BULLETIN 39

Geology of Lincoln and Union Counties, South Dakota

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GEOLOGY OF LINCOLN AND UNION COUNTIES, SOUTH DAKOTA

by

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CONTENTS

BEDROCK GEOLOGY – continued. Page

QUATERNARY GEOLOGY – continued. Page

APPENDICES

ILLUSTRATIONS

PLATES

FIGURES

FIGURES – continued.

TABLES

INTRODUCTION

This report describes a geologic investigation of Lincoln and Union Counties, South Dakota. It is one of a series of cooperative studies conducted by the South Dakota Geological Survey and the U.S. Geological Survey describing the water and mineral resources of South Dakota. This study was designed to:

(1) gather, analyze, and describe geologic data,
(2) locate and evaluate the area's mineral and water resources, and
(3) combine findings of this study with those from other similar studies to further the understanding of the geology of the state and region.

A companion volume, *Water resources of Lincoln and Union Counties*, *South Dakota*, (Niehus, 1994) provides information about the ground water resources of the counties.

Location and Physiography

Lincoln and Union Counties are located in the far southeastern corner of South Dakota (fig. 1). The Big Sioux and Missouri Rivers form the eastern and southern borders of the counties with the states of Iowa and Nebraska, respectively. The combined area of Lincoln (576 square miles) and Union Counties (466 square miles) is 1,042 square miles.

Lincoln and Union Counties occupy part of two physiographic divisions of the Central Lowlands Province (fig. 2; Fenneman, 1931). The Coteau des Prairies is a broad flatiron-shaped highland extending from Marshall County, South Dakota, at the North Dakota border to the area presently under study in the southeastern corner of the state. Although it is described as a steep-sided plateau in the northeastern corner of the state, here it is merely an area of highly dissected loess-mantled hills, standing only about 100 feet above the bordering lowlands. The rugged hilly area between the Big Sioux River and Brule Creek has been included in the Coteau des Prairies division.

The remainder of Lincoln and Union Counties lie within the James Basin. The land surface is flat to gently undulatory, with scattered sloughs occupying small depressions in the land surface. A few small stream valleys are incised into the surface of central and western Lincoln County and adjacent to the Missouri trench in western Union County.

The southern one-third of Union County is in the flood plain of the Missouri River. A sharp escarpment of up to 80 feet separates this lower plain from the rest of the James Basin. The flood plain reaches nearly 10 miles wide and displays a complex array of abandoned river channels and associated features. Oxbow lakes, abandoned sandbars, and dune fields provide more than 30 feet of local relief to the otherwise flat surface.

Previous Investigations

Lincoln and Union Counties have been included in a number of reconnaissance studies dealing with the general geology of South Dakota (Todd, 1894; Darton, 1909; and Rothrock, 1943). Flint (1955) mapped the Pleistocene sediments of eastern South Dakota. Bendrat (1904) produced an early report on the geology of Lincoln County. Todd (1908) described the geology of the Elk Point 30-minute quadrangle, which covers most of Union County. The Pleistocene deposits of the area were described and classified by Chamberlin (1883) and Todd (1899). Several 7.5-minute quadrangles in the study area were mapped as theses by students at the University of South Dakota: Steece (1957), Baird (1957), Tipton (1958), and Jorgensen (1960). Included in these studies are discussions of till lithologies and stratigraphy. A detailed lithological and textural study of till was carried out by Schroeder (1979) in Moody, Minnehaha, Lincoln, and Union Counties.

Sand and gravel resource studies have been completed in Lincoln (Schulz and Jarrett, 1991) and Union (Jarrett, 1988) Counties. Water resource studies have been completed in Lincoln and Union Counties (Niehus, 1997; Niehus and Thompson, 1997; Niehus, 1994), and in the Big Sioux River basin as a whole (Lawrence and Sando, 1991). Ground water surveys have been completed in or around the cities of Canton (McMeen, 1965; Frykman and Iles, 1990), Lennox (Beffort, 1969; Hammond, 1989), Beresford (Baker, 1963), Harrisburg (McMeen, 1964), and Alcester (Frykman and Iles, 1996). Ground water surveys have also been completed for southern Union County (Iles, 1979) and southern Lincoln County (Burch, 1979).

Method of Investigation

Fieldwork was completed during the field seasons of 1986-89. Surface deposits and landforms were mapped on vertical aerial photographs having a scale of approximately 1:70,000 (1 inch = 0.9 miles) and on 1:24,000 scale topographic maps. This information was compiled on 1:100,000 scale base maps.

Widely spaced outcrop data were supplemented by numerous power-auger, core-test, mud-rotary, and hand-auger drill holes. Many of the interpretations in this document were derived from examination of drill cuttings, core, and electric logs from these test holes. Representative samples of core and many drill cuttings were transported to Vermillion for laboratory testing and storage. Some information was obtained from the files of local well drillers and from an inventory of private wells (Niehus, 1994). Test hole logs, outcrop data, geochemistry, and geophysical data compiled during this study have been stored in computer databases or paper files at the office of the South Dakota Geological Survey in Vermillion, South Dakota.

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BEDROCK GEOLOGY

Introduction

Stratigraphic nomenclature used herein conforms to that accepted by the South Dakota Geological Survey (Agnew and Tychsen, 1965) and to the Code of Stratigraphic Nomenclature, (North American Commission on Stratigraphic Nomenclature, 1983). The legal descriptions of map location numbers (MLNs) used on maps and cross sections are presented in appendix A. The bedrock stratigraphy found within the study area is shown in tables 1 and 2 and cross sections in appendix B.

Precambrian Geology

Crystalline Basement Rocks

Crystalline rocks have been found beneath the sedimentary sequence in several drill holes in southeastern South Dakota and adjacent states. Magnetic (Petsch, 1962) and gravity (Bartling, 1990) surveys of the area, corroborated by scattered test hole data, suggest that felsic igneous rocks underlie the southeastern corner of Lincoln County and much of Union County. Granite was encountered at the base of three oil tests drilled in central and southern Union County (table 3, cross sections M-M' and Q-Q' (where it is labeled as p€im), and cross section DD-DD' (where it is labeled p€g) in app. B). Similar lithologies were intersected in nearby wells drilled in Sioux City and Hawarden, Iowa, Ponca, Nebraska, and Vermillion, South Dakota (unpublished data from South Dakota Geological Survey files). Rhyolite has been reported from western Sioux County, Iowa (Munter and others, 1983), and may subcrop in some of the area east of Alcester in north-central Union County.

The geophysical surveys noted above also revealed the presence of a band of mafic intrusives underlying townships 90, 93, and 94 in Union County. Test holes at sec. 25, T. 93 N., R. 50 W., and sec. 24, T. 94 N., R. 50 W. (MLN-252 and -290 in cross section CC-CC' in app. B) reached black, magnetite-rich olivine gabbro (Spink Gabbro) immediately subcropping the sedimentary cover. A strongly foliated metagabbro was intersected in a core hole south of Elk Point, South Dakota (NW NW NW NE sec. 13, T. 90 N., R. 50 W.). These rocks have produced remarkably strong geophysical anomalies. Petsch (1962) measured peak magnetic values of over 2,700 gammas near Spink in central Union County, and Bartling (1990) found gravity values more than 40 milligals above background in this same area.

Sioux Quartzite

Most of the Precambrian surface in Lincoln County and northern Union County is composed of Sioux Quartzite (figs. 3 and 4). Dozens of drill holes have encountered the quartzite in this area (cross sections AA-AA', BB'-BB'', CC'-CC'', and DD'-DD'' in app. B). Cored intervals of Sioux Quartzite from several locations in Lincoln County disclose extremely well indurated pink to white, fine-grained to conglomeritic orthoquartzite with occasional beds of red to purple catlinite. Bergstrom and Morey (1985) have suggested that the age of the Sioux Quartzite is between 1,760 and 1,630 million years. The maximum thickness of the quartzite has been the subject of some debate, with estimates ranging from under 1,000 feet (Gries, 1983) to over 3,000 feet (Baldwin, 1949). Although the structural relationships of the Sioux Quartzite with adjacent Precambrian rocks have not been fully explored, the Sioux Quartzite appears to overlie the crystalline basement rocks in the area (Southwick and others, 1986), except for some minor intrusions. Sklar (1982) described intrusives of Corson Diabase into the Sioux Quartzite in adjacent Minnehaha County, South Dakota. Bendrat (1904) described rocks from a well in northwest Lincoln County similar to those at the Corson Diabase outcrops in Minnehaha County. Drill hole data from Hull, Iowa, (about 18 miles east of Fairview, South Dakota) indicate successive beds of Sioux Quartzite separated by up to six layers (sills?) of rhyolitic quartz porphyry (Norton, 1912; Lugn, 1934). Similar felsic intrusives may extend into the study area.

Sioux Quartzite is extremely resistant to erosion and forms the Sioux Ridge, a rugged highland on the Precambrian surface that extends from near New Ulm, Minnesota, to west of Mitchell, South Dakota. The Sioux Ridge is a remnant of the Transcontinental Arch, a topographically elevated belt that straddled the mid-continent beginning in latest Precambrian or earliest Cambrian (Ojakangas and Matsch, 1982). The south flank of this ridge underlies northern Lincoln County, forming a shoulder-like surface at or above 1,300 feet above sea level. Although it is buried by less than 100 feet of sediment in much of northern Lincoln County, the Sioux Quartzite does not crop out within the study area. However, Sioux Quartzite exposures do exist less than 1 mile north into Minnehaha County, South Dakota, and just east of the extreme northeast corner of Lincoln County in Lyon County, Iowa.

The basement surface of northern Lincoln County appears to be quite craggy and rugged. Drill hole data have delineated deep, irregular valleys incised into the topographically high Sioux Quartzite surface (fig. 3 and cross sections A-A', B-B', and C-C' in app. B).

An escarpment approximately along a line drawn through the towns of Lennox and Harrisburg separates this highland from a low relief basement surface at 600 to 700 feet above sea level to the south (fig. 3). Although valleys eroded into the shoulder of the ridge interrupt the continuity of this escarpment, major segments share a common northeast-southwest trend. This linearity led Shurr (1981) to suggest that the escarpment may be the result of faulting. Seismic and gravity surveys (data on file at the South Dakota Geological Survey) indicate a slope rather than an escarpment along this linearity, suggesting rather that this feature is probably erosional.

Beyond the southern edge of the Sioux Quartzite subcrop area (approximately from the northeast corner of Union County to west of Elk Point; fig. 4), the Precambrian surface slopes to the southeast into the Forest City Basin of Iowa at nearly 30 feet per mile.

The influence of the Sioux Ridge upon subsequent geologic events will be discussed later in this report. For further discussion of the history, structure, and petrology of the Sioux Quartzite, the reader is referred to Baldwin (1951), Southwick (1984), and Southwick and others, (1986).

Paleozoic Geology

Paleozoic rocks, consisting of brown shale, vuggy to massive dolostone and limestone, gray-green shale, and pink, brown, and white sandstone, lie upon the topographically lower areas of the Precambrian surface in southern Lincoln County and in most of Union County (cross sections CC-CC', DD-DD', and DD'-DD'' in app. B). Based upon correlation with better known stratigraphic sequences in Iowa, Nebraska, and Minnesota (Carlson, 1970; Witzke, 1980; Ojakangas and Matsch, 1982; Bunker and others, 1988; Runkel and others, 1998), these rocks range in age from Cambrian through Ordovician, and perhaps into Devonian. The Paleozoic stratigraphy in the study area (tables 1 and 3) is based on a rock formation intersected in three Union County drill holes (Wagner No. 1-Blanchard oil test, Sioux Valley No. 1-Lafleur oil test, and South Dakota Geological Survey test hole R20-2002-1, from which core was recovered over the depths of 411 to 1,035 feet; table 3). This unit consists of clean, well-sorted sand, the uppermost part of which can contain frosted and etched quartz grains, and is interpreted to be the Middle Ordovician St. Peter Sandstone.

The Paleozoic rocks identified in the study area were mainly deposited in a shallow mid-continental basin called the Hollandale embayment (Witzke, 1983; Runkel and others, 1998). The northern boundary of the Hollandale embayment was the Transcontinental Arch. Erosion of Transcontinental Arch rocks periodically supplied sediments to the Hollandale embayment (Witzke, 1983; Runkel and others, 1998). The Upper Cambrian rocks are part of the Sauk Sequence (table 1), which represents a series of depositional cycles of marine, marginal marine, and terrestrial sediments deposited in the mid-continent (Pratt, 1987; Bunker and others, 1988; Runkel and others, 1998). Middle Ordovician rocks in the study area are part of the Tippecanoe Sequence (table 1), which represents a period of marine transgression across the mid-continent (Bunker and others, 1988). An erosional unconformity separates the Sauk and Tippecanoe Sequences in this region. During this erosional period, a significant portion of the Sauk Sequence was removed from elevated portions of the region, such as in the area of the Sioux Ridge (Pratt, 1987; Bunker and others, 1988). The Sioux Ridge, structurally the highest part of the Transcontinental Arch, may have remained emergent during this time, at least locally (Ojakangas and Matsch, 1982; Koch, 1986; Runkel and others, 1998). Possible Devonian carbonates would be part of the Kaskaskia Sequence (table 1; Bunker and others, 1988).

