STATE OF SOUTH DAKOTA
M. Michael Rounds, Governor

DEPARTMENT OF ENVIRONMENT AND NATURAL RESOURCES
Steven M. Pirner, Secretary

DIVISION OF FINANCIAL AND TECHNICAL ASSISTANCE
David Templeton, Director

GEOLOGICAL SURVEY
Derric L. Iles, State Geologist

BULLETIN 34

GEOLOGY OF
YANKTON COUNTY, SOUTH DAKOTA

by

GARY D. JOHNSON

KELLI A. MCCORMICK

Prepared in cooperation with the
U.S. Geological Survey,
James River Water Development District, and
Yankton County

Akeley-Lawrence Science Center
University of South Dakota
Vermillion, South Dakota

2005

CONTENTS

GEOLOGY – continued Page

GEOLOGY – continued Page

Page

APPENDICES

ILLUSTRATIONS

PLATES

FIGURES

FIGURES – continued

ABSTRACT

Yankton County is dominated by the James River Highlands, which include three ridges: James Ridge, a mainly glacial feature trending northwest-southeast; Turkey Ridge, a northwest-southeast trending bedrock high; and Yankton Ridge, an east-west trending bedrock high.

The bedrock of Yankton County is composed of Upper Cretaceous sedimentary rock formations. In ascending stratigraphic order they are the Dakota Formation, Graneros Shale, Greenhorn Limestone, Carlile Shale, Niobrara Formation, and Pierre Shale. The last two are exposed in the northeast on Turkey Ridge and along the Missouri River below Yankton Ridge in the southwest. The Dakota Formation rests on Precambrian basement rock, possibly Sioux Quartzite; some Precambrian diabase, responsible for magnetic anomalies, is also present. Overlying the Pierre Shale in the subsurface on parts of Yankton and Turkey Ridges are possible Ogallala Group rocks of Neogene age.

The bedrock surface has been glacially modified to a great extent, but there remain three deeply-incised areas of the bedrock surface in Yankton County: northwestern Yankton County at the Hutchinson County line, western Yankton County west-northwest of Lesterville, and central Yankton County, east-southeast of Utica. The geometry and timing of formation of these incised areas are unknown.

Pleistocene glacial deposits resulted from possibly four major ice advances. Three advances are thought to have occurred in the pre-Wisconsin (probably pre-Illinoian) and one advance in the late Wisconsin age. All recognized advances deposited outwash and till. No numerical dates exist for the pre-Wisconsin glacial deposits in Yankton County. However, two geographically separated radiocarbon dates of wood within the basal late Wisconsin outwash, yield ages of about 12,880 and 12,540 years before present. This indicates that the late Wisconsin deposits are 12,880 years old or younger.

More than 200 feet of pre-Wisconsin sand and gravel form the core of the James Ridge. Most of the sand and gravel was probably emplaced as frozen, ice-thrusted blocks by the last pre-Wisconsin glacier. The uppermost sediments on the James Ridge consist of late Wisconsin collapsed sediments. The ridge was finally breached in the late Wisconsin by Beaver Creek that developed as a meltwater channel on the ice. Its southeastern end was also breached by the James River trench.

Stagnation moraine covers Turkey Ridge, part of north-central Yankton County, and smaller areas north of Lesterville and north, west, and south of Utica. Ground moraine dominates the northwestern quadrant of the county and the area between James Ridge and the stagnation moraine on the west slope of Turkey Ridge. Slope moraine covers most of Yankton Ridge. Two end moraines occur in the southwestern part of the county. The first, more southerly one, is at the base of the northern flank of Yankton Ridge. The second is a much larger recessional moraine that extends from Hutchinson County southeastward into Bon Homme County and then northeastward into Yankton County. Possible lateral end moraines occur just downslope of Clay Creek and Smoky Run.

Sand and gravel and ground water constitute the major economic geological resources. Agricultural lime from weathered Niobrara Formation chalk is periodically produced. The chalk is also a source of building stone, but has not been exploited since early last century. Such is also the case for cement, which was produced only for Panama Canal construction. Production of expanded shale as a lightweight aggregate has been proposed but never exploited.

INTRODUCTION

Purpose and Scope

This study is one of a series of county studies undertaken to determine the mineral and water resources available for future development (fig. 1). This report describes the surface and subsurface geology of the county. It also provides an interpretation of the geological processes responsible for the formation of the present landscape.

Location and Physiography

Yankton County is located in southeastern South Dakota, separated from Nebraska by the Missouri River. It is part of two physiographic provinces: the James River Highlands, which encompasses most of the county, and the James Basin (fig. 2). The James River Highlands include three physiographic features: Turkey Ridge, James Ridge, and Yankton Ridge (fig. 3). Turkey Ridge and James Ridge have a somewhat northwest-southeast trend, whereas Yankton Ridge trends east-west. Drainage patterns in much of Yankton County also generally trend northwest-southeast (fig. 3); James River, Mud Creek, Smoky Run, Clay Creek, and Turkey Creek more or less parallel James Ridge and Turkey Ridge. On the other hand, Beaver Creek cuts through James Ridge, suggesting a more complex history than that of the other creeks. Marne Creek flows around Yankton Ridge on the north side. The Missouri River flows south of Yankton Ridge.

The James River is 747 miles long (Benson, 1983). Although officially classified as a navigable river, it has long been considered by many as the longest unnavigable river in North America (Flint, 1955).

The county is dominated by prairie farmland, comprising some 65 percent of the total area of 533 square miles; an additional 16 percent is comprised of farmland of statewide importance (Ensz, 1979; U.S. Department of Agriculture Soil Conservation Service, 1985; U.S. Census Bureau, 2000).

Previous Investigations

More than half the geology of Yankton County was mapped by Simpson (1960) following a regional study by Flint (1955). Smaller parts of the county were mapped by Lutzen (1957) and Sevon (1958). Soils, the development of which is dependent in part on the underlying sediments, were mapped by Ensz (1979). Surficial sand and gravel deposits were mapped by Tomhave and Hammond (1987), and the ground-water resources were determined by Bugliosi (1983, 1986).

Vertebrate fossils found in the county were described or documented by Johnson and Milburn (1984) and Pinsof (1985). Many other investigations noted in this study are relied upon in either interpreting geologic processes or in assessing the economic importance of available resources.

Methods of Investigation

Test holes were drilled on approximately a 3-mile grid and at additional points to ascertain the geologic relationships of the glacial sediments and underlying bedrock formations, and bedrock and surface geologic maps of Yankton County were prepared (pls. 1 and 2). Legal locations of test holes and wells used to construct the geologic cross sections are listed in appendix A. An index map of these cross sections is shown in figure 4, the cross section legend is presented in figure 5, and the cross sections are shown in figures 6-15. Because the cross sections are by necessity of small scale, exact elevations of the test holes and contacts between geologic units should be obtained from the lithologic logs, which are available online from the South Dakota Geological Survey web site (http://www.sdgs.usd.edu/). Some information in this report is based on commercially drilled wells and test holes; these are identified as such in the text, are listed in appendix B, and their logs are on file at the South Dakota Geological Survey. Thicknesses of surficial and near-surface deposits shown in the cross sections are based on test-hole data from Tomhave and Hammond (1987) wherever possible, but these test-hole locations are not shown. Observation wells were installed in selected test holes to obtain hydrologic information about the aquifers in glacial sediments (outwash sand and gravel) and in the bedrock.

Acknowledgements

Funds to support this study were provided by the U.S. Geological Survey, South Dakota Department of Environment and Natural Resources, Yankton County, and the James River Water Development District. The cooperation of the officials of these organizations and of many land owners, quarry and gravel pit operators, and residents of Yankton County are greatly appreciated.

This project was initiated by Ronald Helgerson who conducted some preliminary drill tests. The main drilling phase and much of the geologic interpretation were carried out by one of the authors (Gary Johnson). Edward Bugliosi worked closely with Gary Johnson in the field during the main drilling phase and provided insight regarding the nature of the aquifers as initial data became available. Jack Rogers assisted in the field during one summer. Richard F. Bretz willingly shared his knowledge of Pierre Shale stratigraphy and techniques necessary for describing the intricacies of that formation's lithology. Sarah Chadima provided the powder diffraction x-ray analyses of rock samples. Stephen Burch served as geologist on two test holes. Dennis Johnson and Lori Roinstad drafted the figures and plates; Colleen Odenbrett edited and typed the manuscript. Their cooperation, assistance, and patience are greatly appreciated. Drafts of this report were critically reviewed by Jay Gilbertson, Lynn Hedges, and Dennis Tomhave, and their comments and contributions, as well as those by other Geological Survey personnel, are gratefully appreciated.

A special thanks to drillers: Millard Thompson, Jr., Lloyd Helseth, Dennis Iverson, Mark Koffler, Eric Koglin, Tom Conner, and Regina Snyder did the bulk of the drilling; and Gary Jensen,

Robert Gravholt, Ralph Danzl, Tom McCue, Carol Schmig, Carol Bronick, Scott Jensen, and Martin Jarrett drilled additional test holes as this study progressed. Without their much appreciated efforts, this investigation would not have been possible.

GEOLOGY

Pre-Cretaceous Geology

None of the test holes drilled for this study completely penetrated Cretaceous rocks except possibly MLN 1 (figs. 4 and 6; app. A). Little is known about the basement rocks (Precambrian age) beneath Yankton County. The majority of basement rocks are probably Sioux Quartzite, an orthoquartzite (a silica-cemented quartz sandstone) with beds of conglomerate and mudstone, which is locally intruded by Precambrian igneous rock. Knowledge of the basement rocks was meager when Simpson (1960) reported what was known about them. Since then Sioux Quartzite was reported at an elevation of 767 feet in a private well drilled in the eastern part of the county (SW¼ SE¼ sec. 10, T. 95 N., R. 54 W., app. B). It probably also occurs in the northwestern corner at the bottom of MLN 1 (fig. 6) at an elevation of 747 feet ("hit rock" according to the lithologic log), and at an elevation of 815 feet ("granite" recorded by driller) 4 miles farther east (NE¼ SE¼ sec. 3, T. 96 N., R. 57 W.; app. B). The most important information since Simpson's (1960) report was provided by Petsch (1962 and 1967) on magnetic anomalies ("magnetic highs"), which prompted some drilling activity. Moderate anomalies occur about 4 miles southwest of Utica and in an east-west trend in the northern one-third of T. 94 N., R. 55 W. (the De Vol magnetic anomaly; Petsch, 1967). The Gavins Point magnetic anomaly (Petsch, 1962) occurs about 2 miles east of Gavins Point Dam in a north-south trend starting at the north end of T. 93 N., R. 56 W. and continuing into Nebraska. The Jamesville magnetic anomaly is of significantly greater magnitude (Petsch, 1967). It has an east-west trend for about 5 miles and occurs in northwestern Yankton County. A commercial test hole (Rittershaus No. 1 Test, Jamesville Colony, app. B) was drilled in the east end of the trend at NE¼ SW¼ sec. 29, T. 96 N., R. 56 W. to a depth of 1,214 feet. Basement rock of granite was encountered at an elevation of 433 feet. Diabase or gabbro was intersected at an elevation of 415 feet. Diabase and gabbro are intrusive igneous rocks compositionally similar to basalt. Diabase differs from gabbro only in the size of the crystals that make up the rock; diabase has smaller crystals than gabbro.

The most intense magnetic high in Yankton County is the Willowdale magnetic anomaly. It is the third most intense anomaly reported in South Dakota (Petsch, 1967). Two greater anomalies, both of much higher intensity, occur in Day County in northeastern South Dakota (Petsch, 1967). The Willowdale anomaly occurs east of Yankton and trends N 70^{o} W for 4 miles from the east side of sec. 12, T. 93 N., R. 55 W., 4 miles east of Yankton (Petsch, 1962). A test hole was drilled at SE¼ NE¼ NE¼ SW¼ sec. 12, T. 93 N., R. 55 W. (SDGS No. 1 Holzbauer Test; app. B), where basement rock was encountered at an elevation of 420 feet. A few feet of core were obtained; the core is of gabbro and contains crystals of pyroxene, plagioclase, amphibole, magnetite, ilmenite, quartz, and a trace of sulfide minerals. A test hole was also drilled into the Spink magnetic anomaly in Union County. Petsch (1967) described the core obtained from that hole as gabbro with disseminated magnetic particles (mainly magnetite). Veins of green and reddish-brown clay and calcite and joints filled with calcite are also present in the Spink core. Simpson (1960) reported that rock similar to gabbro may have been intersected when a town well was drilled in Yankton in 1896. He quotes Todd (1898) who reported a greenish crystalline rock composed mostly of plagioclase (possibly laboradorite) with some quartz, magnetite, and calcite or dolomite. It is capped by 7 feet of greenish clay encountered at an elevation of 346 feet.

Precambrian geologic structural features are not known with certainty in Yankton County. Seismic activity has occurred infrequently in Yankton County, although several minor earthquakes have occurred in southeastern South Dakota and northeastern Nebraska. Only one earthquake epicenter has been recorded from Yankton County (Arney and others, 1987), in 1879, about 3 miles southwest of Mission Hill. Another occurred 20 miles west of Yankton, in Bon Homme County, in 1945. The last nearby earthquake occurred in 1982, also in Bon Homme County, 27 miles northwest of Yankton. This activity has been ascribed to regional structures such as the Siouxana arch (Becker and Zeltinger, 1983). Sims (1990) and Carlson (2001) show a boundary between two orogens or provinces trending northeast-southwest, cutting through Union County. To the northwest of this boundary is the Superior Craton (mostly a granitic gneiss province overlain in areas by the Sioux Quartzite – quartzite of Baraboo interval); to the southeast is the Penokean Orogen. Sims and Peterman (1986) and Sims (1990) further show this boundary cut by a series of northwest-trending faults, and Sims (1990) extends one of the northwest-trending faults through Yankton County.

Paleozoic rocks probably do not occur in Yankton County, but they do occur in the subsurface to the east in Clay and Union Counties (deposited in the Cambrian, Ordovician, and Devonian Periods; Christensen, 1967; unpublished data from South Dakota Geological Survey files) and in nearby areas of Iowa and Nebraska (Bunker, 1981).

Jurassic and Triassic formations do not occur this far east in South Dakota or adjacent areas (Petsch, 1962). The reader may refer to any introductory geology textbook for the geologic time scale, or see Petsch and McGregor (1969).

Cretaceous Geology

Lower to Upper Cretaceous rocks directly overlie Precambrian basement rocks (Sioux Quartzite, igneous, and metamorphic rocks) in Yankton County. Many of these Cretaceous rocks were deposited in a shallow sea, called the Cretaceous Western Interior Seaway, which existed from about 106 to 67 million years ago in the central portion of what is now the North American continent (Gries and Martin, 1981; McGookey and others, 1972; fig. 16). These rocks record a series of sea level rises and falls (transgressions and regressions, respectively) that occurred in this seaway. They also preserve, as fossils, some of the marine life that existed during this period (Witzke and others, 1983).

Six geologic formations of Early to Late Cretaceous age are recognized in Yankton County. They are, in ascending stratigraphic order (oldest to youngest), the Dakota Formation (often referred to as "artesian sandstone" by drillers), Graneros Shale, Greenhorn Limestone, Carlile Shale, Niobrara Formation (often referred to as "chalk rock" by drillers) and Pierre Shale. Only the Niobrara Formation and Pierre Shale are exposed at the surface in Yankton County (pls. 1 and 2). The Carlile Shale was exposed in several localities in Clay County (Christensen, 1967), but is now largely covered by vegetation. The upper part of the Carlile Shale, in contact with the overlying Niobrara Formation, is exposed in a cutbank on the Nebraska side of the Missouri River south of Meckling, Clay County. The older formations are exposed in several localities along or near the Big Sioux and Missouri Rivers in the Sioux City, Iowa, area (Brenner and others, 1981). All of these formations and their stratigraphic equivalents occur throughout much of the western interior of North America. They have been, and continue to be, described and interpreted in a prodigious array of articles in the scientific literature. A formal description of these formations and regional implications is beyond the scope of this report. The older literature is cited in Christensen (1974) and Simpson (1960); more recent information of regional and local interest is given in Schultz and others (1980), Cobban and Merewether (1983), and Shurr and others (1994).

All of the Cretaceous formations found in Yankton County are thinner than they are several hundred miles to the west. This is a result of a generally slower rate of subsidence along this eastern margin of the Cretaceous Western Interior Seaway relative to the western portion of the basin (Witzke and others, 1983).

