contact.
0.0 - 1.9 M	Clay shale, dark grey weathering light grey showing increasing amount of reddish brown iron staining near the top of the unit, bedding very irregular to indistinct, contains abundant woody organic fragments, basal contact covered.

Figure 4. Measured section of Dakota Formation in Ballou Tile and Brick Co. quarry, Sargeant Bluff, Iowa.

are found within the lower unit. Some of these are laterally continuous across the outcrop, while others appear to fill channels cut into the mudrocks.

The upper, dominantly sandstone unit is characterized by a general fining-upward sequence. The lower 3 to 5 meters of this unit consist of fine to medium-grained sandstone, showing large-scale trough cross-bedding, characteristic of deposition within the upper portion of the lower flow regime. These crossbeds decrease in thickness upward, grading into horizontal beds that show ripple cross-lamination and parting lineation between beds.

In addition to the plant fossils found in the lower unit, angiosperm leaf impressions of forms resembling magnolia, poplar, sassafras, willow and possibly fig (identifications by B.J. Witzke), were collected during the past year from float blocks from the upper sandstone-dominant unit (figure 5). Lesquereux (1874) described a diverse angiosperm assemblage from the Dakota Formation in eastern Nebraska and western Iowa which include the forms collected from this quarry.

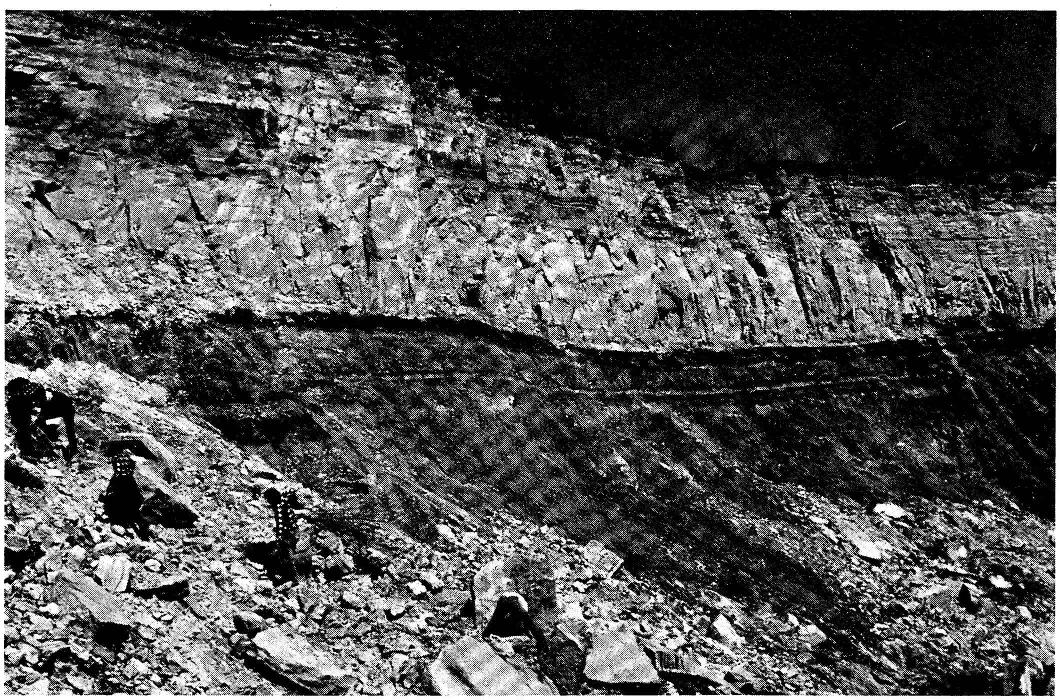
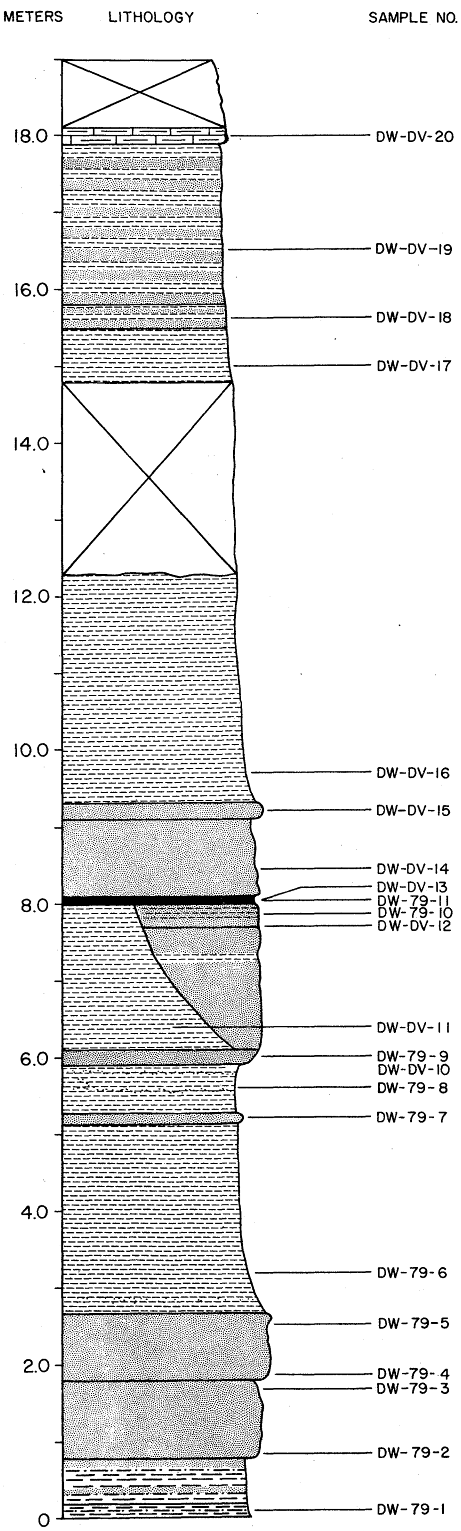


Figure 5. West wall of Ballou quarry showing lower mudrock section overlain by coaly shale and cross-stratified sandstone. Geologists in foreground are examining plant fossils in blocks of sandstone float from upper unit.