The Cambrian to Devonian strata forms a continuous subcrop belt under southern and eastern Union County where the Precambrian surface slopes steeply to the southeast into the Forest City Basin of Iowa. The Forest City Basin formed by emergence of the Nemhi ridge in the Late Paleozoic (Mississippian or Pennsylvanian time) (Steeples, 1982; Sloss, 1988). Although this basin did not exist during deposition of the Cambrian to Devonian rocks, its formation later helped preserve these rocks by creating a topographic low into which younger sediments were deposited. These younger sediments protected the older ones from subsequent erosion.

The Paleozoic strata thin from east to west across southern Union County (compare Sioux Valley No. 1-Lafleur oil test and the South Dakota Geological Survey test hole R20-2002-1 in table 3). Stratigraphic surfaces within the Paleozoic column dip to the south-southeast at about 20 feet per mile and are truncated against the rising Precambrian surface to the northwest (cross sections BB-BB', CC-CC', and DD-DD' in app. B). In central Lincoln and northwestern Union Counties, Paleozoic rocks are restricted to local valleys and swales in the Precambrian surface. Paleozoic rocks are absent in northern Lincoln County.

Undifferentiated Cambrian Rocks

The subtropical to tropical climate of the Early Cambrian (Ojakangas and Matsch, 1982) caused a breakdown of minerals on exposed surfaces of the Precambrian basement rocks. In many parts of the study area, the result was the formation of saprolite (a chemically weathered upper portion of rock) on the Precambrian surfaces (Ojakangas and Matsch, 1982). A white sandy saprolite sporadically mantles the Precambrian lowland surface and locally fills intergranular spaces and fractures in the upper several feet of the Sioux Quartzite in northern Lincoln County. This saprolite is common in the Canton area, sometimes reaching several feet in thickness. An 11-foot thick, red-brown, sticky saprolite with crumbly, rocky zones was intersected in the South Dakota Geological Survey test hole R20-2002-1 in southern Union County (table 3). This red-brown saprolite directly overlies and has a thin gradational contact (approximately 1 inch) with a weathered portion of Precambrian metagabbro.

Other rocks, mainly poorly- to non-cemented sands, also directly overlie the Precambrian surface in the study area. At least some of these sands are derived from underlying Precambrian rocks, (typically Sioux Quartzite in Lincoln County and granite in Union County). Locally these sands are called "wash" (quartzite wash and granite wash). In this study, sands derived locally from the basement rock such as quartzite or granite (Kdqs on cross section J-J' in app. B) are referred to as quartzite-derived or granite-derived sand (table 3), respectively. These sands likely formed from the local Precambrian rocks by chemical weathering, sorting, transportation by water for short distances, and deposition during the Cambrian. However, in northern Lincoln County, many of these sands are not overlain by Paleozoic sediments, and are sometimes interbedded with Cretaceous age rocks, suggesting that not all of the basement rock-derived sands formed during Cambrian time.

Mt. Simon Formation

The Upper Cambrian Mt. Simon Formation (also referred to as the Mt. Simon Sandstone) is widely distributed throughout the mid-continent. It typically directly overlies Precambrian basement rocks (Witzke, 1990; Mossler, 1992), and reaches thicknesses greater than 1,000 feet in Indiana, Michigan, Illinois, and eastern Iowa, but dramatically thins to the west (Witzke, 1990). The Mt. Simon Formation consists of sandstone with minor interbedded shale. The sandstone is variable in its mineralogy and grain size, but is typically a white to gray, medium- to fine-grained, mature quartz sandstone (Uribe, 1994). It is thought to have been deposited in a braided stream to shallow marine environment (Mossler, 1992).

In Union County, the Mt. Simon Formation consists of varicolored quartz-rich sands that directly overlie Precambrian basement rocks or weathered Precambrian basement rocks. In the Sioux Valley No. 1-Lafleur oil test, quartz-rich pink, red-brown, and white sands overlie Precambrian granite (table 3). The upper pink to red-brown sands are believed to be Mt. Simon Formation rocks. The lower white sand could be Mt. Simon Formation or may have formed locally by chemical weathering of the granite surface to form granite-derived wash.

The pink, brown, and gray sandstone directly overlying the saprolite in the South Dakota Geological Survey test hole R20-2002-1 is assigned to the Mt. Simon Formation. In this hole, the sandstone is well sorted and relatively mature. It is quartz-dominated and typically fine- to medium-grained, but thin, fine-grained gravel lenses (up to 1 inch thick) are also present. This unit ranges from strongly cemented (by dolomite and locally pyrite) to poorly cemented. Ferroan oolites are present within the poorly cemented upper portion of the sand. Similar oolites have been noted in south-central Minnesota, where they are believed to have formed in nearshore environments (Mossler, 1992).

The thin, pink sandstone layers in the Mt. Simon Formation in southeastern South Dakota apparently have not been described within this formation in other areas of the mid-continent. It is likely that the pink sandstone originated from the Sioux Quartzite Ridge, which was probably locally emergent along the Transcontinental Arch in the Late Cambrian as previously discussed. Through petrographic studies, some lithic sand grains of the Mt. Simon Formation in southeastern Minnesota have been traced to the Sioux Quartzite (Uribe, 1994), but a pink color has not been described.

The thin, black shale in the Wagner No. 1-Blanchard oil test is tentatively assigned to the Mt. Simon Formation as well (table 3). As previously mentioned, shale layers do occur in the Mt. Simon Formation (Mossler, 1992; Uribe, 1994). However, of the three holes in Union County that are believed to intersect Mt. Simon Formation rocks, the Wagner No. 1-Blanchard oil test is the only one to intersect shale.

Bonneterre Formation

The Upper Cambrian Bonneterre Formation is a carbonate-dominated unit with some shale, siltstone, and glauconite sand (Bunker and others, 1988; Witzke, 1990). It is present across central and western Iowa, eastern Nebraska, and much of Missouri (Bunker and others, 1988). The Bonneterre Formation rocks could have been deposited in a shallow marine or carbonate-rich tidal flat environment (Mossler, 1992) where sedimentation rates were very low [low rates of sedimentation are necessary for the formation of glauconite (Ojakangas and Matsch, 1982)]. Clastic sources for the Hollandale embayment sediments at this time were mainly the Wisconsin Dome and Canadian Shield (Bunker and others, 1988). The Bonneterre Formation occurs a considerable distance to the west and south of these clastic sources, thus clastic rocks (shale and siltstone) are only minor components.

In the South Dakota Geological Survey test hole R20-2002-1, this formation consists mainly of dolostone with minor shale and glauconite sandstone (green sand) and has a cumulative thickness of about 85 feet (table 3). The thickness of this unit appears to be a little less in the Wagner No. 1-Blanchard oil test (59 feet) and considerably less in the Sioux Valley No. 1-Lafleur oil test (43 feet; table 3). Most of the Paleozoic rocks thin to the north and west, so the greater thickness of the Bonneterre Formation in the South Dakota Geological Survey test hole R20-2002-1 (relative to the Sioux Valley No. 1-Lafleur oil test) is somewhat contradictory. It is possible that the upper and lower contacts of this formation in the Sioux Valley No. 1-Lafleur oil test were not well defined, as the formation calls were based on cuttings as compared to those of the South Dakota Geological Survey test hole R20-2002-1, which are based on core.

Wonewoc Sandstone

The Upper Cambrian Wonewoc Sandstone, like the Mt. Simon Formation, is a laterally continuous sandstone that extends across much of the mid-continent. It was deposited in the Hollandale embayment in the Late Cambrian in energetic offshore to nearshore marine environments. This formation typically consists of a fine- to very coarse-grained quartzose sandstone, but dolostone, shale, and feldspathic or glauconitic sandstone also occurs. The Wisconsin Arch and Dome are the probable the regional sources for the clastic sediments of the Wonewoc Sandstone, although the Sioux Quartzite may have contributed locally in the study area (Runkel and others, 1998).

In southeastern South Dakota, the Wonewoc Sandstone consists of white, brown, and gray, fine- to medium-grained, well-sorted, relatively mature quartzose sandstone. It is 64 feet thick in the Sioux Valley No. 1-Lafleur oil test hole, 55 feet in the Wagner No. 1-Blanchard oil test, and 42 feet thick in the South Dakota Geological Survey test hole R20-2002-1. In both the Sioux Valley No. 1-Lafleur oil test hole and the South Dakota Geological Survey test hole R20-2002-1, this formation flowed.

Davis Formation

The Upper Cambrian Davis Formation is recognized in the subsurface of western Iowa, northeastern Nebraska, and northwestern Missouri (Runkel and others, 1998). The Davis Formation is, in part, time equivalent to the Lone Rock Formation in eastern Iowa and southeastern Minnesota.

In Iowa, the Davis and Lone Rock Formations typically consist of siltstone, shale, glauconite sand, and variable amounts of dolostone (Bunker and others, 1988; Witzke, 1990).

In southeastern Union County, the Davis Formation is mainly green-gray shale with thin (typically no more than a few inches thick) dolostone layers and minor sandy lenses. Local zones of glauconite sand (green sand) are also present. The Davis Formation appears to thicken to the south and east in Union County (table 3).

St. Peter Sandstone

The Middle Ordovician St. Peter Sandstone is a time-transgressive unit. It is the basal formation of the Tippecanoe Sequence separated from the Sauk Sequence rocks (such as the Upper Cambrian rocks described above; table 1) by an erosional surface (Bunker and others, 1988). This formation is typically white to light yellow and medium-grained (Ojakangas and Matsch, 1982), with portions consisting of mature, pure quartz sandstone (quartz arenite). In areas of Nebraska, northwestern Iowa, and southeastern Minnesota, the St. Peter Sandstone is less well sorted, contains clay and silt, and is interbedded with shale. The environment of deposition of the St. Peter Sandstone is still argued today. The frosted quartz grains in the upper part of the formation and the dune cross-bedding preserved in the sandstone suggest an eolian environment (Mazzullo and Ehrlich, 1983). Trace fossils (such as burrows) in some parts of the formation suggest to others that it was deposited in a marine environment (Barnes and others, 1992; Barnes and others, 1996). Winfree (1983) suggests that certain sections of the formation are marine, whereas other sections are likely terrestrial (eolian). It is likely, in any case, that the St. Peter was deposited nearshore.

In Union County, the St. Peter Sandstone is typically poorly cemented to unconsolidated, gray to white, fine- to medium-grained, well-sorted and mature. Its thickness varies from 35 and 40 feet in the Wagner No. 1-Blanchard and Sioux Valley No. 1-Lafleur oil tests, respectively, to 25 feet in the South Dakota Geological Survey test hole R20-2002-1. The formation lithology appears to vary in Union County as well. In the Wagner No. 1-Blanchard oil test, the lower part of the St. Peter Sandstone is shaley, but no shale was reported in this formation in the Sioux Valley No. 1-Lafleur oil test and the South Dakota Geological Survey test hole R20-2002-1. However, organic-rich layers were intersected in the South Dakota Geological Survey test hole R20-2002-1. In this same test hole, pink sandstone layers (less than 2 inches thick) are present, but were not reported in cuttings from the other two holes (although these thin pink sandstone layers could easily be missed in cuttings, and thus not reported). These pink sandstones were likely derived from the Sioux Quartzite exposed to the north.

Glenwood Formation

The Middle Ordovician Glenwood Formation is thin, gray-green shale with a sandy base that is probably conformable with the underlying St. Peter Sandstone (Ojakangas and Matsch, 1982; Witzke, 1990). This formation is recognized across the Midwest (Witzke, 1980; Bunker and others, 1988; Nadon and others, 2000). The only test hole in southeastern South Dakota that is known to have intersected this unit is the South Dakota Geological Survey test hole R20-2002-1 in Union County (table 3). In this test hole, the Glenwood Formation is about 12 feet thick. The Glenwood Formation was likely intersected in oil tests in the area, but was not identified. On the natural gamma log, this formation has a slightly higher gamma signature than the Platteville Formation (see below) and a significantly higher gamma signature from the underlying St. Peter Sandstone. On the single-point resistivity log, the Glenwood Formation has a lower signature than both the overlying Platteville Formation and underlying St. Peter Sandstone.