The Cretaceous formations in the study area rise in elevation gently to the east. Some structural relief may be present, based on elevation changes of the Pierre-Niobrara contact shown in the cross sections (figs. 8, 12, and 13), although this is an unconformable contact. Beneath Yankton Ridge, the mean sea level elevation of this contact is typically about 1,300 feet (MLN 80 in fig. 11; fig. 12), but is variable. In the Highway Contractor Well (app. B) located near MLN 97 (fig. 12), the contact is at an elevation of 1,286 feet, and reaches an elevation of at least 1,350 feet locally (MLN 95 to 99 in fig. 12). Beneath Turkey Ridge, the contact reaches an elevation more than 1,400 feet in fig. 9 (MLN 57). It then slopes downward to the north where it is about 1,380 feet in fig. 8 (MLN 36) and 1,330 feet in fig. 6 (MLN 6 and 7).

Dakota Formation

The Dakota Formation is typically composed of light-brown to gray or black, noncalcareous clay and silt, and fine- to medium-grained sand, which is sometimes well cemented. The dark color of the clay and silt is attributed to organic material. Twelve feet of calcareous clay occurs in MLN 94 (fig. 11). Bentonite was recovered from this formation in MLN 3 (fig. 6) and questionably in MLN 94 (fig. 11).

The Dakota Formation underlies all of Yankton County and contains at least two aquifers (Bugliosi, 1986) of regional and historical significance. None of the test holes drilled for this study definitively penetrated the entire formation, so the degree of variation in thickness throughout the county remains unknown. The formation may have been penetrated in MLN 1 (fig. 6); if so, the formation here is only 135 feet thick. A commercially drilled well (Merle Johnson well) at SW¼ SE¼ sec. 10, T. 95 N., R. 54 W. (app. B; near MLN 57 in fig. 9) does penetrate the Dakota Formation where it is 170 feet thick. The formation is penetrated by the SDGS No. 1 Holzbauer Test 4 miles east of Yankton (app. B); there it is 495 feet thick. Simpson (1960) reported a range of 287 to 423 feet thick in the Yankton area. The formation could be as little as 50 feet thick in part of the northwestern corner of the county if the basement elevation is as high as 815 feet, as reported in a private well (Leonard Gunderson well) at NE¼ SE¼ sec. 3, T. 96 N., R. 57 W. (app. B).

Graneros Shale

The Graneros Shale is represented by brown and gray or greenish-gray, generally noncalcareous clay. The clay is calcareous in MLN 54 (fig. 9) and MLN 117 (fig. 13) but there are too few determinations to establish any trend. Six feet of possibly siliceous shale occurs in MLN 94 (fig. 11).

Little is known about the Graneros Shale in Yankton County because it is thin throughout the county. The thickness of the Graneros Shale ranges from 15 to 62 feet based on test-hole data. Its thickness increases from 22 feet in the northwest (MLN 26 in fig. 8) to 44 feet 1 mile east of Volin (MLN 94 in fig. 11). However, it is only 16 feet thick in the north (test hole R1-87-58, NE¼ NE¼ NE¼ SE¼ sec. 12, T. 96 N., R. 56 W.), 1½ miles south of MLN 5 (figs. 4 and 6), and 15 feet thick in MLN 16 (fig. 7). It is 32 feet thick in the extreme southeast (MLN 117 in fig. 13). A thickness of 62 feet was encountered in a well commercially drilled for the town of Utica and logged by the South Dakota Geological Survey (Utica town well, app. B). The variation in thickness can be largely ascribed to the undulatory nature of the conformable contact with the underlying Dakota Formation. In the subsurface, the top of the Dakota is defined as the first significant (greater than 1 meter thick) sandstone encountered by drilling (Brenner and Whitley, 1981). As the Dakota Formation is largely a deltaic sequence with meandering distributary channels represented by the sandstone, the contact elevation will vary. Simpson (1960) gives much greater thicknesses for the Graneros Shale, as he defines the contact with the Dakota Formation to occur at the first sandstone (although he does not clarify how he defines the first sandstone).

Greenhorn Limestone

The Greenhorn Limestone is brown to grayish- or greenish-brown, gritty, and appears as highly calcareous clay in drill cuttings. White specks are often present. Chips of limestone are recovered when presumably the calcite content is high ("pure" limestone). Aragonite may also occur, probably from drilling through *Inoceramus* shells, a large clam that was common when the Greenhorn Limestone was deposited.

The thickness of the Greenhorn Limestone ranges from 30 to 62 feet, based on test-hole data. The Greenhorn Limestone is 62 feet in the northwestern corner (MLN 1 in fig. 6). It thins to the south to 46 feet in MLN 40 (fig. 9) and more so to the east, 32 feet in MLN 16 (fig. 7). Its thickness is 30 to 35 feet in the remainder of the county except 48 feet in MLN 54 (fig. 9). The Greenhorn Limestone is conformable with the underlying Graneros Shale and the overlying Carlile Shale. Some variability in thickness may be a result of arbitrarily picking the upper contact on the electric log. However, this contact is usually well defined and often coincides with the start of bit chatter while drilling. Variability in thickness probably reflects a lateral facies change with the Graneros Shale, although a directional trend is not apparent.

Carlile Shale

Undifferentiated Carlile Shale obtained from the test holes is generally a dark-gray, noncalcareous clay with a greasy luster. Pyrite and selenite may be present. Small amounts of bentonite occur with considerable inconsistencies in the formation. When it is damp and thinly spread, Carlile Shale often resembles graphite.

The Carlile Shale underlies all of Yankton County except where removed by erosion in any deep bedrock channels which may exist (pl. 1). Much of the bedrock surface of the county is represented by this formation. The thickness of the fully preserved formation ranges from less than 160 feet in the north-central part of the county (fig. 8) to more than 200 feet beneath Yankton Ridge (fig. 13) and apparently even thicker at Gavins Point Dam (Simpson, 1960). Rukstad (1963) reported occurrences of Carlile Shale in three test holes, (his Rotary Test Holes 1, 2, and 5), but deeper holes drilled for this study demonstrate that they actually encountered till in hole 1 at the same location as MLN 42 (fig. 9), and possibly the Niobrara Formation in hole 2, located 1 mile east of MLN 42, which occurs as a bedrock ridge to the southeast (figs. 9 and 10). Hole 5, drilled near the northeast corner of Lesterville, in which Rukstad (1963) reported the Codell Member of the Carlile Shale as the first bedrock intersected, may also have encountered the Niobrara Formation instead. Plate 1 illustrates the present interpretation.

The Carlile Shale is generally divided into four members (Simpson, 1960; Shurr, 1980). In ascending order they are the Fairport Shale Member, Blue Hill Shale Member, Codell Sandstone Member and an uppermost member. This uppermost member was questionably called the Sage Breaks Member by Simpson (1960) and was considered an unnamed shale member by Shurr (1980).

The Fairport Shale Member is one of two members (the second being the Codell Sandstone) that can be consistently identified on the basis of lithology in the test holes drilled in Yankton County. Contacts between the remaining members, if present, are largely determined by changes recorded by the electric logs. The Fairport Shale Member may be a light- to dark-brown, gray, or grayish-brown, usually calcareous clay. It may contain calcite laminae and has a greasy luster, but at times is earthy. White specks are nearly always present and represent its most distinguishing character. Shurr (1980) recognized these specks in an outcrop, and they have been identified elsewhere as coccolith-bearing fecal pellets (Watkins, 1986). Presumably similar white specks may also occur in the underlying Greenhorn Limestone, as noted above. Where the Fairport Shale Member is identified in test holes in Yankton County, it is usually 60 to 80 feet thick, but it can be highly variable in thickness.

The Blue Hill Shale Member is inferred in the cross sections by stratigraphic position. It is medium-gray to brownish-gray, calcareous to noncalcareous clay. In MLN 30 (fig. 8) the member contains chips of limestone and calcite, which may be from septarian nodules (Shurr, 1980). Where the Blue Hill Shale Member can be inferred in the cross sections, thicknesses are usually 60 to 80 feet. In MLN 77, (fig. 10), the thickness is only 34 feet, but the Codell Sandstone Member is inferred to be present also. This may suggest erosion of the underlying Blue Hill Shale Member occurred prior to or during deposition of the Codell Sandstone Member.

Except for the possible occurrence in MLN 77 (fig. 10), MLN 113 (fig. 13), Rukstad's (1963) Rotary Test Hole 5, and a private well (English Ski Jump) at NE¼ NW¼ NE¼ SW¼ sec. 13, T. 93 N., R. 57 W. (app. B), the Codell Sandstone Member has not been identified in test holes in Yankton County. Simpson (1960) described it at Gavins Point Dam, when it was temporarily exposed during construction of the dam, as a siltstone with some fine to very fine sand. It is also identified on an electric log of a private well (Oscar Rempfer Well) drilled in the northern part of the county (MLN 16 in fig. 7, app. B).

The uppermost member of the Carlile Shale is here considered as an unnamed member, following Shurr's (1980) usage. It is usually a medium gray, noncalcareous clay. It yielded white specks in only one test hole, MLN 31 (fig. 8). Where identified, the uppermost member varies considerably in thickness, from 30 feet in MLN 60 (fig. 10) to 65 feet in MLN 30 (fig. 8).

The variations in thicknesses of members of the Carlile Shale suggest facies changes reflecting changes in depositional environment. However, it is not possible to adequately infer geologic interpretations based only on the lithology and thickness of the members shown in the cross sections.

Niobrara Formation

The most distinctive bedrock formation in Yankton County is the Niobrara Formation. It weathers to a light to dark yellowish-orange and forms impressive cliffs along Lewis and Clark Lake, Turkey Creek, and at Marindahl Lake. Other exposures (pl. 2) tend to be of much lesser extent. Simpson (1960) suggested it underlies the entire Yankton area except for the James River and Missouri River trenches. However, from extensive test-hole drilling carried out for this study, it is clear that the Niobrara Formation has been completely removed from much of Yankton County. Removal may have occurred during the Tertiary or Quaternary by weathering or stream erosion or during the Quaternary by glacial erosion (pl. 1).

Where the entire formation is preserved, the thickness ranges from about 180 feet in the north (MLN 6 in fig. 6) to about 200 feet in the south (MLN 108 in fig. 13). Simpson (1960) described the unweathered Niobrara Formation as a bluish-gray limestone. Drill cuttings commonly mimic shale, and appear as light- to dark-gray or light- to dark-brown or brownish-gray, calcareous clay. Niobrara Formation cuttings are gritty, however, and nearly always turn brown and effervesce if treated with dilute hydrochloric acid. Evidence of thin seams of bentonite is found in some test-hole samples. Simpson (1960) recognized two members, the lower Fort Hayes Limestone Member and upper Smoky Hill Chalk Member. As they are separated on the basis of thickness of bedding, the members cannot be distinguished in the subsurface. No evidence of a boundary between the two members occurs with certainty in the electric logs.

The contact between the Niobrara Formation and the underlying unnamed member of the Carlile Shale is largely unconformable (Witzke and others, 1983), and the contact displays an abrupt facies change. Simpson (1960) also noted that the contact is disconformable in some places. The contact with the overlying Sharon Springs Member of the Pierre Shale is also largely unconformable (Witzke and others, 1983). Fresh exposures of this contact reveal a highly indurated zone a few inches thick.

Pierre Shale

The Pierre Shale consists of a thick sequence of marine shales which typically vary in color from light to dark gray. Some parts of this formation are also calcareous and detrital beds, although rare, may occur. Fossil fragments, mainly of vertebrates (such as fish scales and marine reptile vertebrae), are common in sections.

The Pierre Shale occurs only on Turkey Ridge and Yankton Ridge and just north of Yankton Ridge (pl. 1). Its known thickness in Yankton County ranges from 57 feet on Turkey Ridge (fig. 6) to nearly 180 feet on Yankton Ridge (fig. 12). Simpson (1960) also noted a maximum thickness of 180 feet, but Schultz and others (1980) show a thickness of about 215 feet. This is in sharp contrast with a thickness of more than 800 feet at Chamberlain, South Dakota, and over 1,200 feet on the flanks of the Black Hills; and more than double that in parts of Wyoming and Montana for equivalent formations (Schultz and others, 1980).

A commonly accepted stratigraphy for the Pierre Shale in Yankton County is presented in Hammond and others (1995). According to Hammond and others (1995), only three members of the Pierre Shale can be identified in the study area: Sharon Springs, Crow Creek, and DeGrey Members. However, at least six members of the Pierre Shale are recognized by one of the authors (Johnson) in Yankton County. In ascending order they are the Sharon Springs, Gregory, Crow Creek, DeGrey (which cannot be differentiated from the overlying Verendrye in the measured sections as interpreted), Virgin Creek, Mobridge, and possibly Elk Butte. According to Johnson, these members cannot all be recognized with confidence in outcrops unless trenches are dug to remove the weathered surface. Not only must trenches be dug to accurately determine the nature of the contacts, but also to reveal thin bentonite seams and, more importantly, reveal evidence of slumping and glacially disturbed sections.

Outcrops were described and measured by Johnson in five localities (fig. 4):

1. An abandoned quarry next to the Wakonda Lime Company quarry, here termed the Wakonda lime quarry section, at NE¼ NW¼ NW¼ SE¼ sec. 35, T. 95 N., R. 54 W.;

2. A road cut northwest of Marindahl Lake, here termed the northwest Marindahl Lake section, at NW¼ NW¼ NW¼ NW¼ sec. 7, T. 95 N., R. 54 W.;

3. An outcrop in a valley north of the old cement plant, here termed the old cement plant valley section, at NE¼ SW¼ SW¼ NE¼ sec. 8, T. 93 N., R. 56 W.;

4. Several outcrops near the U.S. Geological Survey Lake Port triangulation station, here termed the Lake Port composite section, in the NE¼ SE¼ SW¼ NE¼ NE¼ sec. 11, the NW¼ SE¼ NW¼ NE¼ NE¼ sec. 11, the SW¼ NW¼ NE¼ SE¼ NE¼ sec. 11, and the NW¼ SW¼ SW¼ NE¼ NE¼ sec. 11, T. 93 N., R. 57 W.; and

5. An outcrop near the Lesterville Recreation Area at SE¼ NE¼ SE¼ SW¼ sec. 16, T. 93 N., R. 57 W.

Detailed lithologic descriptions of these sections are presented in appendix C. All descriptions except that of the old cement plant valley section were made under the supervision of Richard F. Bretz.

An attempt to measure an additional section in a road cut at NW¼ SE¼ SE¼ SE¼ sec. 23, T. 95 N., R. 54 W. was thwarted when, upon trenching, it was discovered the shale had been badly disrupted by slumping and pressure from glacial ice. Bentonite seams had been terminated and smeared, and a block of Niobrara chalk was found above the Niobrara Formation-Pierre Shale contact. Five plesiosaur (large marine reptile) vertebrae were recovered from this slumped section and identified as *Dolichorhynchops* (*Trinacromerum*) *sp*. by Kenneth Carpenter of the Denver Museum of Natural History. They are catalogued in the University of South Dakota vertebrate paleontology collections as USDVP 1173.

SHARON SPRINGS MEMBER

The indurated zone at the Niobrara Formation-Pierre Shale contact is mostly within the Sharon Springs Member. This zone is gypsiferous, iron-stained, and often contains some jarosite. The Sharon Springs Member consists of olive-black, brownish-black or black, noncalcareous, fissile or platy shale. Unidentified fish remains, mostly as very small scales, are common. Minor amounts of gypsum occur, and staining by iron and jarosite is minor to moderate. Several seams of bentonite occur, ranging from less than 1 inch thick to typically about 4 inches thick and as much as 7 inches thick. The shale is organic-rich (Schultz and others, 1980) and typically gives a significant peak or spike on the natural gamma radiation log. Simpson (1960) distinguishes two units in the Sharon Springs, the lower one bituminous and the upper, nonbituminous. These units could not be recognized in the sections described for this report.

The thickness of the Sharon Springs Member ranges from 3.0 to 11.8 feet in the sections on Yankton Ridge, and 5.3 and 6.7 feet in sections on Turkey Ridge. Members of the Pierre Shale could be recognized with some confidence in only one test hole, MLN 57 (fig. 9). The Sharon Springs Member is 5 feet thick in this test hole. Schultz and others (1980) show the member to be nearly pinched out in the vicinity of Yankton County; Simpson's (1960) thicknesses agree with those given here. The elevation of the contact with the underlying Niobrara Formation in the measured sections ranges from 1,322 to 1,342 feet at Yankton Ridge to 1,352 feet at the northwest Marindahl Lake section to 1,391 feet at the Wakonda lime quarry section on Turkey Ridge.