STONE PARK COMPOSITE SECTION (Stone Park West & Dakota Valley)

Stone Park West - NE 1/4 NW 1/4 NW 1/4 SE 1/4 Sec.2 T89N R48W
Dakota Valley - NW 1/4 SE 1/4 NE 1/4 NE 1/4 Sec.2 T89N R48W Woodbury Co., Iowa
Measured: 5/26/79 - SPW, 8/29/79 - DV, by Don Whitley



Section begins 4.1 meters above drainage ditch along Iowa Highway 12.

INTERVAL	DESCRIPTION
18.0 +	Covered
17.9 - 18.0 M	Shaley limestone, buff to brown, thin bedded, chalky, contains pelecypod and fish scale fragments, sharp basal contact.
15.8 - 17.9 M	Interbedded clay shale and sandstone, thin bedded, clay shale is dark grey, non-calcareous, sandstone is buff to yellow brown, some possible flaser bedding, some ripple cross lamination, fine grained quartz with some mica, varying amounts of limonite cement, basal contact gradational.
15.5 - 15.8 M	Mottled clay shale and sandstone, light grey to buff, some possible flaser bedding, sharp basal contact.
14.8 - 15.5 M	Clay shale, medium to dark grey, thin irregular bedding, some thin interbeds of fine grained sandstone, yellow brown, possible flaser bedding, limonite cement, basal contact covered.
12.3 - 14.8 M	Covered interval, due to main Stone Park Road, soil consists predominantly of silt and clay.
9.3 - 12.3 M	Clay shale, medium grey, some thin sandstone interbeds, fine grained cemented by limonite, sharp basal contact.
9.1 - 9.3 M	Sandstone, brown, thin to medium bedded, fine grained, predominantly quartz and some mica, highly cemented by limonite becoming concretionary in spots, sharp basal contact.
8.1 - 9.1 M	Mottled sandstone and shale, extensive bioturbation has totally destroyed bedding, irregular basal contact.
8.0 - 8.1 M	Lignite, black, high amount of woody organic material, very irregular basal contact.
6.1 - 8.0 M	Dakota valley - clay shale, medium grey to brown with orange brown staining along root casts and fractures, fissile, basal contact gradational. Stone Park West - interbedded sandstone and shale, mottled to irregular stratification, sandstone is fine grained quartz sand, shows ripple cross laminae, abundant burrows or root casts, some of the sand units cemented by limonite becoming concretionary in spots, basal contact gradational.
5.9 - 6.1 M	Sandstone, orange brown, thin-bedded, fine-grained quartz with some mica, moderately well sorted, limonite cement, some ripple cross-laminae, sharp basal contact.
2.7 - 5.9 M	Clay shale, grey, fissile, thin black organic films to coaly seams along some bedding, organic material decreases upward, thin sandstone interbed 2.5 M above base cemented by pyrite, pyrite is concretionary and disseminated through the fine-grained quartz sand, unit coarsens upward increasing in the quantity of sand, sharp basal contact.
1.8 - 2.7 M	Sandstone, buff, massive with thin laminae and small cross laminae, contains thin discontinuous lenses of black organic material, the sandstone is fine-grained, predominantly quartz with some clear mica, coarsens upward, upper portion cemented by limonite, some root casts, sharp basal contact.
0.8 - 1.8 M	Sandstone, grey, thin to medium bedded, shows ripple cross laminae, ripple marks found on some bedding, sand is fine grained coarsens upward, quartz is dominant with some mica and mafic minerals, cemented by calcite near base decreasing upward, some pyrolusite found growing upward as dendrites from some bedding surfaces, basal contact gradational.
0.2 - 0.8 M	Interbedded sand, silt and clay, mottled white to grey, bedding becomes more regular upward, coarsens upward, upper sand shows ripple cross-laminae, some secondary limonite staining, basal contact gradational.
0.0 - 0.2 M	Clay shale, grey to black, thin bedded to laminated, bedding is irregular to mottled, contains silty clay shale interbeds, basal contact covered.

Dakota Valley section descriptions begin at 5.9 M, lignite zone is the marker unit that ties the Dakota Valley section to the Stone Park West section .7 km to the southwest. Measurement of Stone Park West discontinued at lignite due to steepness of slope. Stone Park West descriptions used below 8.1 meters due to better exposures.

Figure 6. Measured section from Stone Park area, north of Sioux City, Iowa.