Platteville Formation

The Middle Ordovician Platteville Formation is typically described as a fossiliferous, dolomitic limestone with silty and shaley sections (Ojakangas and Matsch, 1982; Witzke, 1990). It is also a regionally recognizable unit (Witzke, 1980; Bunker and others, 1988). Like the Glenwood Formation, the only test hole in southeastern South Dakota that is known to have intersected this unit is the South Dakota Geological Survey test hole R20-2002-1 in Union County. In this test hole, it is a thin (about 14 feet) brown (apparently organic-rich) dolostone with zones of well-preserved worm burrows.

Galena Group

The Middle to Upper Ordovician Galena Group rocks consist of a thick sequence of dolostone and limestone, with a basal shaley unit, called the Decorah Formation. The Decorah Formation shale is glauconitic, and thus, typically gray-green in color (Jorgensen, 1960; Ojakangas and Matsch, 1982). The sediments that form the shale are derived mainly from the Transcontinental Arch (Witzke, 1983; Bunker and others, 1988), thus the Decorah Formation is mainly shale across regions in close proximity to this structure. In Minnesota and much of Iowa, the Decorah Formation contains significantly thick dolostone and limestone beds (Bunker and others, 1988).

Galena Group carbonate and cherty carbonate rocks overlie the Decorah Formation across large areas of the mid-continent. In Iowa, these upper dolostone and limestone formations (from base to top) are the Dunleith Formation, which is generally fossiliferous and cherty, and the Dubuque and Wise Lake Formations, which are generally fossiliferous and non-cherty (Witzke, 1990).

In Union County (table 3), the Galena Group dolostone reaches a thickness of at least 92 feet. It is gray with cherty horizons (typically less than 2 inches thick) and chert-filled vugs. This cherty unit probably correlates to the Dunleith Formation (Witzke, 1983 and 1990). In core from the South Dakota Geological Survey test hole R20-2002-1, shell fragments are evident, especially in the cherty zones. One fossil, oriented parallel to the long axis of this core, almost 1 foot in length, and up to about 0.75 inch in diameter, has been tentatively identified as a bryozoan. A dolomite-cemented sandstone, approximately 10 feet thick, separates the upper carbonate rocks from the lower shale in this test hole. The Decorah Formation reaches a thickness of 150 feet in southern Union County. It is mainly gray-green shale with thin sandy lenses and dolostone layers. The dolostone layers are commonly vuggy. Shell fragments commonly occur in thin zones.

Undifferentiated Devonian Rocks

Dolostone and limestone of probable Devonian age are present in the South Dakota Geological Survey test hole R20-2002-1 and the Sioux Valley No. 1-Lafleur oil test (table 3). This carbonate unit is gray and vuggy, with soft, greenish "clay" partially filling the vugs. Cavities (>4 inches in diameter based on a caliper log from the South Dakota Geological Survey test hole R20-2002-1, but of unknown maximum size) are developed locally. Deposits of greenish, silica mud are found in layers a few inches thick in this unit, and thin sandy and shaley zones also occur. Rare molds of brachiopods are present in the South Dakota Geological Survey test hole R20-2002-1. A possible bentonitic clay layer was also identified in this unit.

Undifferentiated Paleozoic Sandstones

Thick sequences of undifferentiated Paleozoic sandstones also occur at the uppermost preserved part of the Paleozoic column in Union County (table 1 and Wagner No. 1-Blanchard oil test, table 3). These sands are directly overlain by the Cretaceous Dakota Formation. Although similar to those of the Dakota Formation, they are distinctive in that they contain dolostone chips and locally contain phosphate pellets.

Undifferentiated Paleozoic sands also may be present in the Canton-Lennox area of Lincoln County (MLN-38 in cross section B-B' in app. B). Here, colorless, white, and pink, well-cemented quartz sands up to 25 feet thick mantle low-lying basement surfaces. White kaolinite claystone commonly occupies virtually all of the intergranular space in these rocks. The primary evidence suggesting a Paleozoic origin for these rocks in this drill hole is a higher percentage of well-rounded grains than in the overlying Cretaceous Dakota Formation. Paleozoic sandstones in nearby Iowa and Minnesota typically contain well-rounded texturally mature grains (Bunker and others, 1988; Mazzullo and Ehrlich, 1983).

Cretaceous Geology

Late Cretaceous age rocks underlie all of the study area except in far northern Lincoln County where glacial sediments directly overlie the high shoulder of the Sioux Ridge. This Cretaceous sequence records the transgression of an epicontinental sea (the Western Interior Seaway; fig. 5) into this portion of the North American interior from about 100 to 67 million years (Obradovich and Cobban, 1975). The general stratigraphic relationships of these rocks in the study area are presented in table 2 and illustrated in the cross sections in appendix B. The Cretaceous rocks in Lincoln and Union Counties are generally flat lying with only a slight dip to the south across the study area. However, in northern Lincoln County, Cretaceous strata ramp more sharply upward onto the Sioux Ridge.

Quartzite-Derived Sand

Quartzite-derived sand (locally termed "quartzite wash") consists of fine- to medium-grained, pink sands deposited adjacent to the Sioux Ridge (Hammond, 1991). The quartzite-derived sand formed by chemical weathering of the Sioux Quartzite. The timing of this chemical weathering is inferred to be during the Cretaceous (Austin, 1970) when the climate was warm and humid. In northern Lincoln County proximal to the Sioux Ridge, the quartzite-derived sand can reach a thickness of at least 100 feet. In this report, quartzite-derived sands are not mapped as a separate unit. Rather, in embayment environments where these sands are often interbedded with white clay or black organic-rich claystones, they are grouped with the Cretaceous undifferentiated rocks. Outside of the embayment environments, these sands can occur as beds within Dakota Formation sediments and are mapped as Dakota Formation.

Dakota Formation

The Dakota Formation underlies a broad arc of territory extending from Manitoba, Canada, to the Iowa–Minnesota area to New Mexico. In South Dakota, it is an important regional aquifer over much of its areal extent.

The Dakota Formation, the lowermost Cretaceous rocks in the region, underlies all of the study area except the Sioux Ridge highlands in extreme northern and southwestern Lincoln County (figs. 6 and 7). Although it is not exposed at the surface in the study area, excellent outcrops exist in Iowa and Nebraska adjacent to North Sioux City at the extreme southern tip of Union County. The thickest interval encountered during drilling in the study area is near the town of Spink in central Union County where 415 feet of Dakota Formation sediments were penetrated.

In the northwestern Iowa-southeastern South Dakota area, the Dakota Formation can be divided into two members: the lower sandstone-dominated Nishnabotna Member and the upper mudstone-rich Woodbury Member (Munter and others, 1983). However, these two members are difficult to distinguish over most of the study area.

The lower beds of the Nishnabotna Member are composed of coarse to medium sandstones interbedded with massive gray to light gray mudstone intervals. Higher in the sequence the Nishnabotna Member grades to very fine, well-sorted sands. Quartz sands predominate in the Dakota Formation, with lesser amounts of muscovite, feldspar, chert, and metamorphic lithic fragments. These sands are subangular to angular and poorly to tightly cemented. Intergranular cements are mainly ferric carbonates, oxides, and sulfides with lesser amounts of calcium carbonate and clayey cements (Witzke and Ludvigson, 1996). Some drill holes, particularly in southern Union County, intersected several feet of siderite- and pyrite-cemented sandstones armoring the upper surface of the Dakota Formation.

The interfingering of sandstones with claystone layers in the Nishnabotna Member is commonly quite complex. These patterns are a relic of the stream-dominated landscapes in which they were formed. Many of these processes are presently active in the flood plains of the Missouri River and the Big Sioux River. The sandstones, especially in the lower portions of the member, were deposited mainly in meandering, sluggish river channels. Mudstones were deposited as overbank flood deposits, oxbow fills, and other fine-grained alluvial fill (Witzke and Ludvigson, 1996).

Carbonized plant remains in upright life positions are preserved in cores from near Canton and Beresford. Thin beds of carbonized debris are common throughout the unit. Nishnabotna Member sediments reach a thickness of greater than 300 feet in central Union County test holes.

Sequences of sediments deposited by tidal oscillations have been observed at upper Nishnabotna–lower Woodbury Member outcrops in northeastern Nebraska. These sequences were deposited during the fluvial to marine transition period within this stratigraphic interval. In general, the contact between the two members is difficult to pinpoint other than at such key locations.

The Woodbury Member, although well exposed just a few hundred feet outside of the boundaries of Union County, is sparsely represented in the study area. Maximum measured thickness is about 130 feet near McCook Lake in far southern Union County. The Woodbury Member appears to thin and become discontinuous northward toward the Sioux Ridge. Shale and siltstones predominate with minor fine sandstones and coal seams. Megaripples, hummocky cross-stratification, and clayey rip-up clasts exist in many beds, recording the passing of strong storms through the area. Marine to brackish water fossils, including teleost fish and inoceramids are common in the Woodbury Member. Crocodile, turtle, shark, and ichthyodectid fish remains have been recovered from outcrops near North Sioux City in Iowa and Nebraska (Ludvigson and others, 1994).

Graneros Shale

The conformable contact of the Graneros Shale with the underlying Dakota Formation has traditionally been drawn at the "first relatively continuous sand below the Greenhorn Limestone" (Schoon, 1971). In the Sioux Ridge area, this indicator has proven to be inconsistent and impractical. Sand lenses often constitute a large fraction of the sediments upward through the Graneros Shale into the lower beds of the Greenhorn Limestone. However, an interval of slightly calcareous mudstones 30 to 60 feet thick exists between noncalcareous Dakota Formation sediments and the highly calcareous Greenhorn Limestone. These sediments typically display a consistently smooth electric and natural gamma log signature, aiding in identifying the interval in subsurface data. The present report recognizes this sequence as the Graneros Shale.

Like the underlying Dakota Formation, the Graneros Shale thins, then truncates against the Sioux Quartzite Ridge in northern Lincoln County (cross section AA-AA' in app. B). This formation also gains a noticeable component of Sioux Quartzite grains derived from the adjacent ridge in its northern areas.

The Graneros Shale is a gray-brown, waxy to gritty, weakly calcareous shale. The unit contains abundant septarian concretions, some over 3 feet across and more than a foot thick. The formation is composed mainly of planar-bedded dark mud, rich in organic carbonaceous debris. It contains countless thin, wavy-bedded fine sandstones and fine siltstone wisps, especially in the lower beds.

Most of the sediments are cemented tightly with ironstone, mainly siderite. Framboids and cubes of pyrite are typically scattered throughout the sediments but also form hard beds at several intervals. A few bentonite beds up to 2 inches thick are persistent markers in the Graneros Shale.

Like the Dakota Formation, the Graneros Shale contains a broad suite of fossils ranging from inoceramids, some ammonites, teleost, and osteoglossomorph fish debris, marine turtles, and shark teeth. A large plesiosaur fossil was discovered just across the Big Sioux River from Jefferson in the late 1800s.

Greenhorn Limestone

The Greenhorn Limestone is composed of interbedded gray, silty, calcareous shale, calcarenite, and hard skeletal limestone containing abundant foraminifera and Inoceramus fragments. Other fossils are also abundant including many types of fish, shark teeth, ammonites, and other marine shellfish. Beds of tightly packed ostrea shells form hard ledges in some outcrops along Brule Creek in central Union County. These outcrops also display fish spines, vertebra, and abundant fish scales. Many of the latter are greater than 1 inch in diameter.

Bentonite beds up to 2 inches thick occur in the formation. A persistent 2-inch thick bed of massive pyrite is at about the middle of the formation at the Brule Creek outcrops.

Characteristics of the Greenhorn Limestone in the study area suggest relatively deep-water deposition. Thin planar-bedded to very low amplitude ripples, high organic carbon preservation, and preservation of delicate sedimentary structures indicate deposition in a poorly oxygenated environment near effective storm-wave base. Regional studies (Weimer, 1988) have established Greenhorn Limestone sedimentation at or near the maximum flooding surface of the Greenhorn eustatic cycle (table 2; Haq and others, 1988).

The Greenhorn Limestone is a key marker throughout the western interior due to its distinctive electric-log signature (high resistivity), abundant temporally distinct macrofauna, relatively constant thickness, and widespread occurrence. Sharp but conformable boundaries separate the Greenhorn Limestone from both underlying and overlying rocks. Like other Cretaceous rock units, the Greenhorn Limestone laps unconformably onto the shoulder of the Sioux Ridge in northern Lincoln County.