GREGORY MEMBER

The Gregory Member on the cross section provided by Schultz and others (1980) is less than 5 feet thick or is even pinched out. Simpson (1960) gives a thickness of 41 to 43 feet, but this is believed to be erroneous, and so likely are many of his remaining measurements. In the sections measured and described for this report, the presence of the Gregory Member is questioned in the Lesterville Recreation Area and Lake Port composite sections as beds possibly belonging to it are 0.4 and 0.2 feet thick, respectively. A bed 0.6 feet thick was assigned to this member in the old cement plant valley section. The Gregory Member is present on Turkey Ridge; it is 3.7 and 2.3 feet thick in the northwest Marindahl Lake and Wakonda lime quarry sections, respectively. It is 4 feet thick in MLN 57 (fig. 9).

One characteristic that differentiates this member from subjacent and superjacent beds is the presence of fine to medium sand-size detrital grains in part of, or throughout the member. Detrital grains are absent at this level in the Lake Port section. Bulk rock x-ray diffraction analysis of the upper 2 inches in the Wakonda section reveals the presence of apatite and quartz. White specks that may be dolomite are present in some of the sections. The member is generally noncalcareous. The overall color is lighter than the Sharon Springs Member, but closer examination reveals a wide array of colors, some resulting from iron-, jarosite- or manganese-staining. Some gypsum is usually present.

The Gregory Member is thought to be absent in Yankton County by Izett and others (1993), Hammond and others (1995), and Witzke and others (1996), as they consider the detrital facies to be a part of the Crow Creek Member. All shale below the detrital facies would therefore belong to the Sharon Springs Member.

CROW CREEK MEMBER

The Crow Creek Member in all of the sections is an argillaceous micrite or "marl." It was measured, but not described at the old cement plant valley locality. The color is usually a very pale orange, but in the Lake Port composite section it is brownish-gray at the base changing upward to pale yellowish-brown and grayish-orange. Detrital grains are sometimes common at the base. X-ray analysis of the lower 2 inches at the Lake Port composite section shows at least 15 percent each of quartz, dolomite, and calcite. Of greater significance is the presence of shale clasts throughout the member. They appear to have been derived from the Gregory Member, as has been observed outside of Yankton County (Bretz and Johnson, 1981). The upper 10 percent of the Crow Creek Member contains numerous worm burrows filled with clay derived from the overlying DeGrey Member.

The detrital grains at the base of the Crow Creek Member have been the focus of considerable attention (Izett and others, 1993). Some of the quartz grains, as well as some microcline and plagioclase grains, all recovered as acid-insoluble residue from outcrops at the old cement plant quarry and House of Mary Shrine (3½ and 6½ miles west of Yankton, respectively) show evidence of shock lamellae. Izett and others (1993) attribute their occurrence to the Manson impact structure created by a meteorite 150 miles to the east-southeast in Iowa. They also suggest that deposition of these grains, as well as other anomalous stratigraphic and biostratigraphic relations, resulted from an impact-triggered tsunami. They and other authors consider the detrital portion of the Gregory Member to be a basal facies of the Crow Creek Member, as mentioned earlier.

The origin of the Crow Creek Member sediments has become a subject of some controversy. The entire member may represent reworked sediments deposited by the above-mentioned tsunami, or this process may be restricted to the basal facies followed by more gradual transgressive deposition (Hammond and others, 1995; Witzke and others, 1996).

The Crow Creek Member tends to thicken slightly toward the east across the study area, a characteristic contrary to the regional trend of eastward-thinning (toward the eastern margins of the seaway; fig. 16) of the Upper Cretaceous formations. Its thickness is 4.0 ± 0.2 feet in the Yankton Ridge sections, but is only 3.3 feet thick in the northwest Marindahl Lake section. It is 8.9 feet thick in the Wakonda lime quarry section and 6 feet thick in MLN 57 (fig. 9). The thickness shown in a cross section by Schultz and others (1980) is less than 5 feet.

DEGREY, VIRGIN CREEK, AND MOBRIDGE MEMBERS

Units above the Crow Creek Member are identified in the Lake Port composite and Wakonda lime quarry measured sections as the DeGrey, Virgin Creek, and Mobridge Members (the Verendrye Member is absent). Thick cover and slumping preclude significant or accurate descriptions in the remaining measured sections. The Lake Port composite section accounts for only one-third of the total section in the Yankton Ridge area. Schultz and others (1980) show the Elk Butte Member to be present above the Mobridge Member, but the combined thicknesses do not account for the discrepancy. Neither the Lake Port composite nor the Wakonda lime quarry measured section agrees with the facies distribution in the middle portion of the cross section provided by Schultz and others (1980).

The DeGrey Member recognized in the Lake Port composite and Wakonda lime quarry sections, and upper reliable parts of the Lesterville Recreation Area and northwest Marindahl Lake sections, consists of noncalcareous dark-gray, dark-greenish-gray or olive-black shale. Iron staining and jarosite staining are common. Very small fish remains are common throughout the section. Bentonite seams up to about 3 inches thick occur in the lower 2 feet, but are much less common in the remaining part of the member. Only 1.8 feet of this member is recognized in the Wakonda lime quarry section. At least 8.9 feet occur in the Lake Port composite section where the boundary with the presumed overlying Virgin Creek Member is covered. Worm burrows are common in the Lake Port section. Teeth and bone fragments, probably belonging to mosasaurs (large marine lizards), are present in the Wakonda section.

The presumed Virgin Creek Member is composed of grayish-black to black shale in the Wakonda lime quarry section and lower part of the exposed portion of the Lake Port composite section. Higher in the Lake Port composite section the color can be grayish-black to black, or olive-black, but mostly brownish-black. In the upper part of the section, the color is mostly dark gray. Iron staining is common throughout both sections. Jarosite is also common in the Wakonda lime quarry section. Worm burrows are common in the central part of the exposed Lake Port composite section, as are *Inoceramus* shell fragments. Fish remains occur throughout the Wakonda lime quarry section, but only in about the lower half of the exposed Lake Port composite section. The Lake Port composite section becomes more or less increasingly calcareous toward the top of the upper half of the exposed part of the member. This coincides with a change from shale to mudstone. The upper one-third of the Wakonda lime quarry section is mostly calcareous shale.

The presumed Virgin Creek Member is 7.4 feet thick in the Wakonda lime quarry section, but is 18.9 feet thick, not including the covered base, in the Lake Port composite section. Bentonite seams up to 3 inches thick occur throughout the lower two-thirds of the Wakonda lime quarry section. They are mostly absent in the lower one-fourth of the exposed Lake Port composite section, but are common, up to 3 inches thick, in the middle one-third of that section; only very thin seams occur in the calcareous part. The thicker bentonite seams in the Wakonda lime quarry section cannot be correlated with confidence with those in the Lake Port composite section. Differences in their spacing, as well as differences in thickness of what is interpreted as the Virgin Creek Member, suggest a much higher rate of sediment deposition at the Lake Port composite locality.

The presumed Mobridge Member is represented by only 2 feet of section at the Wakonda lime quarry locality where it is covered by till. It is represented by 13 feet of section at the Lake Port composite locality where it is covered by till. It is composed mostly of argillaceous micrite or "marl" and calcareous mudstone, all mostly of various shades of gray. A few bentonite streaks occur.

The DeGrey, Virgin Creek, and Mobridge Members described above are considered to be the DeGrey Member by Hammond and others (1995), but they do not discuss this conclusion. Witzke and others (1996) present a section based on the Lake Port composite section described in appendix C. All of the units above the Crow Creek Member are combined into the DeGrey Member as a lower shale and an upper marl, but the member is not discussed. Further study must await the discovery of index fossils before a definitive stratigraphic interpretation can be reached.

Schultz and others (1980) show about 15 feet of marl occurring within their Verendrye Member in their Yankton section. This could be the same as the presumed Mobridge Member described above, except their marl occurs too low in their section. The discrepancy may not be resolved until a measurable section of the upper half of the Pierre Shale becomes exposed. Although the test holes drilled through the thicker sections of Pierre Shale do not reveal the members or presumed members described above, they do show some evidence of an upper thick calcareous section. MLN 107 (fig. 13) has 13 feet of dark-gray slightly calcareous clay at the top and below that, 102 feet of medium-gray mostly calcareous clay. However, in MLN 108 (fig. 13) the upper 71 feet of light- to medium-gray clay may not be calcareous. In MLN 97 (fig. 12) the upper 31 feet is slightly calcareous gray to brown clay, but in MLN 95 (fig. 12) the entire section appears to be calcareous.

Tertiary Geology

Rocks believed to belong to the Tertiary System occur in the subsurface in Yankton County on Yankton and Turkey Ridges. These rocks are thought to be part of the Ogallala Group, which are Neogene in age. The possible Ogallala Group rocks so far have been found only in the subsurface of Yankton County (figs. 6, 12, 13, and 15), but these rocks are likely only thinly covered along the deep ravines on the south slope of Yankton Ridge (as suggested between MLN 107 and MLN 109 in fig. 13). Limited exposures of these rocks occur to the west in southern Bon Homme County (Christensen, 1974) and much more extensive exposures occur across the Missouri River in Nebraska (Simpson, 1960; Burchett and others, 1988).

In Yankton County, the Ogallala Group(?) rocks are composed of light-yellowish-tan to orange-brown, silty, sometimes sandy clay, which is calcareous or noncalcareous. The thickness of these Ogallala Group(?) rocks is variable owing to erosion by glaciation and the terrestrial depositional environment (the underlying Cretaceous formations are marine sediments except parts of the Dakota

Formation). As weathered sediments from the chalky members of the Pierre Shale and weathered Niobrara Formation can also attain nearly the same color as the Ogallala Group(?) cuttings acquired by drilling, it might be argued that the identification of the Ogallala Group in the subsurface is incorrect. However, these deposits, unlike the Upper Cretaceous rocks, are often sandy and sometimes noncalcareous. In a test hole located on Turkey Ridge at NE¼ NE¼ NE¼ SE¼ sec. 12, T. 96 N., R. 55 W., 56 feet of Ogallala Group(?) rocks rest on the Niobrara Formation. The contact is about where the Pierre Shale-Niobrara Formation contact would be expected. This contact position, coupled with a change in the electric log 12 feet below the top of the unit, suggests a contact between members of the Pierre Shale might be present. However, the lower 44 feet of the Pierre Shale, with the possible exception of the included Crow Creek Member, does not weather to the colors found in Ogallala Group rocks.

Deposits on Yankton Ridge (figs. 12 and 13) tentatively identified as Ogallala Group are unlikely to be weathered Pierre Shale for the reason given above. Test hole MLN 96 (fig. 12) just penetrates the top 16 feet of Pierre Shale, which shows no evidence of weathering even though it is at the same elevation as the Ogallala Group(?) in MLN 95 and 97 (fig. 12).

Christensen (1974) described small outcrops of Ogallala Group rocks in western Bon Homme County as consisting of quartz sand and multicolored clays, capped by pale-gray to pale-green silica-cemented sand and conglomerate. They were believed to be the easternmost occurrences of this unit in South Dakota. Because Ogallala Group sediments were transported from western sources, it is to be expected that their occurrences in Yankton County would be of a finer texture. Simpson (1960) divided the Ogallala Group in the study area into a lower unit dominated by sand (some of it grayish-orange) and an upper unit dominated by silty clay. He did not describe any east-west trend in grain size.

Plio-Pleistocene Sediments

Western-Derived Sand

The name “western-derived sand” or “western sand” has been liberally assigned to a variety of multi-colored, quartz- and feldspar-rich sands and gravels in southeastern South Dakota (see the South Dakota Geological Survey lithologic logs database on the Internet at www.sdgs.usd.edu, search word “western”). The source of these sands and gravels is thought to be to the west in the Black Hills or even the Rocky Mountains, thus the name. Minor lithologies, such as limestone and obsidian, found in these sands are consistent with a source some distance from southeastern South Dakota. In Yankton County, these sands may be Pliocene to earliest Pleistocene in age.

Western-derived sand was reported to occur on Turkey Ridge 2 miles south of Irene near the northeast corner of sec. 13, T. 95 N., R. 54 W. by Flint (1955). The alluvium present here (pl. 2) contains sand similar to western-derived sand. As the locality occurs at an elevation of about 1,440 feet, western-derived sand is possible except that the area is underlain by glacial deposits (east end of figs. 8 and 9). Also, what appears to be cross-bedded western-derived sand is incorporated in an outwash terrace 1½ miles to the southwest (NE¼ NW¼ SW¼ NE¼ to NW¼ NW¼ SW¼ NE¼ sec. 23, T. 95 N., R. 54 W., pl. 2). Because it is intermixed with sand of widely varying composition characteristic of outwash, this deposit likely was not originally deposited here, but rather, it was eroded from its original depositional site by glaciation and redeposited as outwash by meltwater. Undoubted western-derived sand does occur about half a mile northeast of this area in Clay County (NW¼ SW¼ sec. 7, T. 95 N., R. 53 W.). It occurs in gravel pits at an elevation of about 1,390 to 1,400 feet, directly overlies the Niobrara Formation, and has been described by Lutzen (1957) and Christensen (1967). Based on vertebrate fossils from this site, Pinsof (1985) assigned a late Blancan age (latest Pliocene).

Western-derived sand occurs in a test hole on Turkey Ridge in northeastern Yankton County at NE¼ NE¼ NE¼ SE¼ sec. 12, T. 96 N., R. 55 W., half way between MLN 7 and 21 (fig. 4). It is 56 feet thick and the base is in contact with Ogallala Group(?) rocks at an elevation of 1,398 feet. This elevation and stratigraphic relationship suggest it could be part of the Bon Homme gravel (see following section), but this is highly uncertain because of the slightly older western sand occurrence in Clay County, which Pinsof (1985) assigned a late Blancan age (latest Pliocene), as noted above.

One western-derived sand deposit that was intersected in a drill hole on Turkey Ridge in Hutchinson County (SW¼ SW¼ SW¼ SW¼ sec. 14, T. 98 N., R. 56 W.) fills a channel that downcuts the Ogallala Group(?) rocks. A sample of this western-derived sand, taken at a depth of 80 feet in this hole, yields an extremely low $^{26}Al/^{10}Be$ value of 1.0, suggesting a burial age date of around 3.5 million years (G. Balco, University of Washington, oral commun., 2002). This burial age date, if accurate, indicates a Tertiary age for both this western-derived sand deposit and the underlying Ogallala Group(?) rocks.

Bon Homme Gravel

Christensen (1974) applied the name Bon Homme gravel to certain western-derived sand deposits found in southeastern Bon Homme and southwestern Yankton Counties. He designated the type section in a then actively-worked gravel pit in extreme southwestern Yankton County, the Kuchta sand pit of Johnson and Milburn (1984). The pit is now depleted of sand and gravel.

The Bon Homme gravel is dominated by light-colored, sand-sized grains of quartz and feldspar. Granite and, rarely, grains of chert and other lithic fragments constitute most of the coarser fraction; the remainder is gravel-sized feldspar grains. It is very clean, as clay is absent except as lenses or spheroidal clay balls. The grains are subangular to subrounded with moderate to high sphericity. These characters attest to a considerable transport distance. Cross-bedding was common in outcrops that are now largely depleted.

All proven occurrences in Yankton County are restricted to the southwest (pl. 2). Thicknesses in test holes range from 12 to 45 feet, with local bases occurring at elevations ranging from 1,491 to 1,521 feet (Qpis in figs. 12 and 13). Some Bon Homme gravel deposits apparently occur higher still, based on outcrop evidence. Test holes have intersected mixtures of large quantities of this sand with outwash (MLN 10 in fig. 7), sometimes requiring careful examination of color and composition before the source can be ascertained.

The age of the Bon Homme gravel was estimated by Christensen (1974) to be late Kansan (middle Pleistocene). Johnson and Milburn (1984) estimated the age to be late Blancan (latest Pliocene) on the basis of mammalian fossils and discussed the problems inherent in correlating glacial ages with North American land mammal ages (Kurtén and Anderson, 1980; Savage and Russell, 1983). Pinsof (1985) used a more complete mammalian faunal list than Johnson and Milburn (1984) and concluded the Bon Homme gravel is early Irvingtonian (earliest Pleistocene) in age.