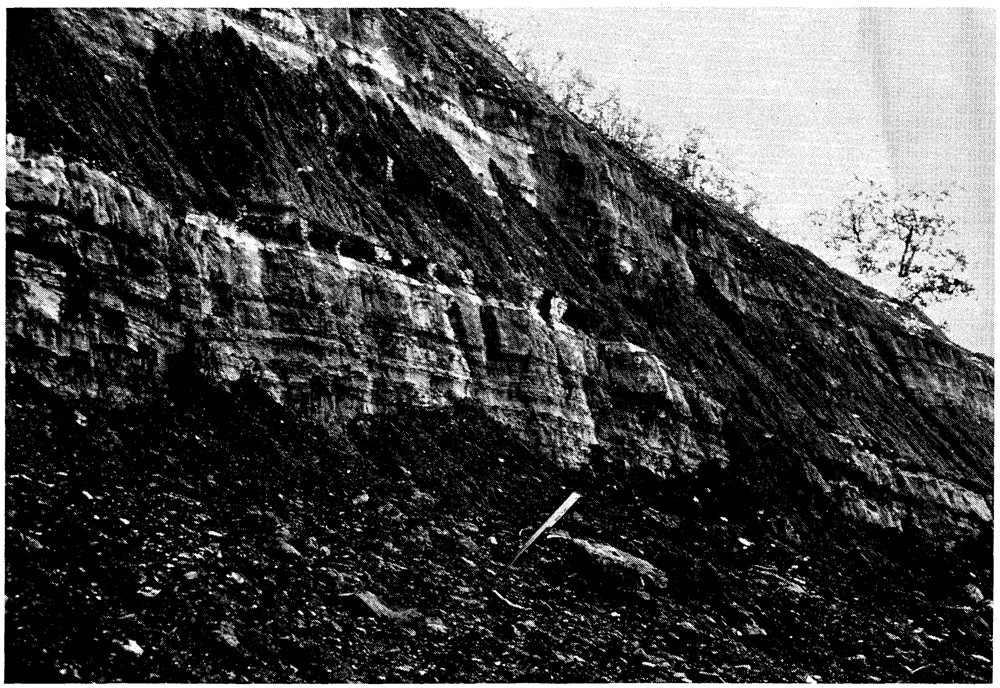


Figure 7. Upper Dakota, Graneros and basal Greenhorn exposure on east side of Rt. 12 just south of west entrance to Stone Park.

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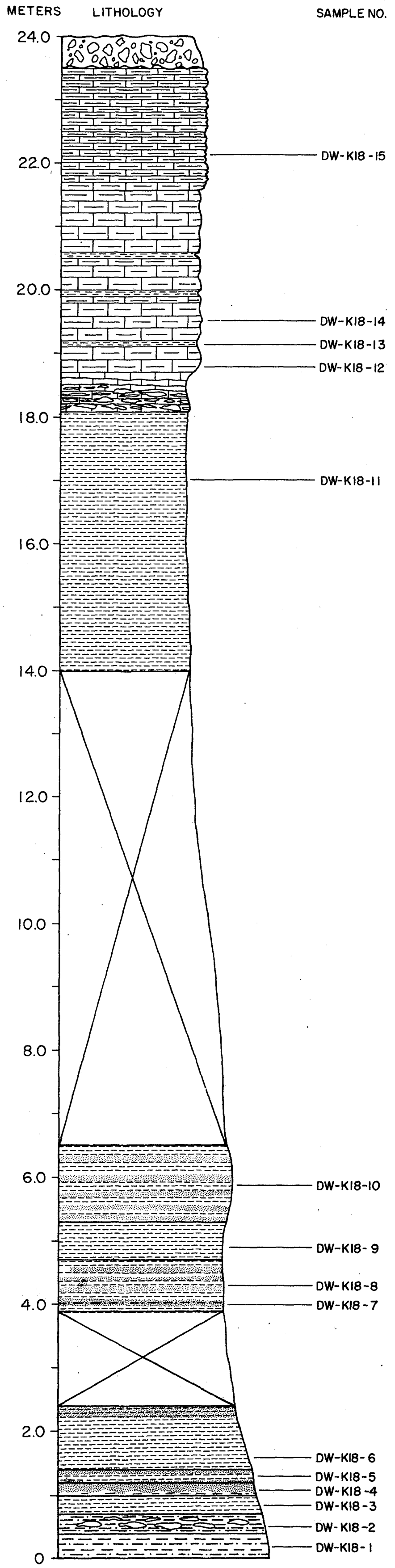
Stop 4. Stone Park, North Sioux City (by R.L. Brenner and D.L. Whitley).

The uppermost Dakota Formation and the overlying Graneros and Greenhorn formations are exposed in a roadcut along the east side of Iowa Highway 12 (figures 6 and 7). These units comprise the bluffs bordering the Big Sioux River meanderbelt and flank the west entrance to Stone Park. The upper part of the section is not as well exposed, but is more safely accessible on the east side of the picnic ground where we will eat lunch. The Dakota lithologies exposed along the highway are similar to those we saw in the dominantly mudcrock unit at Sargeant Bluff. The sandstone bodies consist of medium to very fine grained quartz arenite in fining-upward sequences. The sandstones commonly show ripple cross-laminae which are often cut by root casts and/or burrows. The sandstones grade upward into thinly laminated, silty clay shale, suggesting a decrease in energy from lower flow regime deposition to quiet water deposition from suspension.

K-18 SECTION, APPROX. 7 MILES NORTH OF SIOUX CITY, IOWA

NW 1/4 SW 1/4 NW 1/4 Sec. 15 T90N R48W Plymouth Co., Iowa
Measured: 5/29/79 by Don Whitley



Section begins 0.7 meters above bottom of drainage ditch along Highway 12.