Outcrops along Brule Creek in central Union County are kept freshly scoured by frequent floods. These outcrops display the "normal" dark- to medium-gray color of the Greenhorn Limestone found in the subsurface in contrast to the highly weathered white to yellowish exposures along the Big Sioux River and the Missouri River in neighboring states.

The Greenhorn Limestone averages about 30 feet thick across most of the study area, but may locally be absent. This formation thickens to nearly 50 feet in central Lincoln County, probably due to clastic input from the Sioux Ridge.

Carlile Shale

The Carlile Shale contains, from base to top, the basal Fairport Shale Member, the Blue Hill Shale Member, and the Codell Sandstone Member, although individual members are not always present. The Carlile Shale is up to 230 feet thick in tests drilled for this study and is the uppermost bedrock unit over much of southern Lincoln and northern Union Counties (pls. 1 and 2). Carbonized plant debris, shark teeth, fish scales and vertebra, inoceramids, oyster shells, and ammonites are the most common fossils found in the formation. The lower contact of the formation is sharp and conformable.

The lowermost member of the Carlile Shale, the Fairport Shale Member, is a dark-gray, fissile, greasy, calcareous shale with numerous thin silty beds and silty horizontal burrow traces. Abundant small, white fecal pellets, consisting mainly of foram tests, give outcrops and drill samples a distinctive speckled appearance. Finely disseminated pyrite forms small pellets and nodules at some locations.

Several concretion beds (individual concretions up to 3 feet across and 16 inches thick) occupy positions just above the lower contact of the formation. These concretions commonly contain finely preserved sedimentary structures and fossils. Excellent ammonite specimens have been collected from Fairport Shale Member outcrops near the town of Richland. The Fairport Shale Member has a noticeably high natural gamma log signature making it easy to detect on geophysical logs. It is nearly 100 feet thick in northern Union County.

The Blue Hill Shale Member is a greasy, concretionary, noncalcareous, organic-rich dark gray shale with occasional thin sandstone and silt lenses. Thin greenish and tan bentonite beds are common, especially in the upper half of the member. The Blue Hill Shale Member is well exposed along Brule Creek in Union Grove State Park and along a discontinuous outcrop belt in northeastern Union County (pl. 2, T. 95 N. and T. 94 N., R. 48 W.). Ammonite fossils are commonly preserved in concretions in this member. The concretions reach 6 feet in diameter in and near Union Grove State Park in northwestern Union County.

About 8 feet above this concretion bed is a layer of bone, apatite clasts, and other phosphate-cemented fossil debris. This bed is a distinct marker, traceable over a wide area in eastern South Dakota and northeastern Nebraska. It is probably the largest and most evident of the multiple hard ground deposits in the upper Carlile Shale, representing periods of condensed marine sedimentation on a shelf sheltered from clastic input. Hattin (1975) and Merewether and Cobban (1981) have established that a long period of nondeposition occurred at this time and area.

In the study area, only a few thin scattered sandstone lenses occur in the upper Carlile Shale in the position normally occupied by the Codell Sandstone Member. The hard ground deposits mentioned above may occupy the Codell Sandstone Member’s stratigraphic position in Lincoln and Union Counties. Codell Sandstone beds crop out along the James River valley and tributaries approximately 30 miles west of Lincoln County.

The upper surface of the Carlile Shale is exposed northwest of Vermillion in Clay County (about 8 miles west of Union County) and across the Missouri River from Vermillion in Nebraska. The contact with the overlying Niobrara Formation is undulatory with swales up to 10 feet deep and several tens of feet across incised into its surface. These channels are filled with coarse-bedded silts, woody plant debris, bone, phospatic nodules, shale clasts, and other coarse debris.

Niobrara Formation

The Niobrara Formation is the uppermost bedrock formation in about one-third of Lincoln County and part of northwestern and north-central Union County. It approaches 100 feet in thickness near Worthing in Lincoln County. The Niobrara underlies much of central and southwestern Lincoln County and the higher land around Beresford in northern Union County (pls. 1 and 2).

The Niobrara Formation in this study area is normally medium- to dark-gray interbedded chalk, limestone, and calcareous shale, weathering to white and pale-yellow or tan. Weathered Niobrara Formation is typical of outcrops, but is also found in the subsurface, indicating that this formation was exposed at the surface in the past, as well. The Niobrara Formation lies unconformably on the Carlile Shale. Core retrieved from a drill hole at sec. 22, T. 96 N., R. 50 W. contains highly bioturbated (Thalassinoides, Planolites, Chrondites, and Zoophycos burrowings) chalks with scattered marcasite and pyrite nodules, interbedded with thin, wavy-bedded calci-siltstones. A few light-gray and olive micaceous bentonite beds were penetrated. Hand samples of the rock are very porous and lightweight, especially the chalk intervals.

Fossil inoceramids, often encrusted with oysters, are abundant. Carbonized plant remains, fish scales and bone fragments, plesiosaur bones, and woody fragments have been found in or near the study area. Echinoderms are easily found at outcrops along Beaver Creek northwest of Canton in Lincoln County.

Cretaceous Undifferentiated Rocks

As previously mentioned, the Western Interior Seaway (fig. 5) covered the mid-continent of North America during the Late Cretaceous. At its eastern margin, large portions of the Sioux Ridge remained above sea level, forming a series of islands. Steep-sided canyons (embayments) are present along the Sioux Ridge (cross section A-A’ in app. B). Within these embayments, typical Upper Cretaceous sediments (described previously) grade into sequences of interbedded sandstone and claystone, laminated black organic-rich shale, interbedded opaline spiculite, and massive chert. A section of this sequence of sediments was first recognized and described by Ludvigson and others (1981) along Split Rock Creek in southeastern Minnehaha County, South Dakota. This type section has been assigned the formal name of Split Rock Creek Formation.

In recent years the term Split Rock Creek Formation has been informally expanded to include embayment fill along the entire Sioux Ridge. However, it is not known whether sediments correlate either lithologically or time-stratigraphically from one embayment to another. For this reason, the term Split Rock Creek Formation will not be applied to lithologies described in this report. Rather, the embayment fill sediments, even where they are interfingered with the more typical Upper Cretaceous formations (Dakota Formation, Graneros Shale, etc.), are lumped together as Cretaceous undifferentiated rocks.

The Cretaceous undifferentiated rocks in northern Lincoln County consist of a suite of nearshore facies and embayment fills deposited along the rugged paleoshore of the Sioux Quartzite Ridge (pl. 1). In this area, they are likely nearshore equivalents of the Dakota Formation, Graneros Shale, Greenhorn Limestone, Carlile Shale, and Niobrara Formation (table 2; Holtzheimer, 1987).

The Cretaceous undifferentiated strata record a nearly continuous range of depositional settings from quiet water embayments to wave-battered, rocky shorelines to shallow shelf marine environments, dominated by coarse terrestrial sediments. Locally, these sediments can be separated into discontinuous zones of the more characteristic Cretaceous formations (such as the Carlile Shale and Niobrara Formation). South of the Sioux Ridge, the contact between the Cretaceous undifferentiated rocks and the characteristic Upper Cretaceous stratigraphy is typically placed where the complete sequence of normal marine Upper Cretaceous sediments can first be recognized in hand samples or electric logs.

The Cretaceous undifferentiated rocks normally consist of an often pink-colored lower sand-dominated unit (quartzite-derived sand or “quartzite wash”), and an upper unit composed mainly of mudstone. The lower clastic unit reaches a thickness of at least 100 feet in Lincoln County. It is composed of cross-bedded, fine- to coarse-grained, angular to sub-rounded grains of quartz. Beds of gray, white, and pink mudstones up to 15 feet thick break the sands into irregular depositional sequences. Carbonaceous debris, often containing well-preserved wood, is scattered through the sands. Black carbonized debris forms coal-rich layers in the intervening mudstones.

The upper mudstone-dominated unit, which may correlate with the Split Rock Creek Formation of Minnehaha County (Tomhave, 1994), reaches at least 60 feet in thickness in northern Lincoln County. These sediments are composed of carbonaceous claystones, calcium bentonites, sandy siltstones, hard-bedded phosphatic nodular beds, cherts, and distinctive opaline spiculites. Several beds of quartzite wash are interbedded in these lithologies. The sponge remains that occur throughout this sequence of rocks are diagnostic of well-protected depositional sites. Abundant, well-preserved terrestrial plant and animal fossils suggest that a large expanse of the Sioux Ridge remained emergent, even during periods of extremely high late Cretaceous sea levels.

Bedrock Surface Topography

The bedrock surface in Lincoln and Union Counties ranges between approximately 950 feet above sea level in the Missouri River valley in southern Union County to about 1,400 feet above sea level along the northern border of Lincoln County. Three predominant terrains are distinguishable on pls. 1 and 2: (1) a broad, smooth low bedrock surface occupying southern Union County, (2) a rugged highland in northern Lincoln County, and (3) a surface of moderate relief incised by rivers. The broad, smooth, low bedrock surface occupying southern Union County mimics the present

Missouri River valley but is somewhat larger (pl. 2). The form of this large valley, which is incised into the bedrock surface, indicates that it is the product of erosion along a large master stream. Although this large valley underlies the Missouri River trench in southern Union County, in other counties in southeastern South Dakota it is unrelated to the present-day Missouri River and certainly predates the formation of the Missouri River.

North of a line approximately through Lennox and Harrisburg the bedrock surface is a rugged highland composed mainly of Sioux Quartzite with some undifferentiated Cretaceous rocks (pl. 1). Broad, flat Sioux Quartzite surfaces are separated by steep sided (often vertical to nearly vertical) box canyons eroded into the side of the Sioux Ridge. Topographic patterns are irregular and are probably controlled more by joints and faults in the Sioux Quartzite than by other erosional processes.

The area between the lowlands of southern Union County and the Sioux Quartzite highlands in northern Lincoln County (pls. 1 and 2) is an intermediate surface cut by tributaries that fed into the master stream to the south. Flat-lying chalk, shale, and limestone bedrock have been carved mainly by stream erosion, although erosion by glacial ice and meltwater is also evident.

QUATERNARY GEOLOGY

Quaternary sediments form the surface deposits in almost the entire area of Lincoln and Union Counties (pls. 3 and 4). These sediments range to over 300 feet thick in southern Lincoln County (fig. 8), but more commonly are 150 feet thick or less across most of the study area (figs. 8 and 9). Glacial processes deposited the majority of these sediments.

Quaternary Stratigraphy

Table 4 presents the generalized stratigraphy of Quaternary deposits in the study area. Most of these sediments date to the Pleistocene Epoch, although alluvium along many of the streams has been deposited more recently (Holocene). The oldest Quaternary sediments are the quartz-rich silts, sands, and fine gravels (locally known as western-derived, Newton Hills and Alcester sands). These sands, where present in Lincoln and Union Counties (figs. 10 and 11), are found directly overlying the bedrock or thin paleosols developed on the bedrock. They are probably early to early middle Pleistocene in age, but may be as old as late Pliocene. One period of western-derived sand deposition may be as young as late middle Pleistocene (Flint, 1955).

Pre-Illinoian glacial sediments overlie bedrock or quartz-rich sands (where present) in the study area. At least three, and perhaps four episodes, of pre-Illinoian glaciations (pre-Illinoian 0(?) to pre-Illinoian 3) deposited these sediments (table 4). The youngest pre-Illinoian deposits discussed in this report (pre-Illinoian 3 deposits) are tentatively correlated with the southern Minnehaha pre-Illinoian 3 till. This inferred correlation is the basis for all of the Pleistocene stratigraphy in Lincoln and Union Counties. Thick, laterally continuous glacial-fluvial deposits of sand and gravel commonly separate pre-Illinoian depositional sequences. Discontinuous loess deposits overlie the pre-

Illinoian 0(?) and pre-Illinoian 1 sediments. A much thicker blanket of loess, exposed at the surface, overlies pre-Illinoian sediments in southern Lincoln and in Union Counties (pls. 3 and 4). Although oxidized till, thick outwash bodies or loess help correlations among tills, these units are not always present; thus, correlations of tills across the study area are often tenuous.

No Illinoian glacial deposits are believed to be present in the study area based on recent revisions to the stratigraphy of the glacial deposits in western Iowa and eastern Nebraska (Hallberg, 1986). Tomhave (1994) suggests some Illinoian glacial-fluvial sediments may have been deposited in the study area by meltwater entering Lincoln County from Minnehaha County. However, no definite Illinoian glacial fluvial deposits were recognized in this study in Lincoln or Union Counties.