Pleistocene Stratigraphy

Earlier studies of the glacial geology of the Yankton County region imply a considerable knowledge of the sedimentary units deposited directly or indirectly by glacial activity. Their geomorphic relationships at the surface, described on a regional basis by Flint (1955), and in greater detail by Simpson (1960), are largely correct. The plethora of names derived from outside the region which have been applied to these units, especially by Simpson (1960) and also by Lutzen (1957) and Sevon (1958), suggest a well understood and largely accepted chronology. Simpson (1960) had little information pertaining to the subsurface geology and no isotopic (numerical) dates of any of the units upon which to base his interpretations. The isotopic age of many glacial units is still unknown and to correlate them with units having assigned names such as Mankato substage, Kansan and Nebraskan stages, and so on, is misleading and to some extent outdated. For that reason the units discussed here will be treated conservatively with a minimum of allostratigraphic subdivisions deemed necessary for geomorphic and subsurface differentiation. It will become clear, however, that some subsurface relationships are open to differing interpretations.

More recent work (Matsch and Schneider, 1986; Hallberg, 1986; Hallberg and Kemmis, 1986) has attempted to correlate glacial deposits across the Midwest using lithologies and radiometric and paleomagnetic age dates, among other tools. What has resulted from this work is a reinterpretation of the stratigraphy and timing of the glacial history across the mid-continent of North America. This re-interpretation is the basis for the Pleistocene stratigraphy presented in this study, including the presence of multiple pre-Wisconsin advances, which are likely all pre-Illinoian (see next section), and absence of early and middle Wisconsin glacial deposits in Yankton County.

Two numerical age dates have been acquired for the Pleistocene deposits in Yankton County. These dates (12,880 + 170 and 12,540 + 170 years by Carbon-14 analysis) are from wood recovered in test holes MLN 34 (fig. 8) and MLN 81 (fig. 11), respectively. However, most of the Pleistocene stratigraphy in Yankton County is based on stratigraphic position, yielding only relative ages.

Pre-Wisconsin Stratigraphy

Based on test-hole data, three pre-Wisconsin tills and associated outwash, each package representing a major glaciation or glacial advance, are preserved in the subsurface of Yankton County. The pre-Wisconsin 1 sediments are the oldest glacial deposits preserved in the subsurface of Yankton County, on the basis of stratigraphic position (it is the lowermost till in the study area). Pre-Wisconsin 2 sediments were deposited by the next glacial advance, and are preserved in low areas of the subsurface across much of Yankton County. No units of equivalent ages to the pre-Wisconsin 1 and 2 sediments have been recognized in Clay County (Christensen, 1967). However, in Bon Homme County, Christensen (1974) has a possible till below his Illinoian till (Qit at NE¼ NE¼ NE¼ NE¼ sec. 6, T. 94 N., R. 58 W. and NE¼ NE¼ NE¼ NE¼ sec. 3, T. 94 N., R. 58 W.), which might correlate with the pre-Wisconsin 2 till in Yankton County.

The pre-Wisconsin 3 advance is the youngest of the pre-Wisconsin advances. The pre-Wisconsin 3 sediments are probably equivalent to Christensen's (1974) Illinoian deposits (Qit) in Bon Homme County. Christensen's (1974) interpretation of this till being Illinoian was based on observed features that suggest an "older than Wisconsin" age. As work by Hallberg (1986) suggests that no Illinoian glacial advances reached Bon Homme, Yankton, Clay, or Union Counties, Christensen's (1974) Qit deposits are likely pre-Illinoian, not Illinoian. This also suggests that the pre-Wisconsin tills identified in Yankton County are pre-Illinoian. Across the Missouri River in Cedar County, Nebraska, Lugn (1935) described "Nebraskan" tills underlying "inter-till" sands and gravels and loess in some areas, and cobble and boulder lags that he interpreted to be remnants of "Kansan" till that is underlain by "Nebraskan" till in other areas. Both the "Kansan" and "Nebraskan" tills described in Lugn (1935) are referred to as pre-Illinoian (Hallberg, 1986).

As mentioned previously, no Illinoian glacial deposits are believed to be present in the study area, based on revisions to the stratigraphy of the glacial deposits in western Iowa and eastern Nebraska (Hallberg, 1986).

Late Wisconsin Stratigraphy

The most recent glacial advances occurred during the late Wisconsin. Although there were four or five glacial advances and retreats during this time across the northern great plains (Gilbertson, 1989; Hallberg and Kemmis, 1986), and certainly more than one advance into South Dakota (Hammond, 1991; Tomhave, 1997), the Carbon-14 dates of wood in outwash in Yankton County can only bracket the age of the till in the study area above the outwash as being less than about 12,540 years old, and thus late Wisconsin.

One late Wisconsin till is recognized in Yankton County, the till overlying the outwash with the dated wood. A single late Wisconsin till was recognized in Bon Homme County (Christensen, 1974) to the west and Clay County (Christensen, 1967) to the east, as well. This one late Wisconsin till could represent more than one local advance, as local surges or ice streams of the last late Wisconsin glacier likely occurred (Patterson, 1997a, b; 1998). However, sediments from separate local surges generally cannot be distinguished in rotary drill cuttings. This one late Wisconsin till could also represent more than one post-14,000 year major advance. However, no lithologic break, such as a relatively continuous sand and gravel deposit, which might represent another advance, has been identified in this till sequence. Thus, it is necessary to group these sediments together into one late Wisconsin till sequence for the sake of discussion and analysis in this study.

It seems unlikely that the pre-Wisconsin 3 glacial advance is an older late Wisconsin advance because the time between local late Wisconsin re-advances in the southeastern part of South Dakota would probably not be long enough to allow for a remnant 10-foot thick or more oxidized zone at the top of the lower glacial deposits. The main controlling factor in thickness of the oxidation zone in a till is the degree of aeration; oxygen is needed to oxidize the iron in glacial sediments (Bettis, 2000). In this case, till generally will be oxidized above the water table, not below it, and long-term exposure at the surface of the earth facilitates the oxidation. It is unclear whether the climate post-14,000 years ago was dry enough to lower the water table and favor oxidation of surficial till (Paterson and Hammer, 1987). However, unless the lower (what is herein referred to as the pre-Wisconsin 3 till) till was emplaced during the earliest late Wisconsin glaciation (about 20,000 years ago, pre-dating the James lobe advance), of which there is no evidence (Gilbertson, 1989; Patterson, 1997a), there does not appear to be much time to form a significant oxidized zone in an earlier late Wisconsin till. The earliest recognized late Wisconsin advance of the James lobe is dated around 13,400 years (Gilbertson, 1989; Patterson, 1997a), and the Carbon-14 date of wood in outwash at the base of the recognized late Wisconsin till in Yankton County is around 12,880 to 12,540 years ago, which yields only a potential 1,000 year or so window within which a glacier could advance into Yankton County, retreat, and the upper sediments could oxidize significantly (assuming an adequately dry climate for significant oxidation).

Pleistocene Geology

Terminology

Several terms relating to composition, particle size, and/or process of deposition of glacial sediments are used in the following sections. These terms are defined as follows:

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 is a function of the rocks or sediments over which the ice traveled. In Yankton County, the till typically consists of a silty clay matrix, a variable proportion of sand and pebbles, and few boulders. The small grain size reflects the predominance of shale and chalk in the bedrock 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 Niobrara Formation or chalky members of the Pierre Shale). Local very sandy till likely formed where the ice overrode outwash or, alternatively, where outwash from meltwater flowing within (englacial) or on top of (supraglacial) the ice was let down as the ice melted.

A given till unit, if not strongly eroded, 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. The orange and reddish colors and total thickness of an oxidized till suggest significant weathering, which in turn, suggests a long surface exposure time. To give an idea of the period of time represented by the color and thickness of these oxidized zones, surface exposure time during the Sangamon interglacial period alone (separating late Illinoian from “Eowisconsin” time) could be as long as 10,000 years (Šibrava, 1986). Given that there were no Illinoian and early Wisconsin glaciations in Yankton County, the surface exposure time from pre-Illinoian to late Wisconsin would be considerably longer.

OUTWASH

Outwash is sand and gravel with minor amounts of silt and clay that is deposited by meltwater streams. Most outwash was deposited by meltwater in front of the glacier (proglacial) during advance and retreat, although outwash can also be originally deposited in or on a glacier and let down onto the till surface upon melting of the ice. Unfortunately, without numerical dates for outwash occurring between two tills, it is not possible to distinguish between sand and gravel deposited during the retreat of the last glacier from that deposited during the advance of the next glacier. For the sake of simplicity in stratigraphic notation for this study, we have assumed that the majority of sand and gravel deposited between two tills is outwash from the advancing glacier, thus associated with the overlying till. The Carbon-14 dates (12,880 and 12,540 years) of wood in the outwash basal to the late Wisconsin till in the study area validate this assumption to some degree.

Outwash typically consists of sand- and gravel-sized fragments of igneous and metamorphic rocks, siltstone, sandstone, shale, limestone, individual quartz grains, and rarely pyrite. In Yankton County, these outwash bodies can also contain a variable component of quartz- and feldspar-rich sand (such as the Bon Homme gravel or other western-derived sand). The outwash deposits range from poorly to relatively well sorted, and can be relatively well stratified.

LACUSTRINE

Lacustrine (lake) 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. Some stratification may be present in lacustrine deposits. This stratification often occurs as thin light and dark layers (varves), which represent seasonal sedimentation.

Subsurface lacustrine deposits are rare in Yankton County and difficult to identify in mud rotary drill cuttings. However, more extensive lacustrine deposits are known to occur in the subsurface [for example, late Wisconsin lacustrine deposits in Lincoln and Union Counties (McCormick and Hammond, 2004)].

LOESS

The term “loess” is applied to wind blown silt deposits. Loess typically consists of moderately well sorted, nonstratified silt (with small amounts of clay or sand) deposited by wind during the Pleistocene Epoch. 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 often accumulates in periglacial environments or during interglacial periods.

Pre-Wisconsin 1 Till

The pre-Wisconsin 1 till [Qpw_1t(ox), Qpw_1t] was intersected in two test holes: MLN 3 (fig. 6), where it is almost 100 feet thick and overlies bedrock, and MLN 125 (fig. 14) where it is 20 feet thick and overlies a thick sequence of western-derived(?) sand (Qpis). The pre-Wisconsin 1 till in both holes consists of a partially oxidized zone of yellow-brown to brown to gray, weakly calcareous to noncalcareous silty, sandy (variably pebbly or gravelly) clay. In MLN 3, the partially oxidized zone overlies a thick unoxidized zone of weakly calcareous to noncalcareous silty, sandy, slightly gravelly clay.

Pre-Wisconsin 1 Outwash

Pre-Wisconsin 1 outwash (Qpw_1o) occurs within the till in MLN 3 (fig. 6). This unit is approximately 30 feet thick and consists of fine to coarse sand mixed with partially oxidized, variably calcareous clay. A compositionally similar, but thinner (10 feet thick) deposit of Qpw_1o also occurs directly below the Qpw_1t in MLN 125 (fig. 14). Two other test holes in fig. 14 (MLN 124 and MLN 126) are inferred to have intersected pre-Wisconsin 1 outwash.

Pre-Wisconsin 2 Till

Pre-Wisconsin 2 till [Qpw_2t (ox), Qpw_2t] is typically a weakly calcareous, medium gray, silty, sandy clay. In one hole (MLN 3 in fig. 6), the upper part of the pre-Wisconsin 2 till was partially oxidized. In several locations it contains gravel stringers, sand lenses, or rocks. Locally, it can be pebbly and vary in color from light- to dark-gray. The Qpw_2t sediments in the hole at MLN 3 are brown to gray, moderately calcareous to noncalcareous, silty, sandy clay. The brown to gray color variation likely reflects a highly fractured, mainly unoxidized (gray) till where oxidation has occurred along the fractures, locally giving the clay a brown color.

Pre-Wisconsin 2 Outwash

Pre-Wisconsin 2 outwash (Qpw_2o) is found within and just below the pre-Wisconsin 2 till. The basal outwash was intersected in only one hole (MLN 3 in fig. 6). Outwash deposits basal to and within pre-Wisconsin 2 till vary widely in grain size, ranging from fine sand to medium gravel, and contain a diverse assemblage of rock and mineral fragments (such as shale and chalk from local Cretaceous bedrock formations, igneous and metamorphic rocks, siltstone, sandstone, limestone, individual quartz grains, and rarely pyrite). Outwash occurring within the till sheet commonly contains clay lenses.

Where present in the study area, pre-Wisconsin 2 sediments (usually outwash) typically overlie bedrock. Exceptions to this are where pre-Wisconsin 1 sediments are present (MLN 3 in fig. 6, MLN 125 in fig. 14, and possibly MLN 124 and 126 in fig. 14).

Pre-Wisconsin 3 Till

Pre-Wisconsin 3 till [Qpw_3t (ox), Qpw_3t] is typically a light- to medium-gray, silty to sandy, locally pebbly clay. Gravelly zones and gravel stringers are common, particularly in the lower portions of the deposits. Oxidized portions of the pre-Wisconsin 3 till [Qpw_3t (ox)] are yellow to brown (grading to gray), very silty to very sandy clay. These oxidized zones are not well preserved, and thus, not well characterized. Typically the preserved portions are less than or equal to 15 feet thick. However, on Yankton Ridge, where present, pre-Wisconsin 3 till appears to be mostly oxidized, reaching a thickness of around 30 feet (western parts of figs. 12 and 13). Both unoxidized and oxidized portions of the pre-Wisconsin 3 till are locally calcareous. Rarely, coal is also found within these deposits (MLN 78 in fig. 11).

Pre-Wisconsin 3 Outwash

Pre-Wisconsin 3 outwash (Qpw_3o) is similar to the pre-Wisconsin 2 outwash. Outwash occurring within the till sheet typically ranges in size from coarse sand to gravel with local thin clay lenses, whereas outwash basal to the Qpw_3t commonly has a higher sand content and a wider range of grain sizes. The clast assemblages are diverse as typical of most glacial outwash bodies.

Pre-Wisconsin 3 Lacustrine Deposits

Lacustrine sediments, designated Qpwls in cross sections (MLN 98 in fig. 12), are pre-Wisconsin in age, but cannot be definitively assigned to a specific pre-Wisconsin advance. One possible pre-Wisconsin 3 lacustrine deposit (Qpw_3ls) was intersected in Yankton County (MLN 35 in fig. 8). It is described as a calcareous, gray silt.

The pre-Wisconsin 3 sediments overlie either pre-Wisconsin 2 till or bedrock, and underlie late Wisconsin sediments in the study area.

Undifferentiated pre-Wisconsin Deposits

Outwash designated Qpwo in cross sections (figs. 6-15) are pre-Wisconsin in age, but cannot be definitively assigned to a specific pre-Wisconsin advance. The grain sizes in some of these deposits appear to broadly fine upward (MLN 17 in fig. 7).

Late Wisconsin Till

Late Wisconsin till is present at the surface across Yankton County (pl. 2). This till generally consists of an upper oxidized portion which is typically less than 35 feet thick and a lower unoxidized portion which can reach up to 160 feet thick in some test holes. The oxidized portion of the late Wisconsin till [Qwlt (ox)] typically consists of yellowish-brown, grading downward to brown, silty, sandy clay with a variable pebble and gravel content. Locally, it is calcareous. The unoxidized late Wisconsin till (Qwlt) typically consists of gray, silty, sandy, pebbly clay. Thin gravel stringers are common and the sand and gravel content of the till often increases with depth. Locally it is calcareous. Wood and coal fragments are also found in the Qwlt. An excellent exposure of oxidized and unoxidized late Wisconsin till occurs in a cut bank in NW¼ NW¼ NW¼ NW¼ sec. 17, T. 93 N., R. 57 W.

The late Wisconsin advance deposited sediments on pre-Wisconsin 3 sediments (figs. 6 and 7) and less commonly directly on bedrock (MLN 96, 100, and 101 in fig. 12, MLN 110 in fig. 13) or Bon Homme gravel (MLN 97 in fig. 12, MLN 107 in fig. 13).

Late Wisconsin Outwash

Late Wisconsin outwash (Qwlo, Qwlot) consists of a typically unsorted mixture of sand and gravel of variable grain sizes and is relatively common in Yankton County (figs. 6-15 and pl. 2). Basal late Wisconsin outwash (Qwlo) is relatively continuous in some locations (the east part of fig. 8; the west part of fig. 9; the west part of fig. 10). It is typically less than 25 feet thick but approaches 100 feet thick in places (MLN 43 in fig. 9). Outwash occurring within the late Wisconsin till is discontinuous, diachronous, and usually less than 15 feet thick. Late Wisconsin outwash is typically unsorted, containing a range of sand and gravel grain sizes, as well as silt and clay. Coal is also present in some Qwlo deposits (MLN 85).