INTERVAL	DESCRIPTION
23.5 - 24.0 M	Pleistocene glacial till, erosional basal contact
21.6 - 23.5 M	Shaley limestone, buff to light brown, thin-bedded, chalky, contains abundant pelecypod fragments (Inoceramus sp.) and poorly preserved fish scales, basal contact sharp.
20.6 - 21.6 M	Chalky limestone, grey to off white, thin bedded nature concealed by weathering appears massive, contains pelecypod fragments (Inoceramus sp.) and some fish scale fragments, sharp basal contact.
20.5 - 20.6 M	Shale, grey, thin-bedded, chalky, bentonitic, calcareous, sharp basal contact.
20.0 - 20.5 M	Chalky limestone, light grey to off-white, appears massive, thin bedded nature concealed by weathering, contains some fragments of the pelecypod Inoceramus sp., sharp basal contact.
19.9 - 20.0 M	Shale, grey, thin-bedded, chalky, calcareous, bentonitic, sharp basal contact.
19.2 - 19.9 M	Chalky limestone, light grey to buff, appears massive, thin-bedded nature concealed by weathering, contains some pelecypod fragments (Inoceramus sp.) sharp basal contact
19.1 - 19.2 M	Shale, grey, thin-bedded, chalky, calcareous, bentonitic, sharp basal contact.
18.7 - 19.1 M	Chalky limestone, white to buff, appears massive, thin bedded nature concealed by weathering, some pelecypod (Inoceramus sp.) fragments, sharp basal contact.
18.2 - 18.7 m	Interbedded calcareous clay shale and chalk. Shale interbeds are grey and laterally discontinuous, some secondary selenite along bedding surfaces. Chalk is grey to orange brown and poorly consolidated, basal contact gradational.
14.0 - 18.2 M	Clay shale, dark grey to reddish-brown, becomes increasingly more calcareous upward, thin-bedded, unoxidized lenses of dark grey shale are found surrounded by reddish brown clay shale lateral relationships not observed due to cover, basal contact covered.
6.5 - 14.0 M	Covered interval, due to vegetation and slumping on the steep slopes, soil consists primarily of silty clayey material with scattered fragments of chalky shaley limestone.
5.3 - 6.5 M	Interbedded sandstone and clay shale, alternating beds of sandstone, buff to yellow brown, thin bedded to laminated, some ripple cross laminae and flaser bedding, fine-grained quartz sand cemented by limonite, and laminated clay shale, grey, silty near base, overall fining upward, basal contact gradational.
4.7 - 5.3 M	Clay shale, dark grey, thin-bedded, some white sandstone interbeds possible flaser bedding, sandstone is fine grained quartz, moderately well sorted, silica cement, basal contact gradational.
4.1 - 4.7 M	Sandstone with interbedded shale, possible flaser bedding, fine grained quartz sand alternates with clay shale, sandstone shows some ripple cross lamination, some beds cemented by limonite, clay shale is dark grey, fissile, and silty in some beds, sharp basal contact.
3.9 - 4.1 M	Clay shale, dark grey, fissile, upper portion contains thin, white, sandstone interbeds, fine grained, basal contact covered.
2.4 - 3.9 M	Covered interval, due to vegetation and some slump coverage, soil consists primarily of clay with some silt and fine-grained quartz sand.
1.4 - 2.4 M	Clay shale, grey, fissile, some very thin sandstone interbeds near top of unit, basal contact gradational.
1.2 - 1.44M	Interbedded sandstone and clay shale, sandstone, buff to greenish grey, some ripple cross laminations and possible flaser bedding, fine-grained quartz sand, some beds cemented by pyrite, shale is dark grey, fissile, sharp basal contact.
1.0 - 1.2 M	Sandstone, buff to grey, thin bedded, some possible flaser bedding near base coarsening upward to a clean quartz sand, very fine to fine grained, basal contact gradational.
0.7 - 1.0 M	Clay shale, medium to dark grey, fissile, contains a few thin silt lenses, basal contact gradational.
0.4 - 0.7 M	Silty clay shale, contains concretionary limonite to thin limonite cemented, very fine grained sandstone, discontinuous laterally, irregular gradational basal contact.
0.0 - 0.4 M	Clay shale, dark grey with light grey silty clay shale interbeds, irregular to mottled bedding, basal contact covered.

Figure 8. Measured section of K-18 section on west side of Rt. 12.

Figure 9. Exposure of Graneros and Greenhorn formations on west side of Rt. 14 at K-18 Section stop.

Woody organic debris occurs thorughout the Dakota and often accentuates bedding and organic structures. At one point, accumulation of organic material became rich enough to form a thin lignite seam. The lignite bed is laterally continuous, and was found in both the road cut and picnic ground outcrops, thus making a marker bed for tying the two outcrops together.

As mentioned before the contact between the Dakota Formation and the overlying Graneros Shale is gradational to abruptly gradational and is generally taken as the top of the uppermost major sandstone (greater than 1 meter thick) in the Dakota. The lithology of the Graneros at Stone Park consist of thinly laminated silty clay shale, generally becoming increasingly calcareous upward. Thin (less than 0.1 m thick) interbeds of fine-grained sandstones and siltstones, showing ripple cross-lamination, are common in the picnic ground outcrop indicating lower flow regime conditions alternating with periods of quiet water, suspension deposition.

STOP 5. K-18 Section (by R.L. Brenner and D.L. Whitley).

Portions of the Dakota, Graneros and Greenhorn formations are exposed in a roadcut on the east side of Iowa Highway 12, near the junction with Plymouth County Highway K-18 (figure 8 and 9). The Dakota and Graneros are poorly exposed here; however, the Graneros-Greenhorn contact is well displayed near the base of the prominent bluff. This contact appears to be abruptly gradational over a 0.5 m interval, with the lowest chalky bed being picked as the contact. Wavy thin beds of the underlying calcareous clay shale in a matrix of chalky lime mud, are common just above the contact. The zone of interbedded chalky lime mud and clay shale represents a fairly rapid termination of terrigenous detrital influx. This terrigenous cutoff could either represent a climatic change from humid to more arid conditions, or more likely it may represent the inundation of the siliciclastic source area to the extent that clastic material no longer could reach the study area.