Late Wisconsin deposits are the youngest Pleistocene sediments in the study area (table 4), and as no evidence has been found to indicate that Lincoln and Union Counties experienced more than one late Wisconsin glacial advance, all are attributed to one glacial advance. Thick, locally continuous reddish-brown loess deposits, and thick, relatively continuous glacial-fluvial sand and gravel deposits underlie late Wisconsin sediments. Locally, loess and Holocene eolian silt blanket the late Wisconsin glacial sediments.

Holocene sediments overlying the Pleistocene sediments in Lincoln and Union Counties include fluvial deposits within present-day streams.

Plio(?)-Pleistocene Deposits

Quartz-Rich Sands

The silts, sands, and fine gravels referred to as western-derived sand, Newton Hills sand (Qpis on pl. 3), and Alcester sand (Qpis on pl. 4) consist predominantly of quartz, with variable amounts of feldspar grains, other igneous and metamorphic minerals or rock fragments, and pieces of lignite. They are relatively well sorted and variably colored (white, gray, brown, yellow, green, and orange). Although these sands are similar in appearance, composition, and sorting, it is not known if the western-derived, Newton Hills and Alcester sands are related (temporally or by provenance).

WESTERN-DERIVED SAND

Western-derived sand is believed to be nonglacial fluvial in origin (Flint, 1955). The source for these sands is believed to have extended from the Rocky Mountains to the Black Hills (Wanless, 1923; Flint, 1955), with some components of the sand derived from formations east of the Black Hills in western South Dakota (Flint, 1955). The sands were transported to eastern South Dakota primarily by the ancient White and Niobrara Rivers (Flint, 1955). However, the distribution of western-derived sand near or within more north-south trending bedrock channels in Lincoln County (fig. 10) suggests that the provenance of at least some of these sands may have been to the north-northeast, in what is now southwestern Minnesota.

NEWTON HILLS SAND

The Newton Hills sand is likely fluvial based on grain shape analysis (Baird, 1957). However, it has been suggested that this deposit is proglacial fluvial-lacustrine (Baird, 1957), rather than nonglacial fluvial in origin. The degree of sorting, maturation, and absence of local Cretaceous lithologies indicates that, irrespective of depositional environment, the Newton Hills sand cannot have originated from local Cretaceous rocks. The great thickness of Newton Hills sand (Qpis; over 100 feet in MLN-141 in cross section F-F' in app. B) requires either (1) a significant decrease in stream transport energy for continuous deposition, or (2) post-depositional modification of the deposit. A decrease in stream transport energy could occur either in a fluvial-lacustrine system, as Baird (1957) suggested, or in a relatively topographically low area, where the stream gradient is very low. One possible post-depositional modification could have been ice thrusting, where the glacier moves part of the frozen deposit up and onto another part of the deposit.

Tipton (1958) believed that the Newton Hills sand in Newton Hills State Park overlies a till unit, although Baird (1957) did not. Tipton (1958) further correlated sands that he mapped in the Akron 7.5-minute Quadrangle, which he called Newton Hills sand, to the Atchinson sand (Atchinson Formation of Nebraska) based on similar compositions and stratigraphy – both sand units underlie a volcanic ash (said to be Pearlette "O" by Tipton, 1958). If the Newton Hills sand does overlie till, its age would be constrained to the Pleistocene. Furthermore, if the sand that Tipton (1958) found in the Akron Quadrangle is Newton Hills sand, and the ash overlying it is the Pearlette "O" (dated at 610,000 years; Izett and Wilcox, 1982), then the Newton Hills sand must be Early Middle Pleistocene (although still pre-Illinoian) in age. However, the clay below the Newton Hills sand is interpreted in this report to be Carlile Shale, based on mud rotary drilling [which is consistent with Baird's (1957) analysis].

ALCESTER SAND

The sand in the Alcester area, which will be referred to as the "Alcester sand," although in an elevated location relative to proposed pre-Pleistocene drainages of Union County (fig. 11), does not occur at the highest topographic levels in the area. The sand occurs adjacent to a bedrock high northeast of Alcester (fig. 11 and pl. 2). An unusual feature of the Alcester sand is that it appears to thicken southwestward toward even higher ground in Union County.

The Alcester sand is likely fluvial or glacial-fluvial, based on the presence of medium-sized gravel in the deposit. Thus, the Alcester sand could have been emplaced in one of two ways: (1) by a Tertiary (nonglacial) stream system, possibly part of the west to east drainage that deposited the Ogallala Group rocks, or (2) by an englacial or supraglacial meltwater stream. The distribution of the Alcester sand, a thickening toward the bedrock high capped by Niobrara Formation in central Union County, suggests that part of this sand may have been eolian (syn- or post-depositional, or both) or may have been ice thrusted from lower to higher bedrock elevations as subsequent glaciers advanced over the area. The possible provenance of the Alcester sand is unknown.

Other Deposits

Lacustrine sediments and a paleosol associated with the quartz-rich sands have been intersected in a few drill holes in Lincoln County. The lacustrine sediments, where present, occur within the sands (MLN-201 in cross section I-I' in app. B). Possible paleosols have been found to underlie and overlie the sands (MLN-175 and MLN-180 in cross section H-H' in app. B).

Pleistocene Deposits

Till

Till consists of nonstratified, unsorted debris that has been transported and deposited directly by glacial ice. The composition and grain size of the till are functions of the rocks or sediments over which the ice traveled. In Lincoln and Union Counties, the till consists primarily of a silty clay matrix, a variable proportion of sand and pebbles, and few boulders (based on drill hole data). This small grain size reflects the predominance of shale in the bedrock over which the ice advanced in eastern South Dakota. Local chalk-rich, calcareous till is likely formed where the ice overrode nearby chalky and/or calcareous bedrock units (such as the Fairport Shale Member of the Carlile Shale, the Niobrara Formation, or chalky members of the Pierre Shale). Local very sandy till likely formed where the ice overrode outwash and pre-Illinoian sands, or alternatively, where outwash from englacial or supraglacial meltwater was let down by the ice as it melted. The pre-Illinoian tills contain selenite crystals ($CaSO_4 \cdot 2H_2O$), which typically crystallize within fractures. Calcium carbonate ($CaCO_3$) nodules can be found within any of the till units, but are not a common occurrence. The lowermost (oldest) till units can also be highly compact due to compression by the weight of the overlying sediments and/or ice.

Each till unit typically consists of a yellow to brown (less commonly orange and reddish) upper oxidized zone, and a light-gray to dark-gray to blue-gray lower unoxidized zone. Rarely, tills in Lincoln and Union Counties can have a greenish or olive hue. The greenish or olive hue is indicative of a reduced zone, that is, a zone that had originally oxidized, but was subsequently reduced (Bettis, 2000), possibly by a rising water table. For this report, greenish or olive till is grouped with unoxidized (gray) till. The orange and reddish colors in the oxidized till suggest extreme weathering, which in turn, suggests a long surface exposure time and a low water table.

Distinguishing among separate pre-late Wisconsin till units by lithology is difficult in the field, as all units have a clay-rich matrix. Several indicators that are used to separate till units include the presence of oxidation zones, outwash and loess deposits, electric log signatures, and stratigraphic position. Late Wisconsin can be differentiated from pre-late Wisconsin till units in the laboratory by pebble counts (Schroeder, 1979) and in the field or on topographic maps by geomorphology.

Because multiple glacial advances and retreats have occurred in Lincoln and Union Counties, two or more till units typically overlie the bedrock surface. In areas of bedrock highs, such as in north and central Union County, only one till unit may be present, and locally, loess may directly overlie the bedrock surface. The only extensive area of the subsurface in which till appears to be absent is in southern Union County, beneath the Missouri River flood plain. The absence of recognizable multiple till units or any till unit in some areas of these counties could be due to removal by erosion, nondeposition, or simply no penetration of the units in drill holes.

In this study, four pre-Illinoian till units ($Qpi_{0?}t$, Qpi_1t, Qpi_2t, and Qpi_3t), and one late Wisconsin till unit (Qwlt) have been identified in Lincoln and Union Counties (see legend for the geologic cross sections in app. B). Pre-Illinoian till units are designated as undifferentiated (Qpit) where pre-Illinoian stratigraphy cannot be inferred.

Outwash

Outwash is sand and gravel, with minor silt and clay, deposited by meltwater streams. In Lincoln and Union Counties, outwash typically consists of sand- and gravel-sized fragments of igneous and metamorphic rocks, siltstone, sandstone, shale, limestone, individual quartz grains, and rarely pyrite. These outwash bodies can also contain a variable component of reworked pre-Illinoian quartz-rich sand. The outwash deposits range from poorly to relatively well sorted and can be relatively well stratified.

Outwash bodies are found within till units, between till units, and along surface stream channels (Qpi_1o, Qpi_2o, Qpi_3o, and Qwlo; see legend for the geologic cross sections in app. B). The outwash bodies within till units are typically less than 30 feet thick and laterally discontinuous. However, the outwash bodies between till units are typically thick (>30 feet, in some areas >100 feet) and laterally continuous. Just south of Harrisburg and lying below part of the present-day Long Creek in Lincoln County is a buried, broad valley trending northeast-southwest that is locally filled with 50 feet of sand and gravel (Qwlo; MLN-35 and -36 in cross section B-B' in app. B). In southernmost Union County, as much as 150 feet of sand and gravel underlie the present-day Missouri River and Missouri River flood plain.

Many of the thick (>50 feet) outwash deposits (Qpio and Qo; see legend for the geologic cross sections in app. B) occur between till units in areas that were topographic lows at the time of deposition. It is difficult to constrain the ages of these basal deposits because they can form during both advance and retreat of a glacier. As a result, lower portions of basal outwash deposits could be of the same general age as the underlying till unit, whereas upper portions could be of the same general age as overlying till unit. In areas where outwash deposits overlie unoxidized till, it is difficult to determine whether the body was originally basal to (where erosion removed the oxidized portion of the underlying till unit), or within a till unit.

Outwash terraces are surface- to near-surface deposits of variable thickness. They were originally more laterally continuous but were subsequently subject to major erosion. In Lincoln and Union Counties, short sections of some river valleys (Big Sioux River, Long Creek, and Brule Creek valleys) still have numerous outwash terrace deposits (Qwlot and Qwloa; pls. 3 and 4).

Eolian Deposits

Eolian deposits form via the winnowing of clay-, silt-, and sand-sized particulates from surficial sediments. The most common type of eolian deposit occurring in Lincoln and Union Counties is wind-blown silt called loess (the term loess is applied to eolian silt specifically of Pleistocene age). Loess typically consists of moderately well-sorted, nonstratified silt deposited by wind. It is porous and can maintain vertical or nearly vertical slopes. These deposits can cover all surfaces regardless of topography. Loess deposition is favored in dry climates where there is a supply of relatively fine-grained material, vegetation is minimal, and moderate to strong prevailing winds are common. Thus, loess is often deposited in periglacial environments or during interglacial periods.

Loess discontinuously blankets south-southeastern Lincoln County and much of Union County. Surficial loess deposits in these portions of the study area locally reach a thickness of over 40 feet. These deposits are designated Ql on the surficial geology maps (pls. 3 and 4), as they could range in age from pre-Illinoian to late Wisconsin.

Episodes of loess deposition commonly occur during interglacial periods and are not restricted to the late Wisconsin glaciations (Benn and Evans, 1998). Thus, remnant loess deposits also can be found on buried pre-Illinoian till surfaces in the study area (Qpi_1l, Qpil, and Qpwll; see legend for the geologic cross sections in app. B).

A far less common eolian deposit in the study area is dune sand. A possible pre-Illinoian sand dune was tentatively identified in the subsurface of Union County in sec. 24, T. 94 N., R. 50 W. [Qpids(?) in MLN-252, cross section CC-CC' in app. B]. One possible pre-late Wisconsin dune sand deposit, located adjacent to Brule Creek in west-central Union County (Ql in secs. 15 and 16, T. 93 N., R. 50 W., pl. 4), is also identified in this study. This feature is loess covered, making identification difficult. However, it is an elongate topographic high occurring between Brule Creek and the pre-Illinoian till that forms the higher ground in Union County (pl. 4). The drill hole that intersected this feature penetrated 37 feet of eolian(?) sand which overlies 6 feet of silt (no mention was made in the log of frosted quartz grains in the sand deposit). The shape of this feature, as well as its occurrence between major outwash bodies along Brule Creek and the pre-Illinoian till highlands, are consistent with the interpretation that this is a sand dune.