Outwash designated Qo in cross sections (figs. 6-15) or Qot (pl. 2) is late Wisconsin that may have been reworked during the Holocene. It is possible that some Qo deposits are late Wisconsin or pre-Wisconsin in age.

Late Wisconsin Collapsed Sediments

Late Wisconsin collapsed outwash (Qwloc, Qwlok) deposits consist mainly of sand and gravel, but locally can consist of very sandy, silty brown clay. Late Wisconsin collapsed debris (Qwlcd) deposits consist mainly of oxidized till with highly variable amounts of sand and gravel. The actual thickness of late Wisconsin collapsed outwash and collapsed debris deposits, particularly Qwlcd on James Ridge (pl. 2), is not well constrained, even in drill holes, as no clear break exists between the late Wisconsin and the underlying pre-Wisconsin deposits (figs. 9 and 10).

Late Wisconsin Loess

Loess (Ql) is restricted to the slopes of Yankton Ridge where it overlies late Wisconsin till or Bon Homme gravel. These deposits typically consist of light-brown silt with minor sand or clay and are variable in continuity and thickness.

Lutzen (1957) reports occurrences of loess in eastern Yankton County. His "Peorian" loess (late Wisconsin) occurs at a single locality in SE¼ NE¼ sec. 29, T. 95 N., R. 54 W. It is only 1.5 feet thick. His Tazewell-age loess is over 6 feet thick where sampled (NW¼ NE¼ sec. 24, T. 95 N., R.

54 W.), but he was not sure of its validity because of the 16 percent sand content. The only exposure of loess-like sediment seen in this area in the present study is about 8 or 9 feet thick and overlain by till in a road cut at NE¼ SE¼ NE¼ SE¼ sec. 23, T. 95 N., R. 54 W. Loess was not identified in any of the test holes drilled in this area.

Holocene Geology

Holocene sediments are regarded as those deposited during the past 10,000 years. They are divided into a wide array of deposits in Yankton County and described below.

Eolian Deposits

Holocene loess may overlie late Wisconsin loess, till, and Bon Homme gravel on a portion of the south side of Yankton Ridge (pl. 2). Although a typically thin deposit in Yankton County, Flint (1955) reported a thickness of 34 feet in an auger hole in NE¼ sec. 11, T. 93 N., R. 57 W. It is exposed at the south end of a large, former sand pit in the northwest corner of the same section where it is 25 feet thick.

The age of the loess is probably Holocene, although a late Wisconsin age cannot be discounted. Christensen (1967) suggest these deposits in Clay County might bridge the Holocene-Pleistocene boundary. Christensen (1974) considered it to be mainly Pleistocene in Bon Homme County. Simpson's (1960) specific age assignments are not well documented, but it is curious that his "Mankato Loess" in Bon Homme County contains some artifacts reflecting human habitation, strongly suggesting a Holocene age.

Landslide Deposits

A variety of terms may be applied to sediments that move downslope in response to gravity, a process called mass wasting. Slumping, mentioned in the discussion of measured sections of Pierre Shale (app. C), is an example of mass wasting, as are landslides. Rate of movement is usually imperceptible, measurable only over several years time. However, an unusually wet season may contribute to noticeable movement over a few days. Landslide deposits considered here involve mostly the Pierre Shale, usually covered by a veneer of till or mixed with till (Christensen, 1974). As steep slopes contribute significantly to this process, such deposits are most commonly found on the Missouri River side of Yankton Ridge. They have also been observed in the northeastern part of the county above Turkey Creek. On some hills, blocks of till or shale, with dimensions of several feet to tens of feet across, occur in stepwise fashion downslope. The edges of these blocks are often barren of vegetative cover, thereby producing a sharp contrast with their upper surface. Individual occurrences are too small to depict in plate 2, but wherever the Pierre Shale occurs in association with steep slopes, movement is a possibility. Simpson (1960) shows several areas of landslide deposits on his map. The potential destructive nature of the more active mass-wasting processes must be considered whenever attempts to construct roads, pipelines, or buildings are contemplated in areas of their occurrence.

Colluvium

Colluvial deposits are similar to landslide deposits in that downslope movement is involved. Colluvium is here considered to be a more surficial deposit, restricted to glacial drift and usually only in the soil developed on the drift. It can potentially occur on any slope. It is most noticeable on steeper slopes as numerous low, parallel, horizontal ridges resembling plow furrows. Colluvium deposits are too small to map separately at the 1:100,000 scale in Yankton County. Along steam river valley walls, particularly the James River Valley, colluvium is mapped together with late Wisconsin till as Qwlt.

Alluvium

Holocene streams downcut the late Wisconsin surface sediments and deposit clays, fine silts, and minor sand and gravel. Together these sediments are referred to as alluvium (Qal). They are common in Yankton County (Qal, pl. 2 and figs. 6-10, 14, and 15) and sometimes of sufficient grain size to serve as commercial sources of aggregate (Tomhave and Hammond, 1987). Where the silt content is high, the color may be dark owing to organic material; otherwise the color is light, typical of the sand derived from the till in this region.

The alluvium in the Missouri River flood plain can be divided into overbank deposits, consisting of silt and clay, and channel-fill deposits. Most of the flood plain consists of the overbank deposits. The Missouri River channel-fill deposits are often broad arcuate deposits that readily show up on aerial photographs. They represent abandoned river meander channels (mapped as meander scars on pl. 2) and are composed of varying amounts of clay, silt, and sand (Christensen, 1967; Simpson, 1960; Jorgensen, 1960). The alluvium typically overlies significant thicknesses of late Wisconsin outwash and is thus mapped as Qoa (pl. 2). Qoa is also mapped along the James River Valley floor. The lowermost portion of the James River follows a meander channel abandoned by the Missouri River (pl. 2).

In many places, colluvium grades imperceptibly into alluvial deposits, especially in the numerous tributaries where the alluvium is not of sufficient quantity to be depicted in plate 2. Thicknesses of alluvium are usually limited to a few feet. They are reported in some detail by Tomhave and Hammond (1987). In the James River flood plain (figs. 6 through 12), the alluvial thickness is about 20 feet. In the main part of the Missouri River flood plain, it is up to 70 feet thick (fig. 13).

Travertine

One of the more unusual sedimentary rocks found in Yankton County is travertine (calcareous sinter, calcareous tufa, or "flowstone"). It is composed of calcium carbonate and is the same mineral found in cave formations such as stalactites and stalagmites. It occurs only in a few places where ground water emerges from hillsides as springs. The most extensive deposit consists of cross-bedded travertine-cemented sand and gravel, covering only a few tens of square feet; it is found at NW¼

SE¼ SE¼ NW¼ sec. 17, T. 95 N., R. 55 W. A nearby occurrence was noted by Simpson (1960). Most of the local springs occur only during wet years. The one described here flowed even during the drought years of the 1930s according to a local resident, who also stated that cattle would normally not drink the water, presumably because of high dissolved mineral content. Calcium carbonate dissolved in the ground water forms a precipitate as it emerges from the spring. This process may be enhanced by algae, although the water was not analyzed for their occurrence. The travertine deposits are too small to map at the 1:100,000 scale in Yankton County.

Surface Morphology

The geologic map of Yankton County (pl. 2) is based mainly on geomorphology. Although the boundaries between geologic units are mapped as solid lines, these units typically have gradational contacts. Also to note, the geologic units mapped in Yankton County are almost exclusively late Wisconsin or younger in age. Thus, the drainage on these surfaces is poorly developed in most areas. This is most apparent in areas of moderate to low relief.

Glacial Landforms

One of the major physiographic features in Yankton County, James Ridge (fig. 3), is an enigma in terms of its origin. It is discussed here because it cannot be simply included in the categories of glacial landforms discussed below. It is a major topographic feature running northwest to southeast to the west of the James River (pl. 2). The highest parts of James Ridge reach approximately 1,550 feet above sea level, whereas the surrounding area is less than 1,400 feet above sea level.

James Ridge is draped, in part, by collapsed sediments but cannot be fully accounted for by the processes associated with the deposition of collapsed sediments. Its height in comparison to surrounding area cannot be attributed to the underlying bedrock having an elevated surface. James Ridge is cored by a thick sequence (greater than 200 feet) of sand and gravel (figs. 8-10), and sand and gravel are abundant components of the clay-rich surface sediments (till). The probable age of the core sediments is pre-Wisconsin. The uppermost sediments are probably late Wisconsin in age (and are mapped as Qwlcd). The reader is directed to the sections on “Pre-Wisconsin History” and “Wisconsin History” for more information about the formation of James Ridge.

GROUND MORAINE

Ground moraine is a relatively flat to gently rolling surface formed of debris (mainly till) released by a glacier. In Yankton County, ground moraine (Qwltg) typifies most of the area between Turkey Ridge and the James River, as well as large areas north of the end moraines to the west of the James River (pl. 2).

WATER-MODIFIED GROUND MORAINE

Water-modified ground moraine ($Qwltg_w$) is a relatively flat to gently rolling surface that has had significant modification by meltwater during retreat of the late Wisconsin glacier. The surface is generally formed of till, but small, thin, discontinuous deposits of sand or gravel are common. The surface may be carved by water to form shallow abandoned channels, but is otherwise generally flat, like typical ground moraine. The abandoned channels often define the boundary of the mapped $Qwltg_w$ areas in plate 2; these channels are evident at the 1:24,000 scale, but are difficult to see at the 1:100,000 scale (for example, the area south of Highway 46 that is bounded by the James River and Mud Creek).

In Yankton County, water-modified ground moraine is common adjacent to the James River Valley and may have formed during initial formation of the James River by floods or broad, shallow meltwater drainage systems prior to significant downcutting. The $Qwltg_w$ in the northwest corner of Yankton County north of the James River extends only slightly into Hutchinson County. The $Qwltg_w$ is also mapped between the easternmost end moraine (Qwlte) and the area where Clay Creek and Smoky Run enter the modern Missouri River flood plain. Bluemle (2000) describes similar water carved sediments associated with eskers and outwash plains in North Dakota.

SLOPE MORAINE

Slope moraine ($Qwltg_s$) is a variety of ground moraine that was deposited on significant slopes. Owing to the inclination of the terrain, slope moraine is not flat-lying like typical ground moraine. The higher angle of inclination of the surface on which slope moraine is deposited results in a surface that is commonly deeply incised by streams. In Yankton County, slope moraine is mapped on the slopes of Yankton Ridge and at the northeasternmost corner of Yankton County on Turkey Ridge.

STAGNATION MORAINE

Stagnation moraine is an irregular or hummocky surface formed of debris deposited from ice that has ceased to move. It is characterized by closed depressions and undeveloped drainages. In aerial photographs, stagnation moraine can appear as patterned ground. In Yankton County, stagnation moraine is separated into Qwlts, which has the typical hummocky surface, $Qwlts_1$, which has a more subdued irregular surface (low relief), and $Qwlts_2$, which has a more prominent hummocky surface (high relief) with minor lineations. Stagnation moraine (Qwlts) occurs west and southwest of the James Ridge, adjacent to end moraines, and on Yankton Ridge. Low relief stagnation moraine ($Qwlts_1$) is most common east of the James River in the north central part of the county, but it is also mapped along the lowermost section of Turkey Creek where the creek enters the modern Missouri River flood plain. High relief stagnation moraine ($Qwlts_2$) is restricted to Turkey Ridge.

END MORAINE

End moraines are formed at or near the edge of an active glacier, generally perpendicular to ice flow, at a point on the glacier where rate of melting and rate of glacial advance are equal. The result is the dumping of great quantities of debris along this margin over time. End moraines typically have a higher concentration of boulders than other glacial landforms.

In Yankton County, three end moraines are mapped: $Qwlte_1$, $Qwlte_2$, and Qwlte. The first end moraine occurs on the north slope of the western end of Yankton Ridge, straddling Highway 50 on the west side of the county. It coincides in part with the end moraine depicted by Simpson (1960), more so with Christensen's (1974) Colony Moraine. The Colony Moraine ($Qwlte_1$, pl. 2) extends several miles into Yankton County. Although the Colony Moraine is the southernmost recognized end moraine, it does not represent the southern extent of glaciation because ground moraine lies to the south of it on the crest of Yankton Ridge (compare fig. 15 and pl. 2).

The second end moraine occurs north of Beaver Creek and extends just north of Lesterville. Simpson (1960) did not recognize this end moraine, but Christensen (1974) did. It is the largest end moraine in Bon Homme County; Christensen (1974) called it the Tripp Moraine, as it extends southeastward from the town of Tripp in Hutchinson County (and parts farther northwest) into east-central Bon Homme County. It then turns northeastward into Yankton County where it abuts against James Ridge north of Utica. Christensen (1974) provides an eloquent description of the geomorphic development of the Colony and Tripp Moraines.

Smaller, more poorly developed end moraines (Qwlte) occur between the southern end of the James Ridge and the James River and to the east of the James River, about 6 miles north-northwest of Mission Hill (pl. 2). It approximates an area of end moraine mapped by Simpson (1960). It probably was deposited at the same time as the Tripp Moraine ($Qwlte_2$).

Outwash and collapsed outwash deposits (Qwlo and Qwloc) appear to be more common on the Tripp Moraine ($Qwlte_2$) than the Colony Moraine ($Qwlte_1$). The cause of this difference is unknown.

Lateral-type end moraines are also present in Yankton County. Lateral end moraines form along the sides of an active glacier that is bounded by a valley wall. One lateral end moraine, $Qwlte_L$, is mapped in Yankton County. It is located to the west of, and parallel to, Clay Creek along the edge of Turkey Ridge (pl. 2). The relatively high concentration of boulders on this feature and the fact that it forms a ridge are two characteristics suggesting that it is a form of end moraine. Its position along the side of Turkey Ridge suggests that it is a lateral end moraine.

Another possible lateral end moraine, the crest of which is indicated by a thick dashed line, occurs to the west of, and parallel to, Smoky Run (pl. 2). This feature also has a higher concentration of boulders and forms a small ridge. However, other characteristics of the surface in the area suggest that it is an area of stagnation moraine (and is mapped as $Qwlts_2$ in the northern half; and the southern half of the crest is dominated by ground moraine, Qwltg).

COLLAPSED SEDIMENTS

Collapsed outwash and debris deposits (Qwloc, Qwlok, Qwlcd) have very hummocky surfaces. The late Wisconsin collapsed debris deposits (Qwlcd) are draped on top of the James Ridge (figs. 8-10). Small deposits of collapsed outwash (Qwloc) occur adjacent to Beaver Creek and as part of the end moraines ($Qwlte_1$, $Qwlte_2$) west of the James River. Kames (Qwlok; oval or elongate ridges of collapsed outwash) occur in stagnation moraine on Turkey Ridge and adjacent to Mud Creek east of the James River, on the east side of James Ridge (grouped with collapsed debris as Qwlcd), and on or adjacent to the end moraines west of the James River. Kames are also interpreted to be present along parts of Turkey Creek based on morphology and/or the presence of gravel. Some outwash deposits mapped as Qwlo occurring along the James River Valley at the top of the valley walls, such as the deposits south of Highway 46 along the eastern valley wall of the James River (pl. 2; figs. 7 and 10), are probably also collapsed outwash. However, it is difficult to ascertain the exact method of emplacement of these bodies because the exposures of these deposits are typically poor, thus, some are mapped simply as Qwlo.

OUTWASH TERRACES

Outwash terraces are discontinuous remnants of large, valley-filling sand and gravel deposits. Late Wisconsin outwash terraces (Qwlot) occur along Beaver Creek, Mud Creek, Turkey Creek, and the upper part of the James River (pl. 2). Holocene(?) to late Wisconsin outwash terraces (Qot) are flat areas of mainly sand and gravel that may underlie clay. They occur along the lower half of Turkey Creek in the study area, as well as northeast of Mission Hill adjacent to the Qoa and along some tributaries draining directly into the Missouri River west of the mouth of the James River around the city of Yankton (pl. 2). The Qot in the southeast and just east of Yankton is divided into two levels: the northern upper level (Qot_1) is gravel-rich; the southern lower level (Qot_2) is floored in clay.

MELTWATER CHANNELS

Meltwater channels are valleys carved by meltwater runoff from glaciers. These channels are typically far broader than valleys that could be eroded by modern streams that now occupy them. In these areas, these rivers or streams are said to be underfit.