Overlying the interbedded limestone and shale is a sequence of thin bedded, chalky, shaly limestone and medium to thick bedded chalks. Fossils consist of pelecypods (*Inoceramus* sp.) and assorted fish fragments. Whole pelecypod shells become more common toward the top of the unit. Several thin, calcareous shaly partings probably represent small pulses of clastic input into the area.

Stop 6. Scotts Bottom Section (by R.L. Brenner and D.L. Whitley).

The most accessible outcrop of Carlile Shale in the field-trip area is located at the Scotts Bottom section. Unfortunately, its contact with the Greenhorn is not exposed anywhere in the area. Post-Cretaceous erosion has made the outcrop of Carlile quite rare. At this section, the Carlile consists of thinly laminated, fissile, calcareous clay shale. The shale is highly gypsiferous, showing abundant selenite crystals forming on the exposed surface of the shale. In addition to collecting selenite crystals at this locality, you may want to search for body fossils. Pelecypod and fish (?) remains have been reported; however, they are not very abundant.

The Carlile represents the resumption of clastic input into the area. Deposition took place in relatively quiet water in an environment quite similar to that of the Graneros Shale. The remainder of the Cretaceous sequence has not been found in Iowa and is probably missing because of post-Cretaceous erosion.

STOP 7. Outcrop of Niobrara Formation (by R.F. Bretz).

This is probably the easternmost exposure of Niobrara in the United States. A section approximately 24 feet (7.4 m) thick was measured here and is capped by glacial till with large erratics (figure 10).

The exposure is largely weathered and oxidized to various shades of yellow and orange, but does contain slightly weathered to unweathered cores of yellowish gray, light olive gray, and olive gray carbonate rocks.

The section contains fissile to platy marl and chalk interbedded with well indurated chunky, to blocky, to massively bedded chalk and limestone. Comparison of these characteristics with the Fort Hays Limestone and Smoky Hills Chalk Members in Kansas suggests fluctuating environments creating interbedding of the two units.

Figure 10. Exposure of Niobrara Formation in cutbank of Beaver Creek, Lincoln Co., South Dakota. This is believed to be the easternmost exposure of the formation in the United States.

Fossils found as float and in place in the trenched, measured section include: inoceramids, with and without epifaunally attached ostreids; ostreids, both free living and epifaunally attached to inoceramids; echinoderm fragments in a sparry calcite, found only as float to date but probably occurring in place near the top of the section; coalified plant remains concentrated at approximately 2.5 m in the section; rare fish scales; and burrows, from 1 to 15 cm wide, vertically and horizontally oreinted, accentuated by being heavily iron stained. The echinoderm fragments are significant because of thier rarity in the Niobrara, probably as a result of preservational bias. The only significant echinoderm remains from the Niobrara are the free floating *Uintacrinus socialis* from the Smoky Hill Member in Kansas. Fossil evidence also suggests fluctuating Fort Hays and Smoky Hill environments. Burrows and free living ostreids are concentrated in the well indurated units, as found in the Fort Hays Limestone Member in kansas.

Seventeen samples taken stratigraphically from the section were analyzed for insoluble residue percentages and content, bulk rock x-ray mineralogy, selected trace elements, and fossil content. Results are shown on the hand-out material to be distributed at the stop.

STOP 8. The I-90 sections: Upper Cretaceous opaline spiculites (by R.M. McKay and G.A. Ludvigson).

At this stop cherty opaline spiculites of the Split Rock Creek Formation are exposed along a cutbank of Split Rock Creek, both north and south of the I-90 bridge (figure 11). Their stratigraphy and petrology are discussed