Lacustrine Sediments

Lacustrine sediments accumulate in areas containing ponded glacial meltwater and are often found in association with outwash deposits. These sediments range in grain size from clay to fine sand and range in color from green to gray to black to white to possibly pink. Some stratification may be present in lacustrine deposits. This stratification often occurs as thin, light and dark layers (varves), which represent seasonal sedimentation. Shell fragments (commonly molluscs) can occur within these sediments, and where present, can be radiocarbon dated. However, organic material greater than about 50,000 or 60,000 years cannot be dated by this technique due to a number of paleoenvironmental, analytical, and isotopic factors.

In the subsurface of Lincoln and Union Counties, lacustrine deposits (Qpi$_1$ll, Qpi$_2$ll, Qpi$_3$ll, Qpill, Qpwlll(?), Qwlll, and Qll; see legend for the geologic cross sections in app. B) vary in thickness, from less than 2 feet to more than 50 feet (MLN-17 in cross section A-A', MLN-240 in cross section BB-BB', and MLN-22 in cross section CC'-CC'' in app. B).

Paleosols

Paleosols are buried soils that are the remains of an older, heavily altered surface. In the subsurface of Lincoln and Union Counties, the paleosols may form the upper surface of bedrock, till, or pre-Illinoian sand units. These sediments are typically composed of variably colored clay and silt. Unfortunately, paleosols are difficult to recognize in the subsurface. Furthermore, they are rarely preserved because they are easily destroyed by subsequent glaciation. Thus, in this study, most indicated paleosols (Qpips and Qpwlps; see legend for the geologic cross sections in app. B) are only tentatively identified as such (MLN-174 in cross section H-H' in app. B).

Pre-Illinoian 0(?) Deposits

Pre-Illinoian 0(?) till may be the oldest till intersected in the study area, but the stratigraphy is not well constrained. Furthermore, the pre-Illinoian 0(?) till is only intersected in one drill hole (MLN-177 in cross section H-H' in app. B). In this hole, the unit is 60 feet thick, and is separated from what is believed to be pre-Illinoian 1 till by 25 feet of loess (Qpil) overlain by 10 feet of outwash (Qpi$_1$o).

Pre-Illinoian 1 Deposits

Pre-Illinoian 1 till is the oldest identified till unit that appears to be identifiable throughout most of the study area. Pre-Illinoian 1 till, although spotty in north and central Lincoln County, commonly underlies the pre-Illinoian 2 deposits in Union County.

The pre-Illinoian 1 till is commonly described in lithologic logs as hard or compact. The upper, oxidized part of this till unit can reach a thickness of 60 feet, but is usually less than 15 feet, and is commonly completely absent due to erosion by the overriding pre-Illinoian 2 glacier. Although typically yellow to brown in color, the oxidized portions of this unit are locally bright orange or reddish.

Pre-Illinoian 1 outwash (Qpi$_1$o) occurring within the till unit is typically thin, less than 10 feet thick, and discontinuous, although isolated bodies can reach a thickness of 20 feet. Rare pre-Illinoian 1 lacustrine sediments (Qpi$_1$ll) reach a thickness of 20 feet (MLN-126 in cross section CC'-CC'' in app. B).

Loess clearly separating pre-Illinoian 1 and pre-Illinoian 2 tills was intersected in one hole. This deposit, located in southern Lincoln County (Qpi_1l, MLN-180 in cross section H-H’ in app. B), is limited in areal extent.

Pre-Illinoian 2 Deposits

The pre-Illinoian 2 till occurs stratigraphically between the pre-Illinoian 1 (older) and pre-Illinoian 3 (younger) deposits. This till unit is present beneath most of the study area and directly underlies the majority of the loess in southern Lincoln and most of Union Counties. However, its occurrence is spotty in northern and western Lincoln County.

The pre-Illinoian 2 till is commonly described in lithologic logs as hard or compact. The maximum thickness of this unit is about 160 feet. The upper, oxidized portion can reach a thickness of 60 feet in drill holes. However, this oxidized portion can be completely absent due to erosion by the overriding pre-Illinoian 3 glacier and/or late Wisconsin glacier. The pre-Illinoian 2 oxidized till is commonly reddish-brown but can be orange. Jointing and associated oxidation along the joints are commonly noted within the pre-Illinoian 2 till, giving it a mottled appearance.

Pre-Illinoian 2 outwash (Qpi_2o) occurring within the till unit is relatively thin and discontinuous in its distribution (generally less than 40 feet thick). However, these deposits appear to be more common than the pre-Illinoian 1 outwash of similar occurrence.

Pre-Illinoian 2 lacustrine deposits (Qpi_2ll) occurring within the till unit are present in several drill holes and can be thick (MLN-17 in cross section A-A’ and MLN-56 in cross section C-C’ in app. B). The thickest pre-Illinoian 2 lake sediments fill eroded valleys within the pre-Illinoian 2 till, suggesting that these formed during glacial retreat.

Pre-Illinoian 3 Deposits

The pre-Illinoian 3 till (probably equivalent to Qpi_3t in southern Minnehaha County; Tomhave, 1994) is limited in spatial extent. It becomes discontinuous in the subsurface of central Lincoln County and pinches out in the southern part.

The pre-Illinoian 3 till is commonly calcareous. The maximum thickness of this unit is about 110 feet in the study area. As with the older pre-Illinoian tills, it can be hard or compact. Unlike the older pre-Illinoian tills, the greater portion of this unit is oxidized, and in some cases, it is completely oxidized. The oxidized portion can reach a thickness of 75 feet in drill holes. The oxidized pre-Illinoian 3 till sheet is commonly reddish-brown. Jointing in this till unit has also been noted in the lithologic logs.

Pre-Illinoian 3 outwash (Qpi_3o) is less common within the pre-Illinoian 3 till as it is in the pre-Illinoian 2 till. The thickness of these deposits can range from less than 5 feet to around 20 feet. Outwash directly underlying the pre-Illinoian 3 till can reach a thickness of more than 100 feet

(MLN-33 in cross section B-B' in app. B), but is typically much thinner (MLN-84 in cross section D-D' and MLN-138 in cross section F-F' in app. B).

Pre-Illinoian 3 lacustrine deposits (Qpi_3ll) were intersected in a few drill holes in northern Lincoln County. These deposits are typically thin (<15 feet) compared to the pre-Illinoian 2 lacustrine sediments and are limited in spatial extent (MLN-39 in cross section B-B' and MLN-85 and -86 in cross section D-D' in app. B). However, thicker pre-Illinoian 3 lacustrine deposits do occur (MLN-70 in cross section C-C' in app. B).

One loess deposit was encountered between pre-Illinoian 3 and late Wisconsin deposits in the study area (Qpwll; MLN-156 in cross section G-G' in app. B). This deposit could have been deposited anytime between the pre-Illinoian 3 and the late Wisconsin glaciations.

Late Wisconsin Deposits

The late Wisconsin till (Qwlt) covers most of Lincoln County, but is limited in areal extent in Union County. Where present, late Wisconsin till is typically exposed at the surface. Locally, it can be covered by loess, particularly in southern Lincoln County, adjacent to the loess-covered pre-Illinoian till (pl. 3). A veneer ($\leq$ 10 feet) of late Wisconsin till locally overlies pre-Illinoian till south of its mapped extent in southeastern Lincoln County (pl. 3). However, as these deposits are discontinuous and difficult to distinguish in the field, they are not mapped.

The late Wisconsin till has a maximum thickness of about 150 feet in drill holes. The oxidized portion of this till is typically less than 30 feet thick.

Late Wisconsin outwash (Qwlo) occurring within the till unit is relatively thin (typically <20 feet). Thick late Wisconsin outwash occurs in many river valleys (the Vermillion River valley in cross section AA-AA' and the Big Sioux River valley in cross section DD'-DD'' in app. B). Outwash is common at the base of the late Wisconsin till (Qwlo and Qo), but it does not commonly directly overlie pre-Illinoian 3 till (cross sections AA-AA', BB-BB', CC-CC', DD-DD', and DD'-DD'' in app. B).

Late Wisconsin lacustrine deposits (Qwlll) are typically present near the surface (buried by soil and colluvium) in Lincoln County. These sediments range from 5 to 20 feet thick. The thicker lake deposits are commonly associated with outwash. One near-surface late Wisconsin ice-perched lake deposit, discovered in Lincoln County near Lake Alvin (SW NW sec. 9, T. 99 N., R. 49 W.) contains fossils dated at 11,770 $\pm$ 500 years before present (Steece, 1966).

A thick sequence of Quaternary lacustrine (Qll) and outwash (Qo) is present in northwestern Union County (MLN-240 in cross section BB-BB' in app. B) and may also be late Wisconsin in age. No definite age can be assigned to this sequence because no till occurs beneath it to help bracket the relative age. However, this lacustrine-glacial-fluvial system has downcut pre-Illinoian 1 and 2 sediments, indicating that it is pre-Illinoian 3 in age or younger.

Late Wisconsin loess is grouped with all surficial loess deposits (Ql) in the study area (pls. 3 and 4). These deposits are typically yellow and up to 10 feet thick. In southern Lincoln and in Union Counties, the late Wisconsin loess commonly overlies typically brown to reddish-brown loess (up to 30 feet thick) of pre-Illinoian, Illinoian, or early Wisconsin age, which in turn overlies the pre-Illinoian till. A carbon-14 analysis from a tree buried in the loess overlying the pre-Illinoian till near Brule Creek (NE NE SW SE sec. 15, T. 93 N., R. 50 W.) in west-central Union County yielded an age of 14,980 ±220 years before present (unpublished data from South Dakota Geological Survey files), indicating that the tree grew during the late Wisconsin. Because wind-blown silt continues to be deposited today, the late Wisconsin loess is not necessarily the loess which is immediately exposed at the surface.

Holocene Deposits

Alluvium

Alluvium (Qal) consists of clay and silt, with lesser amounts of sand and gravel deposited by recent streams, and is typically black or dark-brown and rich in organic matter. In the study area, alluvium has been deposited in stream valleys since the last glacial retreat. In southern Lincoln and north to central Union Counties, which are blanketed by loess and underlain by pre-Illinoian till, ancient (pre-Holocene) alluvium accumulated probably since at least the pre-Illinoian 3 retreat, and in some cases since the pre-Illinoian 2 retreat, and is now overlain by Holocene deposits. The total thickness of alluvium (including ancient alluvium) on the older till surfaces reaches 30 feet in long-used stream valleys. On the late Wisconsin surface, alluvium is typically less than 10 feet thick and averages 5 feet or less.

Colluvium

Colluvium (Qc) consists of unconsolidated, unsorted debris moved down slopes by gravity. Colluvium is mapped in Lincoln County east-northeast of Beresford.

Lacustrine Sediments

Holocene lacustrine deposits are limited in areal extent and thus not mapped in the study area. Lacustrine sediments can be found in closed depressions that fill with water to form intermittent lakes in years of high rainfall. Lacustrine sediments are also found in oxbows in the Big Sioux and Missouri River flood plains.

Tufa Deposits

Tufa deposits are restricted in areal extent. They do occur locally in Lincoln County along a section of the Big Sioux River in Newton Hills State Park (secs. 12 and 13, T. 97 N., R. 49 W., and secs. 16 through 18, T. 97 N., R. 48 W.). The tufa, composed of calcium carbonate, forms gently sloping terraces that directly overlie Carlile Shale. It is deposited by springs that seep to the surface along the contact between the Newton Hills sand (Qpis) and the Carlile Shale (Kc).

Eolian Deposits

Silt has been redeposited in Union and southern Lincoln Counties throughout the Holocene, particularly where vegetation is sparse. The sources of the eolian silt (lumped with the Pleistocene loess as Ql on pls. 3 and 4) are the surficial deposits of Pleistocene outwash, till, and loess. Dune sand (Qds) has been deposited along the Missouri River in Union County during the Holocene as well. The sources of these sands are Holocene bar (Qb) and point bar (Qpb) sediments deposited along the Missouri River. Older Holocene sand dunes may continue to migrate or may be stabilized by present-day vegetation.

QUATERNARY LANDFORMS

The surficial geology of Lincoln and Union Counties are presented in plates 3 and 4, respectively. The majority of landforms and surface geology is the result of multiple glacial ice advances and retreats during the Pleistocene.

Glacial Landforms

Ground Moraine

Ground moraine is a relatively flat to gently rolling surface formed of debris (till) released from beneath a glacier. A slightly more variable topography is formed where a thin veneer of sediments was let down from within and on top of the retreating glacial ice (ablation moraine) onto ground moraine. In these cases, ground moraine becomes transitional to stagnation moraine (see below). In Lincoln and Union Counties, ground moraine (Qwltg) with little to no overlying ablation moraine typifies the area near the terminus of the late Wisconsin ice.