These 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. An example of an underfit modern river within a Pleistocene meltwater channel is the James River. For clarity, the meltwater channel symbol was not used along the major rivers and creeks (such as James River and Beaver Creek).

Small meltwater channels are mapped on various types of moraines (for example, ground moraine and stagnation moraine). These channels likely represent short-lived or discontinuous (partially supra- or englacial) meltwater systems and are mapped where strongly evident. Thus, the distribution of these small meltwater channels are rather random in appearance.

LOESS-COVERED TERRANE

Loess that blankets a surface gives that surface a distinctive morphology. Loess generally subdues the topography like a blanket of snow, but where it is downcut by streams, loess forms relatively steep hills. The high slope angle is due to the capacity of loess to maintain nearly vertical slopes typified in southwest Yankton County on the southern slope of Yankton Ridge (pl. 2).

Glacially Modified and Nonglacial Landforms

TURKEY RIDGE

Turkey Ridge (fig. 3) is formed by an elevated bedrock surface that has been modified by glaciation. It consists of glacial sediments (till and outwash) overlying Tertiary-aged sands and clays (possible Ogallala Group rocks; pl. 1) that in turn overlie Upper Cretaceous rocks (Pierre Shale or Niobrara Formation). Possible western-derived sands (nonglacial, Plio-Pleistocene deposits) overlie and downcut the Tertiary sediments at some localities on Turkey Ridge. The rivers that deposited the Tertiary sediments appear to have locally eroded the Pierre Shale (MLN 95 and 97 in fig. 12). Turkey Ridge likely existed as a subtly elevated area relative to the pre-glacial river valleys, but its present form and relief is due to significant glacial modification to either side of the ridge.

YANKTON RIDGE

Yankton Ridge (fig. 3) is formed by an elevated bedrock surface that has been somewhat modified by glaciation as it is overlain by till and loess. Linear features on the south slope are probably erosional, formed by the incision of Holocene streams. Like Turkey Ridge, Tertiary sediments and western-derived sands are preserved on the ridge. Also like Turkey Ridge, it was likely a subtly elevated area relative to the pre-glacial river valleys, but its present form and relief arose from significant glacial modification around the ridge.

HOLOCENE RIVER AND STREAM CHANNELS

Holocene stream channels may occupy glacial meltwater channels (such as the northwest-southeast trending section of Beaver Creek, pl. 2), or they may incise exposed till or bedrock surfaces.

TERRACES

Terraces can be both erosional and depositional. Whether depositional or erosional, terraces are generally flat and are slightly to moderately elevated above the stream or river channel. The greater the elevation of the terrace above the stream or river, the greater amount of downcutting has occurred between formation of the terrace and the present time.

Terraces occur along the tributary valleys of, and also within the trenches of the James and Missouri Rivers in Yankton County. Although the James River Valley was eroded during the late Wisconsin by meltwater from the glacier, its floor continues to be modified by the present-day James River. Terraces (grouped with the alluvium as Qoa, pl. 2) are apparent along parts of the river on 1:24,000 scale topographic maps (for example, the James River Valley on the Mission Hill quadrangle from NE¼ NE¼ sec. 5, T. 94 N., R. 55 W. to SE¼ SE¼ sec. 32, T. 95 N., R. 55 W.). These terraces consist mainly of sand and gravel, and may have been originally deposited by glacial meltwater, but have been redeposited by the present-day James River.

BEDROCK EXPOSURES

The Pierre Shale (Kp) and Niobrara Formation (Kn) are exposed at the surface in several areas of Yankton County (pls. 1 and 2). The most continuous exposures occur along the Missouri River bluff from the western edge of Yankton essentially to the Yankton-Bon Homme County boundary. Both Pierre Shale and Niobrara Formation are exposed on the edge of the bluff facing the Missouri River. Along Lewis and Clark Lake, one can see oxidized yellow to orange Niobrara Formation above unoxidized dark-gray Niobrara Formation (fig. 17).

The other significant Pierre Shale and Niobrara Formation bedrock exposures occur along Turkey Creek and along the edge of Turkey Ridge at and south of Lake Marindahl adjacent to Clay Creek. The outcrops of Niobrara Formation along Turkey Creek, about 2.5 miles north of Volin, have been intermittently quarried (see Economic Geology section).

Tertiary Ogallala Group(?) rocks could be very near land surface (simply grassed over; for example, between MLN 108 and 109 in fig. 13), although no Tertiary Ogallala Group(?) rocks have been noted at the surface in Yankton County by any geologists.

QUATERNARY HISTORY

Pre-Pleistocene Geography

Based on the Yankton County bedrock map (pl. 1), pre-glacial drainage may have extended from the Hutchinson County boundary to the Clay County boundary. Flint (1955) also suggested that a drainage was present through Yankton County. It is not clear from the present study whether this pre-glacial drainage initially flowed southeast to northwest or northwest to southeast. This is because the bedrock surface has been glacially modified to the extent that the direction of pre-glacial drainage cannot be confidently determined. Flint (1955) thought it flowed northwest to southeast, entering the ancient White River valley at Vermillion, South Dakota, in southeastern Clay County, although he was not certain that this drainage existed prior to diversion by glaciation of east-flowing rivers to south-flowing rivers. His uncertainty is indicated by the dotted boundary along this former valley (Flint, 1955, pl. 7).

Prior to the Quaternary glaciation of eastern South Dakota, about 2 million years ago, rivers flowing from the high lands (the Black Hills and areas south of the Black Hills) continued eastward beyond the present-day Missouri River (Flint, 1955). One of these rivers, the Niobrara, which presently flows from Nebraska into the Missouri River near Springfield in Bon Homme County, may have continued northeastward into Yankton County. Christensen (1974) suggested it entered Yankton County from Bon Homme County at secs. 18, 19, and 30, T. 94 N., R. 57 W. (pl. 1). He further postulated that it re-entered what is now the Missouri River trench in the vicinity of Yankton. He had earlier (Christensen, 1967) precluded the possibility that it could have entered Clay County east of Yankton County.

The present-day bedrock surface of Yankton County (pl. 1) provides little evidence for the existence of a Niobrara River channel where these previous workers have suggested. Nor is there any bedrock valley shown on Christensen's (1974) Cretaceous bedrock map where he postulates the ancient Niobrara River flowed north of Yankton Ridge and south of Tabor (compare pl. 2 and fig. 10 in Christensen, 1974).

Assuming that the ancient Niobrara River did flow through southwestern Yankton County, it is likely that the ancient Niobrara River used at least part of the northwest-southeast channel that enters Yankton County from the Hutchinson County line. If the ancient Niobrara River entered Yankton County in the northern part of T. 95 N., as suggested by the bedrock channel carved into the Carlile Shale on Christensen’s (1974) Cretaceous bedrock map of Bon Homme County (but not interpreted as such by Christensen, 1974), it could have flowed north-northeast, entering the northwest-southeast channel in the northeast corner of T. 96 N. (pl. 1).

Pre-Wisconsin History

The geologic history of the Pleistocene epoch in eastern South Dakota was dominated by glacial advances and retreats. The deposits and landforms developed during the oldest of the glacial advances are buried under or destroyed by the more recent ones. Thus, generally the least is known of the oldest glaciations, and the most is known of the most recent, late Wisconsin glaciation.

The centers for the pre-Wisconsin glaciations are believed to have entered South Dakota from the northeast, based on striation orientations on the exposed Sioux Quartzite surface (Bierman and others, 1999), although local topography may have redirected these glaciers. Pre-Wisconsin (pre-Illinoian) deposits are also found in Iowa, eastern Nebraska, northeastern Kansas, and northern Missouri (Hallberg, 1986).

Pre-Wisconsin 1 Glaciation

It is likely that the pre-Wisconsin 1 glaciation greatly modified the bedrock surface across the study area, despite the now limited spatial extent of the pre-Wisconsin 1 sediments in Yankton County. Flint (1955) described the pre-Pleistocene landscape across the present-day James Basin (fig. 2) as having relatively little relief. The James Basin was likely developed by glacial modification of pre-Pleistocene drainages. The pre-Wisconsin 1 glacial erosion, meltwater erosion, and river diversion may have combined to initiate the erosional modifications that subsequently, through multiple glaciations, led to the James Basin and the prominence of Turkey and Yankton Ridges.

The original spatial extent of the pre-Wisconsin 1 sediments prior to the pre-Wisconsin 2 glacial advance is unknown. The presence of pre-Wisconsin 1 sediments in the northern section of the main, central pre-glacial channel in Yankton County (MLN 3 in fig. 6), and in the deep partial channel southeast of Utica (MLN 125 in fig. 14; see also Pre-Pleistocene Geography section above), suggests that the pre-Wisconsin 1 glaciation deepened some pre-existing channels in the bedrock surface. However, the pre-Wisconsin 1 glacier may not have been significantly thick in Yankton County, as pre-Wisconsin 1 deposits are rare, and no pre-Wisconsin 1 sediments are identified on either Turkey or Yankton Ridges. Alternatively, pre-Wisconsin 1 deposits could initially have been considerably more extensive and later removed by pre-Wisconsin 2 glacial erosion.

Pre-Wisconsin 2 Glaciation

The pre-Wisconsin 2 glaciation likely further modified the bedrock surface. This glaciation is presumed to have significantly contributed to the widening and deepening of the lowland between Turkey and Yankton Ridges, and to have eroded parts of the Pierre Shale and Tertiary Ogallala Group(?) rocks on Turkey Ridge. Although now limited in extent, sediments from the pre-Wisconsin 2 glacial advance likely covered all of Yankton County prior to the pre-Wisconsin 3 glacial advance, with the possible exception of Yankton Ridge in southwestern Yankton County. Preserved pre-Wisconsin 2 sediments vary in thickness from a few feet to over 100 feet in bedrock lows. Thin pre-Wisconsin 2 sediments are also recognized on Turkey Ridge, but none have been recognized on Yankton Ridge. Thus, either pre-Wisconsin 2 sediments were not deposited on Yankton Ridge, or they were subsequently eroded.

Basal pre-Wisconsin 2 outwash is common within low areas of the bedrock surface suggesting that the meltwater from this glacial advance roughly followed those bedrock channels and drained to the southeast into what is now southeastern Clay County.

Pre-Wisconsin 3 Glaciation

The pre-Wisconsin 3 glaciation may have had little influence on most of the bedrock surface in Yankton County as by this time much of the study area was covered by the sediments from the previous glaciations. The exception to this may be Yankton Ridge where only the pre-Wisconsin 3 deposits (of the pre-Wisconsin glaciations) are recognized in this study, and Turkey Ridge where thick deposits of pre-Wisconsin 3 sediments occur. Cretaceous and Tertiary bedrock may have been further eroded from these two ridges by the pre-Wisconsin 3 glacier. Most certainly the pre-Wisconsin 3 glacier modified the underlying pre-Wisconsin sediments.

Sediments from the pre-Wisconsin 3 glacial advance are pervasive in the subsurface in Yankton County including both Turkey and Yankton Ridges suggesting that either the pre-Wisconsin 3 glacier was thick or little of it was removed by the late Wisconsin glaciation.

Outwash directly underlying pre-Wisconsin 3 till appears to be most common and thickest in and around the James Ridge (MLN 47 and 48 in fig. 9). However, in the northern part of the county, these outwash deposits are also common above some of the deeper pre-glacial drainages (see the western part of fig. 6).

It is likely that the core of the James Ridge formed during the pre-Wisconsin 3 glaciation. Evidence for the thick sands and gravels that core the James Ridge being emplaced as frozen blocks by thrusting of pre-Wisconsin outwash (Qpw_3o, Qpwo, Qo, figs. 8-10) include the thin deposits of Qpw_3o or Qpwo to the northeast of the ridge (as compared to the more western sections), the anomalously thick outwash deposits that form the ridge itself, the presence of a thick (greater than 100 feet) block of Niobrara Formation within the deposit (fig. 9, a block that is much too large for transport by meltwater; a smaller block is shown in fig. 10), and the northwest-southeast orientation of the ridge itself (which would be parallel to the front margin of the advancing glacier). Ice thrusting is a relatively common process during glaciation and it is usually associated with certain geologic features, such as partly buried meltwater trenches or aquifers and nearby escarpments (Bluemle and Clayton, 1984). Conditions favoring ice thrusting of large blocks are outlined in Bluemle and Clayton (1984) and will not be discussed here.

Alternative theories for the formation of the core of the James Ridge include 1) ice-thrusting by the late Wisconsin glacier and subsequent modification as a medial moraine, 2) a large crevasse in the pre-Wisconsin 3 ice sheet that filled with sand and gravel deposited by meltwater, and 3) a large, late Wisconsin subglacial meltwater channel. No evidence exists to definitively prove any of the theories mentioned in this study although ice-thrusting was most likely involved (Johnson and McCormick, 2004).

Wisconsin History

Early and Middle Wisconsin History

Based on work conducted in Minnesota (Matsch and Schneider, 1986), no glacial advances of early and middle Wisconsin age reached Yankton County. As there was also no Illinoian glacial advance in Yankton County (Hallberg, 1986), a significant period of time elapsed (greater than 250,000 years) between the pre-Wisconsin 3 glaciation and the late Wisconsin glaciation (Šibrava, 1986). This length of time would easily allow for the thickness of the oxidation zone in the pre-Wisconsin 3 till observed in test-hole data (up to 30 feet preserved after subsequent erosion during the late Wisconsin).

Late Wisconsin Glaciation

During the late Wisconsin prior to 14,000 years ago, the glacial center or dome for the ice sheet (the Laurentide ice sheet) that covered much of the Midwest, including eastern South Dakota, was located in what is now northern Canada. This center shifted through time, and the dome (the Keewatin dome) for the Des Moines and James lobes post-14,000 years ago was centered in the Northwest Territories between Victoria and Baffin Islands (Andrews, 1987). The late Wisconsin Laurentide ice sheet entered northeastern South Dakota from the north-northwest, and was split into two main lobes (the Des Moines lobe and the James lobe) by what is now called the Coteau des Prairies (fig. 18). The Des Moines lobe advanced through northeastern South Dakota east of the Coteau des Prairies into southeastern Minnesota and points farther south, whereas the James lobe advanced southward through the James Basin between the Coteau du Missouri and the Coteau des Prairies (fig. 18). Both lobes overtopped portions of the Coteaus during these advances, although how many times is not known. Radiocarbon dates of Des Moines lobe ice margins in Minnesota indicate multiple advances of the Laurentide ice sheet during the late Wisconsin (Patterson, 1997a). In northeastern South Dakota, five end moraine complexes were deposited by the Des Moines lobe and three end moraine complexes were deposited by the James lobe (Gilbertson, 1989).

ADVANCE OF THE LATE WISCONSIN GLACIER

The one identifiable late Wisconsin advance in the study area occurred some time after 12,500 years ago, based on Carbon-14 dates on wood intersected in glacial outwash basal to the late Wisconsin till (MLN 34 in fig. 8 and MLN 81 in fig. 11). This glacier may have advanced beyond the present-day Missouri River and into Nebraska, as indicated by the presence of late Wisconsin till on Yankton Ridge and by possible till and outwash (underlying Holocene sediments) in channel cuts exposed along the north shore of the Lewis and Clark Lake west of the city of Yankton (fig. 17). The southernmost late Wisconsin end moraine ($Qwlte_1$, the Colony Moraine of Christensen, 1974) does not mark the southernmost extent of the late Wisconsin glacier, but is close to its southernmost extent. Yankton Ridge essentially stopped the southern advance of this late Wisconsin glacier, such that the ice that overrode the ridge was relatively thin and retreated before an end moraine could form south of the ridge. Meltwater draining south of Yankton Ridge along the present-day Missouri River Valley likely inhibited formation of an end moraine south of the ridge. The retreat of this glacier to the northern foot of Yankton Ridge did leave some stagnation moraine on the ridge top and slope moraine on the flanks.

The Colony Moraine ($Qwlte_1$) is now constrained to the northern foot of Yankton Ridge in Bon Homme and Yankton Counties. If it ever extended farther east, across southern Yankton County and into Clay County, it has since been breached and destroyed by the James River, Smoky Run, and Clay Creek. Christensen (1967) mapped end moraine east of the Vermillion River close to the Missouri River flood plain in the southeastern part of Clay County in T. 93 N., R. 51 W. and T. 92 N., R. 51 W.. It is possible that this end moraine complex is an eastern extension of the Colony Moraine.

