Cretaceous Sea Cliffs and Structural Blocks
on the Flanks of the Sioux Ridge,
South Dakota and Minnesota

George W. Shurr
U.S. Geological Survey
MS 934, Box 25046
Denver Federal Center
Denver, Colorado 80225
and
Department of Earth Sciences
St. Cloud St. University
St. Cloud, Minnesota 56301

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 (Merrewether, 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

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:

x₁ Browns Valley, Minnesota
x₂ Ortonville, Minnesota
x₃ Central Lyon County, Iowa
x₄ 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 River 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
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
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 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 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. Non-marine 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 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 Level  
Kn Niobrara Formation  
Kc Carlile Shale  
Kd Dakota Sandstone  
Kg Graneros Shale  
Kgh Greenhorn Formation

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 Desmocapitace 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.

ACKNOWLEDGEMENTS

R. F. Bretz of the South Dakota Geological Survey and E. A. Merewether of the U.S. Geological Survey reviewed the manuscript. Conversations with G. A. Ludvigson and B. J. Bunker of the Iowa Geological Survey provided useful insights into the geology of northwestern Iowa and surrounding regions. Technical assistance was provided by Terri Ericson and Margaret Shurr. The study was made possible by funding to the U.S. Geological Survey by the U.S. Department of Energy.

REFERENCES CITED


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

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


hosted by the
Department of Earth Sciences, Iowa State University, Ames, Iowa

published by the
Iowa Geological Survey, 123 N. Capitol, Iowa City, Iowa 52242
Donald L. Koch, Director and State Geologist