Stagnation Moraine

Stagnation moraine is an irregular surface formed of debris deposited from ice that has ceased to move. It is characterized by closed depressions and undeveloped drainages. Late Wisconsin stagnation moraine (Qwlts) typifies much of the surface of Lincoln County and occurs discontinuously in western Union County.

End Moraine

End moraines are formed at or near the edge of an active glacier. These features commonly mark the farthest advance of a major glacial episode. A remnant of a possible late Wisconsin end moraine (Qwlte) is mapped north of the Missouri River flood plain southwest of the intersection of State Highway 50 and Interstate 29 in Union County (pl. 4). Other remnants of this end moraine are present to the west in Clay County (Christensen, 1967).

Collapsed Outwash

Collapsed outwash deposits are formed by collapse of englacial or supraglacial clay, sand, and gravel as the ice melts. Late Wisconsin collapsed outwash deposits (Qwloc) are mapped northwest of Tea in Lincoln County.

Outwash Terraces

Outwash terraces (Qwlo) are discontinuous remnants of large, valley-filling sand and gravel deposits. In Lincoln County, outwash terraces are present along the valley walls of the Big Sioux River north of Fairview, extending into Minnehaha County (Tomhave, 1994), and along sections of Beaver, South Beaver, Long, and East Brule Creek valleys (pl. 3). In Union County, outwash terraces are present along the valley walls of Brule Creek and its northern branches (East and West Brule Creeks, pl. 4). Along the valley walls of the Big Sioux River, from Fairview in Lincoln County south to the Missouri flood plain in Union County, the outwash terraces are covered by a veneer of alluvium from Holocene floods and are mapped as Qwloa (pls. 3 and 4).

Pre-Holocene Stream Terrace

Two possible ancient (pre-Holocene) stream terraces (Qt) occur along the Brule Creek valley in west-central Union County. Stream terraces can be erosional or depositional features. Erosional terraces are those in which the tread (the planed surface) has been formed primarily by lateral erosion. Depositional terraces are essentially abandoned flood plains. They formed when the river downcut older alluvial valley fill. Erosional terraces may not consist of alluvium, as they may form on any preexisting sediment or rock. Depositional terraces can consist of alluvium, sand, and/or gravel. Both terraces in Union County consist of oxidized to unoxidized silty, sandy clay, which is likely till, suggesting that these level surfaces are erosional terraces. The northern terrace is higher in elevation than the adjacent late Wisconsin outwash terraces. The southern terrace is only slightly higher in elevation than the creek itself and is not directly associated with a late Wisconsin outwash terrace. Both terraces are interpreted to be late Wisconsin in age.

Meltwater Channel

Meltwater channels are valleys carved by meltwater runoff from glaciers. These channels are far broader than valleys that could be eroded by modern streams that now occupy them. These broad channels were eroded during the Pleistocene when large volumes of meltwater were flowing at very high rates.

Meltwater channels typically contain sand and gravel. However, the glacial runoff that carved these channels sometimes eroded the surficial sediments rather than deposited them. This was the case along sections of meltwater channels in Lincoln and Union Counties where the channels are locally floored by till.

Loess Hills

Loess that blankets a surface gives that surface a distinctive morphology, typified in southeastern Lincoln and north to central Union Counties by relatively steep, sharply ridged hills. This morphology is due to the capacity of loess to maintain nearly vertical slopes. Thus, as loess-blanketed highlands are eroded by streams, very deep, steep-sided ravines are formed. Generally, older surfaces are more dissected by stream erosion. Quaternary loess (Ql) blankets southeastern Lincoln County and most of the northern half of Union County (pl. 4).

Nonglacial Landforms

Recent Stream Channels

Recent stream channels are valleys cut and occupied by Holocene streams. Alluvium (Qal) typically floors these valleys. Recent stream channels may occupy Pleistocene meltwater channels, or they may incise exposed till or bedrock surfaces.

Bedrock Exposures

The Niobrara Formation (Kn) and Carlile Shale (Kc) crop out in Lincoln County, and Carlile Shale (Kc) and Greenhorn Limestone (Kg) crop out in Union County. Invariably, these outcrops are located along stream channels, where streams have eroded overlying sediments, and are now incising the bedrock surface. In Lincoln County, the Niobrara Formation crops out along Beaver Creek. The Carlile Shale used to crop out along the Big Sioux River in the Newton Hills, but it is presently covered by a thick layer of tufa (pl. 3). In Union County, the Carlile Shale and Greenhorn Limestone crop out along Brule Creek. The Carlile Shale crops out along small creeks east of Alcester, as well as along the bluffs above the Big Sioux River. The Greenhorn Limestone used to be exposed along the Big Sioux River valley 1 to 2 miles upstream of Richland but is now covered by a veneer of loess and topsoil.

Upper Cretaceous rocks also crop out along the Missouri River valley in Nebraska (Greenhorn Limestone, Graneros Shale, and Dakota Formation), and along the Big Sioux River valley in Iowa (Niobrara Formation, Carlile Shale, Greenhorn Limestone, Graneros Shale, and Dakota Formation).

QUATERNARY HISTORY

Pre-Pleistocene Geography

The topography of Lincoln and Union Counties immediately prior to the onset of Pleistocene glaciation is probably closely approximated by the configuration of the bedrock surface shown in plates 1 and 2. Although the bedrock surface was modified during the four to five glacial advances in the area, it is likely that large-scale features, such as master stream drainages and bedrock highlands, are preserved. Figures 10 and 11 illustrate major bedrock drainages and inferred direction of flow.

Prior to Pleistocene glaciations, a drainage system had developed on the bedrock surface with various tributary streams draining into master streams, such as the ancient White River (Flint, 1955). The tributaries dissected the bedrock surface in generally southwest- and southeast-trending patterns. One of these tributaries (channel A, fig. 10) flowed from northeast to southwest across Lincoln County (Flint, 1955), paralleling the preexisting northeast-southwest trending linear escarpment in the Sioux Quartzite (fig. 3; see also the Sioux Quartzite section under Precambrian Geology), and entering the ancient White River in Turner County. Another tributary (channel B, fig. 10) flowed southeastward from the Canton area into Iowa. Three smaller tributaries fed into channel B, two of which joined it at Canton. The other tributary (west of Fairview) flowed from southwest to northeast, becoming confluent with channel B in Iowa.

South of Hudson, a tributary may have flowed from Iowa southwest across northern Union County, and drained into the ancient White River west of the Union County line (channel C in fig. 11). This tributary has since been subjected to erosion and is no longer a continuous channel. A smaller tributary, which flowed southwestward out of southern Lincoln County into Union County (channel D in fig. 11), joined a major tributary to the ancient White River in northwestern Union County. This system entered the ancient White River in east-central Clay County (fig. 11).

The ancient White River and another major drainage, the ancient Niobrara River, became confluent just east of the city of Vermillion in Clay County (Flint, 1955; Christensen, 1967). This single master stream, flowing from northwest to southeast, carved a deep trench in the bedrock in southern Union County (fig. 11) and underlies on its southern boundary the present-day Missouri River trench. This bedrock channel has been greatly widened by subsequent glaciations.

In sec. 28, T. 92 N., R. 49 W. in east-central Union County, another tributary fed into the ancient White River. This tributary roughly followed the present-day Big Sioux River south beginning in Iowa in T. 94 N., R. 48 W. (fig. 11). This tributary may have been part of the channel B river system (fig. 10) that drained into Iowa from east-central Lincoln County.

Plio(?)-Pleistocene

Quartz-rich (western-derived, Newton Hills, Alcester) sands (Qpis) were deposited probably in late Pliocene or early to early middle Pleistocene time. These sands may have been deposited by the same streams that cut the pre-Pleistocene channels, as deposits commonly occur along the margins and sometimes the floor of these bedrock channels (figs. 10 and 11). The occurrence of lacustrine deposits within these sands is consistent with deposition by, or adjacent to, a river system.

Pleistocene

Southeastern South Dakota has experienced multiple pre-Illinoian glaciations (Richmond and Fullerton, 1986). Pre-Illinoian glaciers approached South Dakota from the northeast based on glacial striations carved into Sioux Quartzite outcrops (Baldwin, 1949). In Lincoln and Union Counties, it appears that there may have occurred as many as four pre-Illinoian glacial advances.

Pre-Illinoian 0(?) Glaciation

The pre-Illinoian 0(?) sediments fill an early or pre-Pleistocene bedrock channel and overlie pre-Illinoian sand (Qpis). This glacial advance may have either just reached parts of the study area, or most of its deposits were eroded (mainly by subsequent glaciers), as the pre-Illinoian 0(?) sediments were intersected in only one drill hole. Greater than 20 feet of loess overlies this deposit, suggesting that a significant amount of time lapsed between the retreat of the pre-Illinoian 0(?) glacier, and the advance of the pre-Illinoian 1 glacier.

Pre-Illinoian 1 Glaciation

The pre-Illinoian 1 glaciation likely modified the bedrock surface in the study area during its advance and retreat. The pre-Illinoian 1 sediments may have covered much of Lincoln and Union Counties. They filled some of the deepest bedrock channels in the area (MLN-18 in cross section A-A’ in app. B) and were deposited on the bedrock high in Union County. This bedrock high may have slowed, and eventually stopped the southward advance of the pre-Illinoian 1 glacier in Union County, as sediments from this advance appear to be very thin or absent within the ancient White River channel in southern Union County (cross sections BB-BB’, CC-CC’, and DD-DD’ in app. B).

Meltwater from the retreating pre-Illinoian 1 glacier appears to have been directed primarily outside the study area, as thick outwash bodies are not common above the pre-Illinoian 1 (or below the pre-Illinoian 2) till north of the ancient White River channel. Based on constructed cross sections, channel A (fig. 10) trending northeast-southwest across northern Lincoln County may have been one of the topographic lows directing pre-Illinoian 1 meltwater outside the study area. Although shifted to the west, the ancient White River was probably still present. Thus, as many of these tributaries in Lincoln County still fed into the ancient White River, large volumes of sand and gravel that were washed from the retreating pre-Illinoian 1 glacier ultimately were deposited in southern Union County within the ancient White River channel (cross sections BB-BB' and CC-CC' in app. B).

A long period of exposure occurred after the retreat of the pre-Illinoian 1 glacier forming a thick oxidized zone in the upper part of the pre-Illinoian 1 till ($Qpi_1t(ox)$; MLN-182 in cross section H-H', MLN-194 and -195 in cross section I-I', and MLN-244 in cross section K-K' in app. B). The limited distribution of loess overlying the pre-Illinoian 1 till and outwash may be due to nondeposition between glacial cycles or erosion during the next (pre-Illinoian 2) glacial advance.

Pre-Illinoian 2 Glaciation

The pre-Illinoian 2 advance was a major glaciation in the region with thick deposits extending from northernmost Lincoln County (cross section A-A' in app. B) to the ancient White River channel (the western part of cross section N-N' and the southern parts of cross sections BB-BB' and CC-CC' in app. B) and also likely to northeastern Nebraska. This glaciation could have greatly modified the land surface, eroding much of the pre-Illinoian 1 till. In some areas, the pre-Illinoian 2 glacier may have completely excavated older deposits in bedrock channels and subsequently deposited its own sediments. The pre-Illinoian 2 glacier was probably quite thick or present for a long period in the study area, as thick pre-Illinoian 2 deposits are found on some of the highest portions of the bedrock high in Union County (cross sections L-L', M-M', and N-N' in app. B). It is likely that during this glacial advance the ancient White River was shifted westward across Turner County. This major drainage established a northwest-to-southeast flow, perhaps intersecting the southwest corner of Lincoln County, and continuing into Clay and southern Union Counties (Christensen, 1967).

Meltwaters from the retreating pre-Illinoian 2 glacier deposited moderately thick sequences of sand and gravel in topographically low areas across Lincoln County. A significant volume of the pre-Illinoian 2 glacial runoff likely found its way into the ancient White River system, as well, eroding much of the pre-Illinoian 2 till that partially filled the trench (the southern parts of cross sections BB-BB' and CC-CC' in app. B).

At least one long-term lacustrine-glacial-fluvial system was established during the pre-Illinoian 2 glaciation (Qpi_2ll; MLN-17 in cross section A-A' in app. B). The thickness of this sequence of sediments and deep erosional incision into pre-Illinoian 2 till suggest that this system existed through most of the glacial retreat.

A long period of exposure occurred after the retreat of the pre-Illinoian 2 glacier as indicated by thick oxidized zones in the upper part of the pre-Illinoian 2 till (cross sections F-F', H-H', L-L', and M-M' in app. B) and the development of joints along which oxidation occurred. Deposition, during this period of surface exposure, was either limited, or was eroded by subsequent glaciation, based on the paucity of loess between the pre-Illinoian 2 and pre-Illinoian 3 tills in the study area.