Marne Creek probably formed during deposition of $Qwlte_1$, draining some of the meltwater from the edge of the glacier along the foot of Yankton Ridge to both the west and east. There remains a drainage divide in sec. 31, T. 94 N., R. 57 W. where Holocene streams drain off the north slope of Yankton Ridge and are captured by Marne Creek and West Marne Creek (Bon Homme County), forming almost 90 degree bends (pl. 2).

Some workers have mapped late Wisconsin end moraine on top of Yankton Ridge (Simpson, 1960; Christensen, 1974). Because Yankton Ridge is cored by a higher bedrock surface, the interpretation of the geomorphology of the surficial features is complicated. The interpretation presented here is that the linear features on the south slope of the ridge are not crests of an end moraine complex; rather, these features likely arose from post-glacial erosion. Flint (1955) also identified Yankton Ridge as a bedrock high, not an end moraine complex, although he does have the end moraine on the north slope of Yankton Ridge extending south of Marne Creek.

During this time of maximum advance, the older outwash core of the James Ridge was covered by late Wisconsin ice. The ridge probably split the glacier into two small lobes that first moved past the sides of the ridge, modifying its shape, and then overriding it. The hummocky, uppermost, very sandy deposits on the ridge are interpreted as late Wisconsin collapsed debris (Qwlcd). Well-developed late Wisconsin kames are also associated with the ridge on its eastern edge.

LATE WISCONSIN ADVANCE OVER TURKEY RIDGE

The late Wisconsin glacier overrode Turkey Ridge. However, geologic mapping, drill-hole data, cores, and electric logs suggest that the majority of till on Turkey Ridge is pre-Wisconsin, that late Wisconsin deposits are relatively thin on the ridge, and thus, the authors believe that the hummocky surface of the top of Turkey Ridge is best described as high relief stagnation moraine ($Qwlts_2$), not end moraine, as some previous workers (Christensen, 1967) have suggested. Some linear features, particularly on the west slope of Turkey Ridge, could be end moraines of some kind (medial or lateral?). A possible moraine crest is also mapped on the top of the ridge (sec. 9, T. 96 N., R. 54 W.). Most of the linear ridges on Turkey Ridge, however, could as easily be erosional features and ice disintegration features.

Results from this study suggest that, initially the late Wisconsin glacier was split by Turkey Ridge into two sublobes. Through time, late Wisconsin ice overrode Turkey Ridge in Yankton County, but the momentum of the ice on the ridge was slowed considerably. As the late Wisconsin glacier on the west and east sides of Turkey Ridge in Yankton and Clay Counties continued to progress southeastward, it sheared away from the slower moving ice on top of Turkey Ridge. At this point, the ice on the ridge stagnated. At least one lateral end moraine ($Qwlte_L$) formed on the western slope of Turkey Ridge (pl. 2; the ridge between Clay Creek and Smoky Run, figs. 7 and 8). Clay Creek formed as an ice marginal stream on the upslope side of this lateral end moraine. Downslope of this ice margin are two other streams, Smoky Run and Mud Creek, which also formed as ice marginal meltwater channels (although only the northern section of Mud Creek may have formed in this way). Adjacent to Smoky Run and the northern section of Mud Creek on the downslope sides are linear features, which are mapped as probable lateral end moraine crests in stagnation moraine (pl. 2). It is not clear how these lateral end moraines might temporally correlate to end moraines in other parts of Yankton County.

Meltwater drained down Clay Creek from the stagnating ice on the top of Turkey Ridge. The lateral end moraine ($Qwlte_L$) acted to direct water runoff from Turkey Ridge parallel to the ridge and down Clay Creek. As the active ice margin retreated to its second position, defined by Smoky Run, the lateral end moraine acted as a barrier for meltwater between Clay Creek and Smoky Run, and water from both drainages ran into a meltwater drainage now buried by the Missouri River flood plain in northwestern T. 94 N., R. 54 W. The section of the Qoa northwest of Volin at the confluence of Smoky Run and Clay Creek (pl. 2) may have developed as a delta or fan originally, although it has since been buried by Holocene overbank deposits.

Other ambiguous features to develop are Turkey Creek and an adjacent drainage to the east; their origin is not fully understood. Clearly, these drainages in northeastern Yankton County, originated as meltwater channels. However, it is not clear whether these meltwater channels were initially subglacial or ice marginal. Turkey Creek trends north-northwest to south-southeast across the northwest-southeast trending Turkey Ridge, thereby crossing the crest of Turkey Ridge, with some sections of the valley being relatively straight, narrow, deep, and incised into bedrock. These features suggest parts of it could have initially formed beneath the ice. Subglacial channels are controlled by hydraulic gradient, which is controlled mainly by the surface slope of the ice, not land topography; thus channels can run across slopes and valleys, and even up hills (Benn and Evans, 1998). There are several near right angle direction changes along Turkey Creek. This is probably caused by both structural (for example, by fracture systems in the Niobrara Formation) and subglacial affects.

Both kames and terraces, which can be identified on 1:24,000-scale topographic maps, occur immediately adjacent to sections of Turkey Creek, and some lineation of kames trend into Turkey Creek. The presence of kames, particularly where they are associated with incised channels, suggests an englacial or supraglacial system (that collapsed onto the surface as the ice melted), whereas the terraces suggest an ice marginal or proglacial system. One such lineation of kames associated with an incised channel (section 33 in T. 96 N., R. 54 W. to sections 3 and 4 in T. 95 N., R. 54 W.) and several linear ridges trend into the main branch of Turkey Creek (pl. 2). The linear system of kames may represent the remnants of an englacial or supraglacial tributary; the linear ridges could have formed in a crevasse (Patterson, 1997a, b; Benn and Evans, 1998). Linear features such as these are often found adjacent to and trending toward what are interpreted as subglacial channels (Patterson, 1997a, b). Further, the valley of Turkey Creek is deep and narrow in places which supports a subglacial interpretation. In such subglacial systems, large meltwater channels cut through the ice onto the substrate, whereas smaller tributaries remain ice-supported. These large meltwater channels have the energy necessary to erode the large volume of bedrock and glacial sediments to create the valley of Turkey Creek.

The tributary to Turkey Creek that runs for more than 3 miles along the eastern boundary of Yankton County bordering Turner and Clay Counties was also a major meltwater drainage. Part of this tributary is incised into bedrock and terraces are present along some other parts. During the late Wisconsin, this tributary drained water to the lower section of Turkey Creek then into a drainage now buried by Missouri River alluvium. Today a drainage divide exists along this channel (sec. 1, T. 95 N., R. 54 W.). The northern part now drains into the Vermillion River, the southern part into the James River.

During glacial retreat, meltwater from the stagnating ice on Turkey Ridge drained into Turkey Creek; thus Turkey Creek, in a sense, acted as a proglacial channel. It may be that at this time some of the terraces along the creek were deposited. Along the southern extent of the main branch of Turkey Creek (near the town of Volin) there are two levels of terraces (pl. 2). This locality may represent different base levels in a proglacial system. Alternatively, the outwash in both terraces may have been deposited originally in the subglacial system, and later erosion by the "proglacial" stream formed the lower terrace as the ice retreated.

RETREAT OF THE LATE WISCONSIN GLACIER TO A RECESSIONAL POSITION

The late Wisconsin glacier retreated from the near maximum ($Qwlte_1$) position to a position now defined by $Qwlte_2$ and probably also the two Qwlte areas mapped east of the James Ridge. Together, these moraines extend east-west across the central part of Yankton County and define a recessional moraine complex. This complex, the southern extent of the Tripp Moraine, extends to the west then north-northwest across Bon Homme County (Christensen, 1974). It cuts across the southwestern corner of Hutchinson County and continues northwestward.

LATE WISCONSIN MODIFICATION OF JAMES RIDGE

The advance of the late Wisconsin glacier through Yankton County no doubt modified, and likely shaped the James Ridge into its present-day form (relatively narrow and elongated parallel to ice flow direction). The present surface of the ridge resulted from meltwater drainage and collapsing of debris from the ice during glacial retreat.

At the recessional moraine ($Qwlte_2$-Qwlte) position, meltwater coming off the glacier drained west-southwest following the front margin of the glacier and forming the western limb of Beaver Creek (west of sec. 33, T. 95 N., R. 56 W.; pl. 2) in west-central Yankton County. Meltwater also drained southeast from the Beaver Lake vicinity, ultimately downcutting into the James Ridge, forming the southern limb of Beaver Creek, and perhaps initiating the downcutting of the lowermost section of the present-day James River and Missouri River Valleys. Discontinuous meltwater channel scars are apparent on the surface of the James Ridge on the section north of Beaver Lake, suggesting that parts of the meltwater drainage system along the James Ridge were supraglacial or englacial. The straightness of the James River Valley at and south of the $Qwlte_2$-Qwlte complex to the Missouri River flood plain also suggests that downcutting began while ice was still present. The presence of ice on either side of the meltwater channel would have constrained the drainage to one direct path.

Over time the headward cutting of the northwest-southeast trunk of Beaver Creek led to the capture of the western branch. This stream capture resulted in a change of the drainage direction of the western branch from west to east and then southeast. The almost 90 degree bend of Beaver Creek on James Ridge is good evidence of this stream capture. The valley of Beaver Creek is wide relative to the size of the present-day creek (fig. 10; pl. 2). It is a good example of an underfit stream.

RETREAT OF THE LATE WISCONSIN GLACIER OUT OF YANKTON COUNTY

As the late Wisconsin glacier retreated from its recessional $Qwlte_2$–Qwlte position and out of the county to the north, it left behind ground moraine, water-modified ground moraine, stagnation moraine to the north of $Qwlte_2$-Qwlte complex and west of Turkey Ridge, and collapsed outwash over James Ridge. The presence of water-modified ground moraine ($Qwltg_w$) adjacent to the James River, Mud Creek, and between the eastern Qwlte and the confluence of Smoky Run and Clay Creek onto the present-day Missouri River flood plain suggests nonchannelized meltwater was released from the glacier at various times during retreat.

Proglacial meltwater during and after this second retreat drained southward, breaching the $Qwlte_2$-Qwlte complex in the areas of Beaver Creek and the James River. A considerable amount of this meltwater probably drained into the lower James River via Mud Creek. Unlike Smoky Run and Clay Creek, several outwash terraces are present along the southern extent of Mud Creek, beginning about 1 mile north of the confluence of Mud Creek and the James River, and progressing across the water-modified ground moraine ($Qwltg_w$) leading into the James River.

FORMATION OF THE JAMES RIVER

As suggested above, the James River in Yankton County likely formed in stages, mainly during retreat of the James lobe from this area. The straight lowermost section of the James River Valley between the $Qwlte_2$–Qwlte complex and the present-day Missouri flood plain, likely formed where ice was present to constrain the meltwater flow. Perhaps the water was following a crevasse, or perhaps it was initially a subglacial drainage.

North of the $Qwlte_2$–Qwlte complex, water-modified till ($Qwltg_w$), outwash, and outwash terraces occur on the bluffs above the present James River Valley. As previously suggested, it is possible that the water-modified till and outwash deposits on the bluff along the James River Valley record initial processes leading to channelization of the meltwater to form the valley itself. The $Qwltg_w$ may represent glacial outburst flood events, common occurrences for some types of glaciers (Shoemaker, 1992; Benn and Evans, 1998). Outwash and perched outwash terraces on the bluffs above the valley may represent the remnants of a widespread outwash deposit in an initially shallow trench which was subsequently eroded, they may represent discontinuous deposits in a mostly erosional system, or they may represent supra- and englacial meltwater deposits let down during melting of the ice. Significant downcutting of the James River Valley and connection of locally channelized segments of the valley may have corresponded to periodic(?) releases of flood waters from Lake Dakota (fig. 2) and other lakes north of Yankton County. Similar ideas have been suggested by previous workers (Flint, 1955; Ensz, 1993). Evidence for possible outburst flood events north of Yankton County is found as close as northern Hutchinson County where late Wisconsin fluvial terraces and outwash plains are apparent from surface mapping and lithologic logs of test holes.

Holocene History

Throughout the Holocene epoch, 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 bedrock, and infills glacial lakes. Wind has also been a force during this present epoch, winnowing fine sand and silt from Pleistocene and older Holocene deposits, or simply remoblizing Pleistocene loess. Soil continues to develop by alteration of exposed sediments. Landslides or sediment creep also shape the landscape through the mass movement of glacial deposits along exposed slopes, particularly on Turkey and Yankton Ridges.

Landscape development is very immature in Yankton County compared to the Nebraska side of the Missouri River. This immaturity is due to the more recent (late Wisconsin) glacial modification in South Dakota as compared to adjacent Nebraska (where pre-Illinoian glacial sediments, Tertiary deposits, and even older rocks constitute much of the surficial sediments; Burchett and others, 1988; Hallberg, 1986). The landscape west of the Missouri River in South Dakota is even further developed than in Yankton County, as it is an even older surface (deposits are Tertiary and Cretaceous in age).This is evident from examination of the shaded relief map of South Dakota (U.S. Geological Survey, 1964).

ECONOMIC GEOLOGY

Sand and Gravel

In terms of volume, Yankton County probably possesses some of the largest deposits of sand and gravel in South Dakota. However, only those deposits at or very near the surface are of direct economic importance. These are described by Tomhave and Hammond (1987). The sand and gravel derived from outwash and related deposits are widely used as an aggregate. Its quality is sometimes diminished, depending on specific use, because it may contain softer rocks such as limestone or highly weathered igneous and metamorphic rock.

Quartzite in the sand and gravel chemically reacts with portland cement which causes it to slowly deteriorate (Kay Kassube, Department of Earth Sciences and Physics, University of South Dakota, unpublished report for the South Dakota Department of Transportation). Deterioration of cement is also caused by chemical reaction with dolomite in the aggregate (Duke and others, 1996). Small amounts of pyrite (iron sulfide) are common; it weathers to iron oxide to produce red spots and eventually pits on the surface of finished concrete.

The sand and gravel from the western-derived Bon Homme gravel produces an excellent aggregate, as the grains are composed almost entirely of quartz and feldspar, which are very hard. Unfortunately, these deposits are limited in area and often covered by excessive overburden, making most of them uneconomical. All known economic deposits are now depleted.

Ground Water

The deeper deposits of sand and gravel are often indirectly economically important because they serve as aquifers from which water can be pumped through wells for agricultural and domestic use. Two of the bedrock formations, the Dakota Formation and to a lesser extent the Niobrara Formation, also are sources of ground water. This subject is treated in detail by Bugliosi (1983, 1986).

Agricultural Lime

Weathered chalk from the Niobrara Formation is used in the production of lime for treating soils with an excessive acid content. Although the "chalk cliffs" along Lewis and Clark Lake and Marindahl Lake testify to the abundance of this rock, much of the rock is not exposed. Excessive overburden limits the economic viability of this resource. Exposed chalk has been quarried at sites along Turkey Creek in eastern Yankton County for lime production. Only one quarry has been intermittently active during the latter part of the twentieth century. Excessive overburden, lack of weathered chalk (unweathered chalk cannot be easily recovered), and an unpredictable agricultural economy preclude more extensive development.

Cement

Shale and limestone (or chalk) can be combined and processed into portland cement. Lack of accessible volumes of these materials exclude cement production in Yankton County. Of significant historical importance, however, is that some of the cement used in the construction of the Panama Canal was produced just west of Yankton from the Pierre Shale and Niobrara Formation (Simpson, 1960).

Building Stone

Also of historical interest is the use of rock from the Niobrara Formation as building stone. It is easily quarried, assuming accessibility, but has a rather short life span before it starts to crumble if not properly maintained. It was used by pioneers in the area (Simpson, 1960) because it was the only dimension stone locally available. As it has favorable insulative qualities, it was investigated during the 1970s for possible use in building construction according to information in the files of the South Dakota Geological Survey.

Expanded Shale

Lightweight aggregate can be produced from kiln-fired shale and a variety of other materials. The desirable qualities and steps required to produce lightweight aggregate are described by Kirstein (1988). Lee and others (1961) suggested an area west of Yankton might serve as a resource for expanded shale. Specifically, they suggested the Pierre Shale in the W½ sec. 9, T. 93 N., R. 56 W., and parts of adjacent sections 8 and 4. They estimated as much as 15 million cubic yards of useable shale lay above the Crow Creek Member in this area. However, the demand for lightweight aggregate is not sufficient enough to warrant the cost of overburden removal and mill construction.

REFERENCES CITED

Andrews, J.T., 1987, *The late Wisconsin glaciation and deglaciation of the Laurentide ice sheet*, in Ruddiman, W.F., ed., *North America and adjacent oceans during the last deglaciation:* The geology of North America: Boulder Colorado, Geological Society of America, v. K-3, p. 13-37.