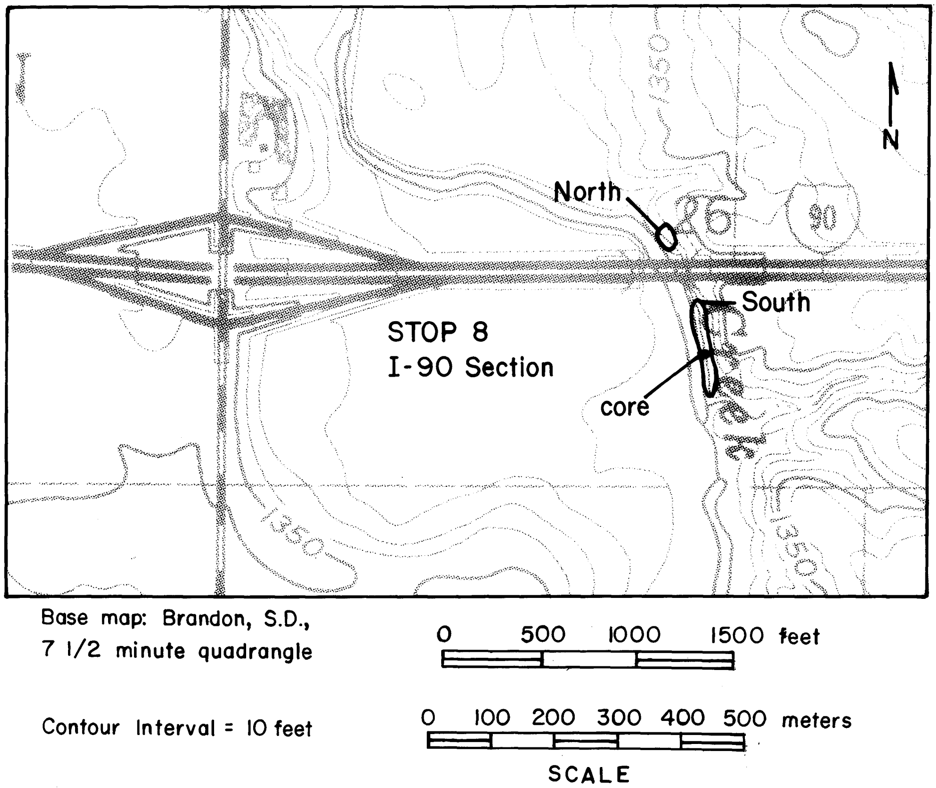


Figure 11. Map showing exact locations of Split Rock Creek Formation exposures along the cutbank of Split Rock Creek at Stop 8.

in detail elsewhere in this guidebook (Ludvigson, et al., this volume). I-90 south is the principal exposure with its base at an elevation of 1304 feet a.s.l. The section was cored to an elevation of 1294 feet (Ludvigson, et al., this volume, figure 2).

The entire section consists of light gray to white, occasionally iron stained and variably cherty, laminated to bioturbated opaline spiculites (or porcelanites). The upper half of the exposure is very cherty and has a vuggy appearance. Petrographically these rocks are seen to be intensely bioturbated (Ludvigson, et al., this volume, Plate IID, F), while the less cherty porcelanites are laminated to moderately bioturbated (Ludvigson, et al., this volume, Plate IIE). This section correlates well both in lithology and time to Risty Farm section C (see STOP 10) which is along the northern basin margin. Based upon this correlation, the embayment had a depositional gradient of 13 feet per mile from Risty Farm to I-90 during the upper portion of Split Rock Creek deposition.

But why are these highly unusual siliceous spiculitic rocks here? For reasons explained in the text we believe the porcelanites to be Late Cretaceous in age, and a shallow water facies equivalent of the Niobrara Formation. In this light, it is really not extraordinary that these rocks are here, for the Late Cretaceous was one of the most successful time periods in geologic history for sponges (Gignoux, 1955; Moore, 1955). The silicious spicules present are dominantly monaxon and tetraxon forms. These are the prevalent siliceous spicule morphology of the class Demospongea, which presently and throughout geologic history has commonly inhabited shallow marine waters (Berquist, 1978; Finks, 1960, 1970; Finks et al., 1961; Rigby, 1969; Storr, 1976; Wiedenmayer, 1977). North American paleolatitude reconstruction of the Late Cretaceous places southeast South Dakota at approximately 40° north (Dott and Batten, 1971, p. 386). At a somewhat similar latitude today, along the northwest coast of Florida, siliceous demosponges are a common faunal element where wave activity is low, where there is a nutrient influx from rivers, and where the substrate is hard (Storr, 1976). These conditions could easily have been duplicated within the Split Rock Creek marine embayment upon the Sioux Quartzite Ridge. Perhaps sponges thrived along the rocky margins of the basin, and their disassociated remains were distributed throughout the small basin by animals and physical processes.

Still these rocks possess anomalous aspects. Modern shallow water sponges occur with diverse biotas (Sara, 1970; Storr, 1976; Wiedenmayer, 1977), but within the Split Rock Creek Formation, sponge spicules are the only common faunal element observed. Were other invertebrates common? Mollusc molds and burrowed fabrics strongly suggest that they were, but why weren't they preserved? Certainly there are many more questions to be asked and answered concerning numerous aspects of these unusual rocks.

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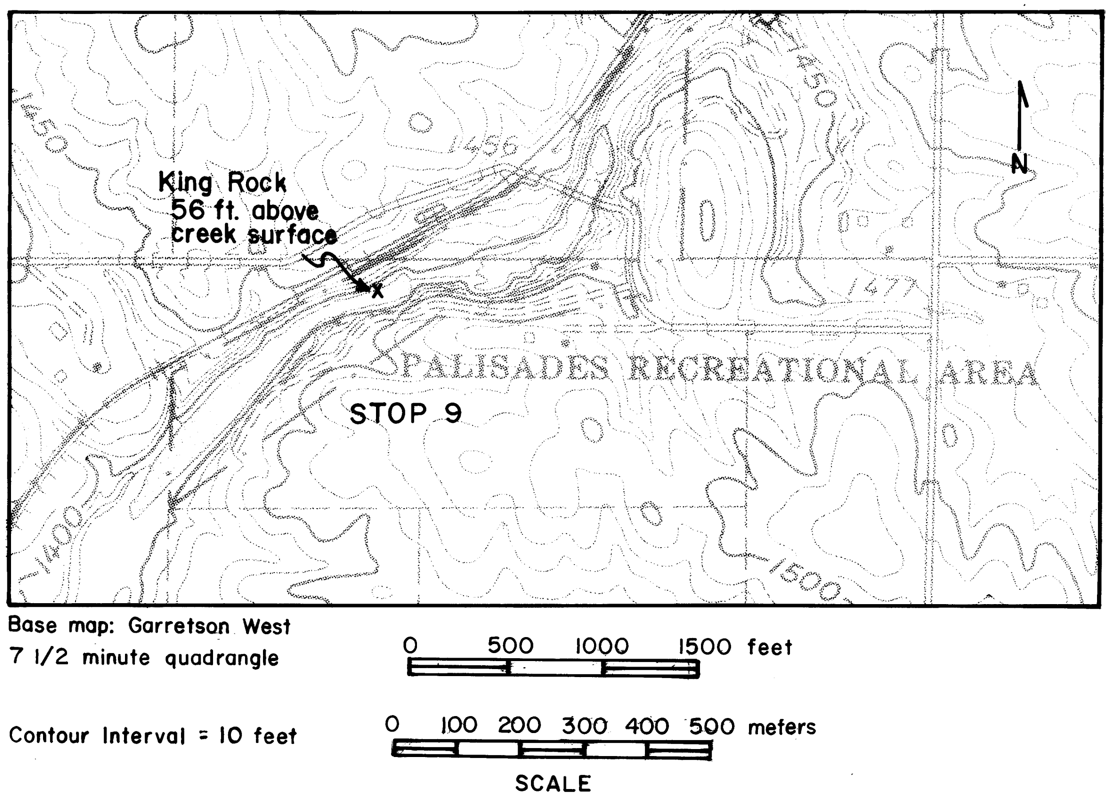