Pre-Illinoian 3 Glaciation

The pre-Illinoian 3 glacial advance likely extended only to southern Lincoln or northern Union Counties, as pre-Illinoian 3 till is spotty in occurrence in southern Lincoln County, and was not found in Union County. The pre-Illinoian 3 glaciation may not have greatly modified the land surface throughout the study area. However, local modification of the land surface occurred in the eastern part of Lincoln County. In this area, the pre-Illinoian 3 glacier appears to have planed the older pre-Illinoian 2 surface as it advanced, and subsequently deposited a thick pre-Illinoian 3 till above the elevated pre-Illinoian 2 surface (MLN-139 in cross section F-F' in app. B).

Channeled meltwater from the pre-Illinoian 3 glaciation locally deposited thick sequences of sand and gravel in Lincoln County (Qpi_3o; MLN-33 in cross section B-B' in app. B). The distribution of these deposits suggests that most of the meltwater flowed out of Lincoln County to the southwest and southeast and did not enter Union County.

A long ice-free period followed the pre-Illinoian 3 retreat, probably extending through the Illinoian and into the early Wisconsin stages in the study area. Large portions of pre-Illinoian till were oxidized during this period of surface exposure (MLN-16 in cross section A-A' in app. B). In some areas, complete oxidation of pre-Illinoian 3 till occurred (Qpi_3t(ox); MLN-155 in cross section G-G' in app. B). Loess deposition likely resumed across the area following the pre-Illinoian 3 retreat based on work carried out in Minnehaha County (Tomhave, 1994). However, in Lincoln and Union Counties, few if any loess deposits are preserved between the late Wisconsin and pre-Illinoian 3 tills. Typically, the deposits of pre-late Wisconsin loess intersected by drill holes (Qpwll; MLN-169 in cross section AA-AA' in app. B) could be pre- or post-pre-Illinoian 3 in age, as they are underlain by bedrock or till believed to be older than Qpi_3t.

Late Wisconsin Glaciation

At the beginning of the late Wisconsin, the center of glaciation on the North American continent (in what is now Canada) shifted westward from previous glacial periods. Subsequently, late Wisconsin ice entered what is now eastern South Dakota from the north rather than the northeast (Hallberg and Kemmis, 1986). In South Dakota, the glacier was split by the Coteau des Prairies (fig. 12) into two lobes, the James and Des Moines lobes. The Des Moines lobe was diverted to the south-southeast into what are now Minnesota, Iowa, and eastern South Dakota. Meltwater from this lobe deposited a large volume of outwash along parts of the Big Sioux River valley across eastern South Dakota and its eastern tributaries (such as Rock River in Iowa) (Tomhave, 1994; Hammond, 1991).

The James lobe followed topography, moving into the lowland (James Basin) now occupied by the James River (figs. 2 and 12). This lobe was bounded on the east by the Coteau des Prairies and on the west by the Coteau du Missouri (Hallberg and Kemmis, 1986). The lobe reached as far south as the southern edge of South Dakota (Flint, 1955; Hallberg and Kemmis, 1986).

The late Wisconsin glacier approached the study area from the northwest. As it approached Lincoln County, the late Wisconsin ice stalled on the Sioux Ridge in Minnehaha County (Tomhave, 1994), which forced the ice to advance into northern Lincoln County from the west-northwest. A sublobe of the glacier moved east-northeast, likely following a persistent topographic low that was roughly paralleling bedrock channel A (fig. 10). This sublobe advanced across the present-day Big Sioux River into Iowa, making the Iowa border a close approximation to the late Wisconsin ice margin (pl. 3).

The late Wisconsin ice ramped onto the elevated pre-Illinoian till surface in southeastern Lincoln and northern and central Union Counties (fig. 12) and eventually stalled. However, west of the study area, the ice continued to advance from the northwest and entered southern Union County using the ancient White River channel. The White River channel was subsequently diverted to the south (Christensen, 1967).

In northern and northwestern Lincoln County, the late Wisconsin glacier modified the land surface, probably eroding much of the pre-Illinoian 3 deposits, and modifying low areas in the pre-Illinoian till and bedrock (cross sections A-A', B-B', and C-C' in app. B). In central and southern Lincoln County, late Wisconsin ice that overrode the pre-Illinoian surface deposited less than 100 feet of debris (MLN-174 in cross section H-H' in app. B).

The ice that emplaced the ground moraine in Lincoln County must have been thin, carried little sediment, and retreated quickly from southeast to northwest, as significant ablation moraine is not evident on this surface. The stagnation moraine northwest of the ground moraine in Lincoln County, and east of the loess-covered elevated pre-Illinoian surface in Union County, was likely also deposited by ice that was not very thick or heavily laden with silt and clay when it melted, as the hummocky surface is generally subdued.

Deposition of thick, spatially continuous outwash was ongoing through the late Wisconsin glaciation. Some meltwater channels cut into pre-Illinoian outwash, depositing sands and gravels that mixed with pre-Illinoian outwash.

In southwestern Union County, the late Wisconsin glacier deeply eroded thick, pre-Illinoian sand and gravel deposits within the ancient White River valley (southern part of cross section BB-BB' in app. B). Possible dissected late Wisconsin end moraine occurs in southwestern Union County at the edge of the present-day Missouri River trench and in southeastern Clay County (Christensen, 1967), roughly delineating the southern and southeastern terminus of the ice sheet.

In Union County, from the onset of late Wisconsin glaciation, meltwaters flowed along the now buried ancient White River channel, depositing sand and gravel. The new meltwater channel, which became the present-day Missouri River trench (cross section BB-BB' in app. B), was one of three major drainages for the late Wisconsin meltwater.

The second major drainage for late Wisconsin meltwater in the study area was the Big Sioux River. Meltwaters from both the Des Moines and James lobes flowed down this channel in counties north of the study area. During the late Wisconsin glacial maximum, ice blocked meltwater that was flowing south into Lincoln County through present-day Sioux Falls. The meltwater was redirected north and east around this blockage (Flint, 1955; Tomhave, 1994) and followed the eastern margin of the James lobe, establishing the northern portion of the Big Sioux River in Lincoln County. Thus, the upper part of the Big Sioux River in Lincoln County was ice marginal to the James lobe. The southern half of the Big Sioux River bordering eastern Lincoln County and the entire length bordering eastern Union County were part of an interlobate drainage fed from the James and Des Moines lobe meltwaters. It is not clear when this section of the river was first established, but it could have developed following the pre-Illinoian 3 glaciation, and have been used for meltwater drainage by each subsequent glaciation in the region.

The third major drainage for late Wisconsin meltwater in the study area was the ancestral Vermillion River valley (Christensen, 1967), part of which is present in southwestern Lincoln County. During glacial retreat, meltwater from the stagnating part of the late Wisconsin ice flowed into the ancestral Vermillion River in western Lincoln County using the smaller Long Creek channel. Significant outwash terraces are still present along the Long Creek valley (pl. 3).

Roughly paralleling the section of the Big Sioux River from Fairview to Hudson is a meltwater channel within which Pattee Creek now flows (pl. 3). The channel is floored by pre-Illinoian till, and outwash was either not deposited or subsequently eroded along this channel. This small drainage system likely was utilized strictly by local meltwater, and perhaps for only a short time. The lack of sand and gravel deposits along this channel may suggest that its gradient was high, draining late Wisconsin meltwater off the elevated pre-Illinoian surface to the Big Sioux River valley.

Several smaller tributaries channeled meltwater across Lincoln and Union Counties to the major regional drainages. Outwash terraces typically remain along sections of these channels. In Lincoln County, these smaller tributaries include valleys now occupied by the lower section of Ninemile Creek near Lake Alvin, Beaver Creek, South Beaver Creek, West Brule Creek, and East Brule Creek. In Union County, these smaller tributaries include valleys now occupied by West Brule Creek, East Brule Creek, and Brule Creek.

West Brule Creek and Brule Creek valleys in particular have numerous outwash deposits. Sections of these valleys were formed by ice marginal streams. In southern Lincoln and northernmost Union Counties, West Brule, East Brule, and the main Brule Creek valleys likely were drainages for meltwater throughout most of the late Wisconsin from glacial advance to retreat.

The lower part of the Brule Creek valley from sec. 22, T. 93 N., R. 50 W. to sec. 19, T. 92 N., R. 49 W. in Union County differs from other sections in that it is very narrow. Furthermore, from sec. 19, T. 92 N., R. 49 W. to the Big Sioux River, an extensive surficial outwash deposit is present (pl. 4). The section of the valley from sec. 22, T. 93 N., R. 50 W. to sec. 19, T. 92 N., R. 49 W. was likely an ice marginal meltwater channel confined on one side by the pre-Illinoian highland and on the other by the late Wisconsin ice sheet. As the confined meltwater was unable to meander, it cut through older till to bedrock. Large volumes of sand and gravel were then deposited as the meltwater flowed out of this confined valley.

Holocene

Throughout the Holocene, the forces that shaped the landscape in the study area have been primarily erosional. Streams are responsible for most of the erosion. Running water carries sediments from hilltops to topographically lower areas, downcuts Pleistocene sediments, and infills glacial lakes. Wind has also been a force during the Holocene, winnowing fine sand and silt from Pleistocene and older Holocene deposits, or simply remobilizing Pleistocene dune sands and loess. Soil continues to develop by alteration of exposed sediments, primarily the till. Landslides also shape the landscape through the mass movement of bedrock and glacial deposits along exposed slopes.

ECONOMIC GEOLOGY

Water Resources

Perhaps the most important resource in Lincoln and Union Counties is water. Both surface and ground water are abundant commodities in the study area. The primary surface water sources are the Missouri and Big Sioux Rivers. The primary ground water sources are the sand and gravel in the Big Sioux and Missouri River trenches, the sandstone of the Dakota Formation, and major buried outwash bodies. The quartz-rich sands can also be a viable ground water source, locally. Both surface and subsurface sources can provide fresh water for industrial, municipal, irrigation, and domestic use. A companion study to this report, titled *Water resources of Lincoln and Union Counties, South Dakota* (Niehus, 1994) provides information on water resources in the study area. It is available through the U.S. Geological Survey.

Sand and Gravel

Sand and gravel are important resources in Lincoln and Union Counties. Sand and gravel are used primarily in road construction and as concrete aggregate. Many of these deposits are at or near the land surface, making mining of them easy and inexpensive. Two information pamphlets discussing the sand and gravel resources in the study area are available: *Sand and gravel resources in Lincoln County, South Dakota* (Schulz and Jarrett, 1991), and *Sand and gravel resources in Union County, South Dakota* (Jarrett, 1988). These pamphlets are available at the South Dakota Geological Survey.

Oil and Gas

No commercial quantities of oil and gas have been found in southeastern South Dakota, although several oil tests have been drilled in the region. However, this does not completely rule out the possibility that oil and gas may occur within the bedrock formations of eastern South Dakota.

Quartzite

The Sioux Quartzite is actively quarried just north of the Lincoln County line in Minnehaha County, where it commonly occurs at or near the land surface (Tomhave, 1994). It lies close to the surface in parts of Lincoln County, as well, but does not crop out. Due to its hardness and uniformity, the Sioux Quartzite is commonly used in the construction industry. Modern uses of the Sioux Quartzite include concrete aggregate, road construction, riverbank stabilization, and the production of ferro-silicon for the steel industry. As the Sioux Quartzite is attractive in appearance, it has also been used historically as building and monument stone. A more complete list of uses for the Sioux Quartzite can be found in Jarrett (1990).

Other Mineral Resources

No economic mineral deposits have yet been found in eastern South Dakota. However, Precambrian, Paleozoic, and Cretaceous rocks have all drawn interest as potential sources for a variety of mineral deposits. It has been suggested that the Sioux Quartzite could be host to unconformity vein-type uranium deposits (Cheney, 1981) and paleoplacer gold deposits (Southwick and others, 1986).

In parts of the Midwest, the Paleozoic carbonate rocks (a thin sequence of which is locally present beneath southern Union County) have also been targeted for mineral exploration. The Sauk Sequence and part of the Tippecanoe Sequence (table 1) of the mid-continent are of particular interest, as they are known to be potential hosts to stratabound lead- and zinc-sulfide Mississippi Valley-type deposits (Pratt, 1987; Pratt, 1989).

The Cretaceous-age rocks adjacent to the Sioux Ridge also have potential as hosts to mineral deposits. These rocks, representing a nearshore sedimentary facies (mapped as Cretaceous undifferentiated in pl. 1), may host high-grade sedimentary manganese deposits (Cannon and Force, 1983; Hammond, 1988).

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