Figure 12. Map of the Palisades State Park showing Split Rock Creek gorge cut into Sioux Quartzite and the location of King Rock at Stop 9.

Storr, John, R., 1976, Ecological factors controlling sponge distribution in the Gulf of Mexico and the resulting zonation: *in* Harrison, F.W. and R.R. Cowden (eds.), *Aspects of Sponge Biology*, p. 261-276.

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STOP 9. Palisades State Park: King and Queen Rocks (by R.F. Bretz).

At this stop we will view the gorge of Split Rock Creek, cut into the top of the Sioux Quartzite Ridge (figure 12). At the deepest part of the gorge, the quartzite is exposed in 60-foot cliffs.

Conglomerate and shale beds are a minor portion of the Sioux Quartzite here and are poorly exposed. Only the quartzite itself can be easily viewed. Ripple marks are common and can be seen on many bedding surfaces.

The Sioux Quartzite Ridge is a series of east-west trending synclines. At the Palisades, the beds dip southwest at about 6.5° and are fractured into three major sets of joints which trend N 45° to 75° W, N 10° W to N 15° E,

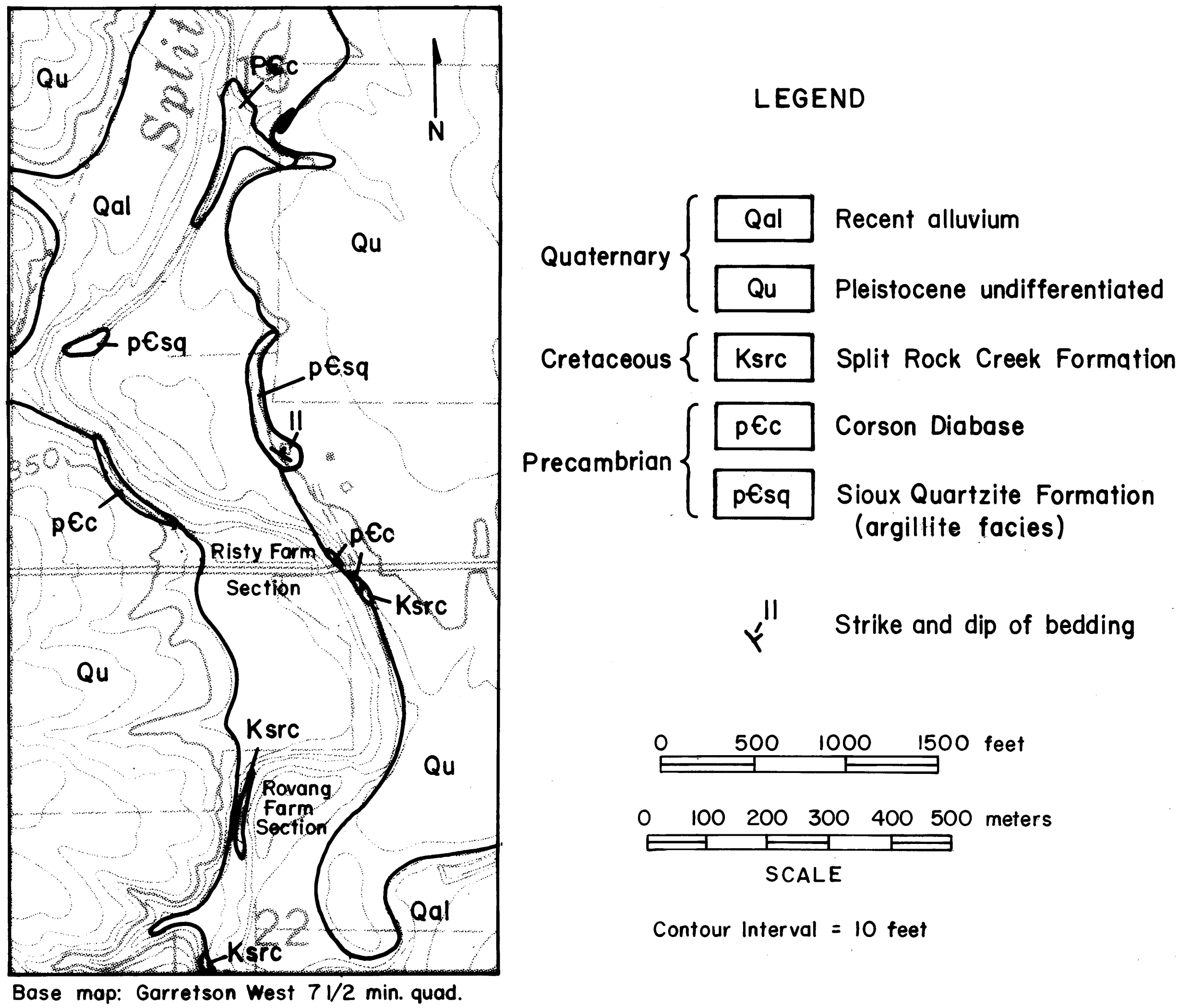

Figure 13. Geologic map of the Risty and Rovang Farm area showing the exact locations of sections to be viewed at Stop 10. Modified from Stach, 1970.

and N 55° to 70° E (Baldwin, 1949). We are on the flank of one of these anticline-syncline sets, which forms one of the local highlands. This highland is probably the one from which the quartzite blocks in the basal diamictite (to be viewed at the next section) were derived.

For information on local history, see the Palisades State Park leaflet to be handed out at the stop.

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STOP 10. The Risty and Rovang farm sections: the Cretaceous-Precambrian unconformity (by G.A. Ludvigson and R.M. McKay).

At this stop, cutbanks along Split Rock Creek expose relief on the Cretaceous-Precambrian contact at the northern edge of the depositional basin of the Split Rock Creek Formation. On the south side of the county road bridge, the contact dips 15° to the south (figure 13).

The basal unit of the Split Rock Creek Formation at the Risty farm (see Ludvigson, et al., this volume, figure 5) consists of a diamictite. The diamictite was probably deposited by southward flowing mudflows derived from the deeply weathered Corson Diabase, mixed with lithic fragments of argillite and quartzite from the Sioux Quartzite. Some of the relief on the Precambrian surface here may be related to differential weathering during the Cretaceous, as the exposures to the north of the county road indicate complex contact relationships between the Corson Diabase and argillites of the Sioux Quartzite.

Overlying the diamctite is a 5 meter section of laminated opaline spiculites, with an interbedded calcium bentonite. The spiculite-diamictite contact parallels the basal unconformity, but bedding in the spiculite becomes horizontal in the upper part of the section. The dipping units are preserved in their depositional position. The upper meter of the section is a rubbly chert which has been petrographically identified as a chalcedonic opaline spiculite.

The Rovang farm section (figure 13) is located approximately 700 to 1,000 feet (210-305 m) southwest of the Risty farm section and has a similar stratigraphy (Ludvigson, et al., this volume, figure 6). Here, the basal contact undulates rather than dipping in one consistent direction, although outcrops of opaline spiculites along the creek bed several hundred feet to the south indicate a general southward dip. Interestingly, two bentonites are exposed in the Rovang farm section, and only one at the Risty farm section. The Rovang farm section has been a good fossil collecting locality. Molds of molluscs, fish vertebrae, and land plants are commonly found in the laminated opaline spiculites here. Brian Witzke of the Iowa Geological Survey has found a small sequoia branch mold here.

Weathering profiles in the Corson Diabase exhibit several interesting characteristics. Most of the exposed Corson Diabase is altered to saprolite, although fresh unaltered exposures have been noted upstream in the bed of Split Rock Creek. Iron stained horizons beneath the Split Rock Creek Formation are probably paleosols. Sub-horizontal iron stained and calcite cemented features in the saprolite parallel the surface of the unconformity, and may represent sheeting fractures, subsequently mineralized during soil formation or later after burial.

These exposures very clearly display the field relations of the Split Rock Creek Formation, but are still enigmatic in several respects. How are the bentonites between the two sections correlated? Is the lower bentonite beneath the creek surface at Risty farm, or could the diamictite at Risty farm be partly contemporaneous with spiculite and bentonite deposition at Rovang Farm? No current winnowed deposits are seen in the transition from diamictites to opaline spiculites. Does this mean that the diamictites could be subaqueous slides, or that they are subaerial mudflow deposits, and the protected embayment of the Split Rock Creek Formation had no appreciable wave energy? What is the geometry of the Corson Diabase, and what is its relation to the geometry of the depositional basin of the Split Rock Creek Formation?

Hopefully, our trip has left you with the impression that there are challenging problems remaining, and their resolution is required before the timing and patterns of sedimentation on the eastern margin of the Western Interior seaway can be fully understood.

Iowa Geological Survey Guidebook Series

No.

1. Koch, D.L., Prior, J.C., and Tuthill, S.J., 1973, Geology of Pikes Peak State Park, Clayton Co., Iowa, 10 p.

2. Anderson, R.R., ed., 1978, Geology of East-Central Iowa, 42nd Annual Tri-State Field Conference: field trip guides and associated papers;

   Trip 1; Ludvigson, G.A., Bunker, B.J., Witzke, B.J., and Bounk, M.J., A field guide to the Plum River Fault Zone in East-Central Iowa, 49 p.

   Trip 2; Hallberg, G.R., Fenton, T.E., Miller, G.A., and Lutenegger, A.J., The Iowan erosion surface: an old story, an important lesson, and some new wrinkles, 94 p.

   Trip 3; Grant, S.C., Anderson, R.R., and Dorheim, F.H., Applied geology problems in the Cedar Rapids area, 41 p.

   Trip 4; Prior, J.C., and Heathcote, R.C., Geomorphology and basal Maquoketa stratigraphy in the vicinity of Dubuque, 17 p.

   Trip 5; Dorheim, F.H., and Anderson, R.R., Geology and history of Stone City, 10 p.

3. Hallberg, G.R., Fenton, T.E., Kemmis, T.J., and Miller, G.A., 1980, Yarmouth revisited: 27th Field Conference, Midwest Friends of the Pleistocene; field guide, with contributions by Baker, R.G., Bicki, T., Wickham, J., Lutenegger, A.J., and Lineback, J., 130 p.

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