Arney, R.D., Blankenau, D.F., and Hammond, R.H., 1987, *Recorded earthquakes in South Dakota, 1872-1986*: South Dakota Geological Survey General Map, scale 1 in. = 26 mi.

Becker, D.J., and Zeltinger, J.M., 1983, *Comment on "Seismicity of the Colorado lineament"*: Geology, v. 11, p. 559-560.

Benn, D.I., and Evans, K.J.A., 1998, *Glaciers and glaciation*: New York, New York, Oxford University Press Inc., 734 p.

Benson, R.D., 1983, *A preliminary assessment of the hydrologic characteristics of the James River in South Dakota*: U.S. Geological Survey Water-Resources Investigations Report 83-4077, 122 p.

Bettis, A.E., 2000, *Weathering zone recognition and interpretations in sequences of glacial deposits*: Minneapolis, Minnesota, Advances in site characterization for environmental and engineering projects workshop notebook, Midwest Geoscience Group Workshop, 5 p.

Bierman, P.R., Marsella, K.A., Patterson, C., Davis, P.T., and Caffee, M., 1999, *Mid-Pleistocene cosmogenic minimum-age limits for pre-Wisconsin glacial surfaces in southwestern Minnesota and southern Baffin Island: A multiple nuclide approach*: Geomorphology, v. 27, p. 25-39.

Bluemle, J.P., 2000, *The face of North Dakota, 3rd edition*: North Dakota Geological Survey Educational Series 26, 205 p.

Bluemle, J.P., and Clayton, L., 1984, *Large-scale glacial thrusting and related processes in North Dakota*: Boreas, v. 13, p. 279-299.

Brenner, R.L., Bretz, R.F., Bunker, B.J., Iles, D.L., Ludvigson, G.A., McKay, R.M., Whitley, D.L., and Witzke, B.J., 1981, *Cretaceous stratigraphy and sedimentation in northwest Iowa, northeast Nebraska, and southeast South Dakota*: Iowa Geological Survey Guidebook Series 4, 172 p.

Brenner, R.L., and Whitley, D.L., 1981, *Description of Stop 4, Stone Park, North Sioux City*, in *Cretaceous stratigraphy and sedimentation in northwest Iowa, northeast Nebraska, and southeast South Dakota*: Iowa Geological Survey Guidebook Series 4, p. 162-164.

Bretz, R.F., and Johnson, G.D., 1981, *Evidence of basement block control on Upper Cretaceous Pierre Shale deposition, southeastern South Dakota*: Geological Society of America Abstracts with Programs, v. 13, no. 4, p. 192.

Bugliosi, E.F., 1983, *Major aquifers in Yankton County, South Dakota*: South Dakota Geological Survey Information Pamphlet 28, 7 p.

_____1986, *Water resources of Yankton County, South Dakota*: U.S. Geological Survey Water-Resources Investigations Report 84-4241, 41 p.

Bunker, B.J., 1981, *The tectonic history of the Transcontinental Arch and Nemaha Uplift and their relationship to the Cretaceous rocks of the central midcontinent region*, in *Cretaceous stratigraphy and sedimentation in northwest Iowa, northeast Nebraska, and southeast South Dakota*: Iowa Geological Survey Guidebook Series 4, p. 1-23.

Burchett, R. R., Dreeszen, V.H., Souders, V.L., and Prichard, G.E., 1988, *Bedrock geologic map showing configuration of the bedrock surface in the Nebraska part of the Sioux City* $1^o x 2^o$ *quadrangle*: U.S. Geological Survey Miscellaneous Investigations Series Map I-1879.

Carlson, M.P., 2001, *Island arcs, accretionary terranes and Midcontinental structure, New understandings of the geologic architecture of the U.S. Midcontinent*: Nebraska Conservation and Survey Division Resources Notes, v. 15, no. 1, p. 15-18.

Christensen, C.M., 1967, *Geology and water resources of Clay County, South Dakota; Part I: Geology*: South Dakota Geological Survey Bulletin 19, 86 p.

_____1974, *Geology and water resources of Bon Homme County, South Dakota; Part I: Geology*: South Dakota Geological Survey Bulletin 21, 48 p.

Cobban, W.A., and Merewether, E.A., 1983, *Stratigraphy and paleontology of Mid-Cretaceous rocks in Minnesota and contiguous areas*: U.S. Geological Survey Professional Paper 1253, 52 p.

Duke, E.F., Hansen, M.R., and Johnston, D., 1996, *Mineral reactions in dolomitic aggregate in concrete pavements of eastern South Dakota*: Geological Society of America Abstracts with Programs, v. 28, no. 4, p. 7.

Ensz, E.H., 1979, *Soil survey of Yankton County, South Dakota*: U.S. Department of Agriculture Soil Conservation Service, 172 p.

_____1993, *The development of the James River trench and resulting soils in Yankton County*: Proceedings of the South Dakota Academy of Science, v. 72, p. 215-219.

Flint, R.F., 1955, *Pleistocene geology of eastern South Dakota*: U.S. Geological Survey Professional Paper 262, 173 p.

Gilbertson, J.P., ed., 1989, *Quaternary geology of northeastern South Dakota*: South Dakota Geological Survey Guidebook 3, 57 p.

Gill, J.R., and Cobban, W.A., 1973, *Stratigraphy and geologic history of the Montana Group and equivalent rocks, Montana, Wyoming, and North and South Dakota*: U.S. Geological Survey Professional Paper 776, 37 p.

Gries, J.P., and Martin, J.E., 1981, *Composite outcrop section of the Paleozoic and Mesozoic strata in the Black Hills and surrounding areas,* in Rich, F.J., ed., *Geology of the Black Hills, South Dakota and Wyoming*: Field Trip Guidebook, Rocky Mountain Section, Geological Society of America, American Geological Institute, p. 261-292.

Hallberg, G.R., 1986, *Pre-Wisconsin glacial stratigraphy of the Central Plains region in Iowa, Nebraska, Kansas, and Missouri*: Quaternary Science Reviews, v. 5, p. 11-15.

Hallberg, G.R., and Kemmis, T.J., 1986, *Stratigraphy and correlation of the glacial deposits of the Des Moines and James lobes and adjacent areas in North Dakota, South Dakota, Minnesota, and Iowa*: Quaternary Science Reviews, v. 5, p. 65-68.

Hammond, R.H., 1991, *Geology of Lake and Moody Counties, South Dakota*: South Dakota Geological Survey Bulletin 35, 49 p.

Hammond, R.H., Watkins, D.K., Witzke, B.J., and Anderson, R.R., 1995, *The Crow Creek Member, Pierre Shale (Upper Cretaceous) of southeastern South Dakota and northwestern Nebraska: Impact tsunamite or basal transgressive deposit*?, in Diffendal, R.F., Jr., and Flowerday, C.A., eds., *Geologic field trips in Nebraska and adjacent parts of Kansas and South Dakota, Guidebook 10*: Nebraska Conservation and Survey Division, p. 109-120.

Izett, G.A., Cobban, W.A., Obradovich, J.D., and Kunk, M.J., 1993, *The Manson impact structure:* $^{40}Ar/^{39}Ar$ *age and its distal impact ejecta in the Pierre Shale in southeastern South Dakota*: Science, v. 262, p. 729-732.

Johnson, G.D., and McCormick, K. 2004, *The origin of James Ridge, Yankton County, South Dakota*: Proceedings of the South Dakota Academy of Science, v. 83, p. 339.

Johnson, G.D., and Milburn, S.E., 1984, *Pathological evidence of an injured equid, and associated fossils of late Blancan(?) age from the Bon Homme Gravel, Yankton County, South Dakota*: Proceedings of the South Dakota Academy of Science, v. 63, p. 77-84.

Jorgensen, D.G., 1960, *Geology and shallow ground water resources of the Missouri Valley between North Sioux City and Yankton, South Dakota*: South Dakota Geological Survey Report of Investigations 86, 54 p.

Kirstein, D.S., 1988, *Rocks that float?*: West Virginia Geological and Economic Survey, Mountain State Geology, p. 10-13.

Kurtén, B., and Anderson, E., 1980, *Pleistocene mammals of North America*: New York, Columbia University Press, 442 p.

Lee, K.Y., Petsch, B.C., Rothrock, E.P., and Agnew, A.F., 1961, *Possible expanded shale resources near Yankton, South Dakota*: South Dakota Geological Survey Mineral Resources Investigations Map 1, scale 1 in. = 700 ft.

Lugn, A.L., 1935, *The Pleistocene geology of Nebraska*: Nebraska Geological Survey Bulletin 10, 223 p.

Lutzen, E.E., 1957, *Geology of the Irene quadrangle, South Dakota*: Vermillion, South Dakota, University of South Dakota, unpublished M.A. Thesis, 128 p.

Matsch, C.L., and Schneider, A.F., 1986, *Stratigraphy and correlation of the glacial deposits of the glacial lobe complex in Minnesota and northwestern Wisconsin*: Quaternary Science Reviews, v. 5, p. 59-64.

McCormick, K.A., and Hammond, R.H., 2004, *Geology of Lincoln and Union Counties, South Dakota*: South Dakota Geological Survey Bulletin 39, 43 p.

McGookey, D.P., Haun, J.D., Hale, L.A., Goodell, H.G., McCubbin, D.G. Weimer, R.J., and Wulf, G.R., 1972, *Cretaceous System*, in Mallory, W.W., and others, eds., *Geologic atlas of the Rocky Mountain region, United States of America*: Denver, Colorado, Rocky Mountain Association of Geologists, p. 190-228.

Paterson, W.S.B., and Hammer, C.U., 1987, *Chapter 5: Ice core and other glaciological data*: in Ruddiman, W.F., and Wright, H.E., Jr., eds., *North America and adjacent oceans during the last deglaciation*: The Geology of North America, v. K-3, p. 91-109.

Patterson, C.J., 1997a, *Contributions to the Quaternary geology of southwestern Minnesota*: Minnesota Geological Survey Report of Investigations 47, 78 p.

_____1997b, *Southern Laurentide ice lobes were created by ice streams: Des Moines lobe in Minnesota, USA*: Sedimentary Geology, v. 111, p. 249-261.

_____1998, *Laurentide glacial landscapes: the role of ice streams*: Geology, v. 26, p. 643-646.

Petsch, B.C., 1962, *Magnetometer survey of southeastern South Dakota*: South Dakota Geological Survey Mineral Resources Investigations Map 3.

_____1967, *Vertical-intensity magnetic map of South Dakota, ground magnetometer survey*: South Dakota Geological Survey Mineral Resources Investigations Map 4, scale 1 in. = 11.6 mi.

Petsch, B.C., and McGregor, D.J., 1969, *South Dakota's rock history*: South Dakota Geological Survey Educational Series 3, 39 p.

Pinsof, J.D., 1985, *The Pleistocene vertebrate localities of South Dakota*, in Martin, J.E., ed., *Fossiliferous Cenozoic deposits of western South Dakota and northwestern Nebraska*: Rapid City, South Dakota, South Dakota School of Mines and Technology, Museum of Geology, Dakoterra, v. 2, pt. 2, p. 233-264.

Rothrock, E.P., 1943, *A geology of South Dakota, Part I: The surface*: South Dakota Geological Survey Bulletin 13, 88 p.

Rukstad, L.R., 1963, *Water supply for the city of Lesterville, South Dakota*: South Dakota Geological Survey Special Report 23, 16 p.

Savage, D.E., and Russell, D.E., 1983, *Mammalian paleofaunas of the world*: Reading, Massachusetts, Addison-Wesley Publishing Company, 432 p.

Schultz, L.G., Tourtelot, H.A., Gill, J.R., and Boerngen, J.G., 1980, *Composition and properties of the Pierre Shale and equivalent rocks, northern Great Plains region*: U.S. Geological Survey Professional Paper 1064-B, 225 p.

Sevon, W.D., 1958, *Geology of the Marindahl quadrangle, South Dakota*: Vermillion, South Dakota, University of South Dakota, unpublished M.A. Thesis, 99 p.

Shoemaker, E.M., 1992, *Subglacial floods and the origin of low-relief ice-sheet lobes*: Journal of Glaciology, v. 38, no. 128, p. 105-112.

Shurr, G.W., 1980, *Exposures of Greenhorn Formation and Carlile Shale (Upper Cretaceous) at Lake Traverse, western Minnesota*: The American Association of Petroleum Geologists Bulletin, v. 64, p. 942-945.

Shurr, G.W., Ludvigson, G.A., and Hammond, R.H. (eds.), 1994, *Perspectives on the eastern margin of the Cretaceous Western Interior Basin*: Geological Society of America Special Paper 287.

Šibrava, V., 1986, *Introduction*: Quaternary Science Reviews, v. 5, p. 1-10.

Simpson, H.E., 1960, *Geology of the Yankton area, South Dakota and Nebraska*: U.S. Geological Survey Professional Paper 328, 124 p.

Sims, P.K., 1990, *Precambrian basement map of the northern mid-continent, U.S.A.*: U.S.G.S. Miscellaneous Investigations Series, Map I-1853-A.

Sims, P.K., and Peterman, Z.E., 1986, *Early Proterozoic Central Plains orogen: A major buried structure in the north-central United States*: Geology, v. 14, p. 488-491.

Todd, J.E., 1898, *The first and second biennial reports on the geology of South Dakota with accompanying papers 1893-6*: South Dakota Geological Survey Bulletin 2, 139 p.

Tomhave, D.W., 1997, *Geology of Spink County, South Dakota*, South Dakota Geological Survey Bulletin 38, 61 p.

Tomhave, D.W., and Hammond, R.H., 1987, *Sand and gravel resources in Yankton County, South Dakota*: South Dakota Geological Survey Information Pamphlet 27, 47 p.

U.S. Census Bureau, 2000, Geographic Comparison Table, electronic document <http://factfinder. census.gov/servlet/GCTTable?_bm=y&-geo_id=04000US46&-_box_head_nbr=GCT-PH1&- ds_name=DEC_2000_SF1_U&-format=ST-2>, accessed March 11, 2005.

U.S. Department of Agriculture Soil Conservation Service, 1985, *Important farmland, Yankton County, South Dakota*: Map 4-R-39106.

U.S. Geological Survey, 1965, *State of South Dakota, shaded relief*: Washington, D.C., U.S. Geological Survey, scale 1:500,000.

Watkins, D.K., 1986, *Calcareous nannofossil paleoceanography of the Cretaceous Greenhorn Sea*: Geological Society of America Bulletin, v. 97, p. 1239-1249.

Witzke, B.J., Hammond, R.H., and Anderson, R.R., 1996, *Deposition of the Crow Creek Member, Campanian, South Dakota and Nebraska*, in Koeberl, C., and Anderson, R.R., eds., *The Manson impact structure, Iowa: Anatomy of an impact crater*: Geological Society of America Special Paper 302, p. 433-456.

Witzke, B.J., Ludvigson, G.A., Poppe, J.R., and Ravn, R.L., 1983, *Cretaceous paleogeography along the eastern margin of the Western Interior Seaway, Iowa, southern Minnesota, and eastern Nebraska and South Dakota*, in Reynolds, M.W., and Dolly, E.D., eds., *Mesozoic paleogeography of the west-central United States*: Denver, Colorado, Rocky Mountain Section of the Society of Economic Paleontologists and Mineralogists, p. 225-252.

APPENDIX A

List of map location numbers and corresponding legal locations of all test holes used in cross sections

The following list contains the map location numbers (MLN) and legal descriptions of all test-hole logs shown on figure 4 and used to construct the cross sections in figures 6 through 15. These logs, plus the logs of additional test holes used in plate 1 and others that did not penetrate bedrock, are available from the computer files of the South Dakota Geological Survey. The map location numbers refer only to this report. Any request for logs should contain the legal description. An asterisk (*) after the map location number indicates a private well.

MAP LOCATION NUMBER	LEGAL DESCRIPTION
FIGURE 6, CROSS SECTION A-A'	
MLN 1	SE¼ SE¼ SE¼ SE¼ sec. 36, T. 97 N., R. 58 W.
MLN 2	NE¼ NE¼ NE¼ NE¼ sec. 04, T. 96 N., R. 57 W.
MLN 3	NW¼ NW¼ NW¼ NW¼ sec. 06, T. 96 N., R. 56 W.
MLN 4	SW¼ SW¼ SW¼ SW¼ sec. 34, T. 97 N., R. 56 W.
MLN 5	NE¼ NE¼ NE¼ NE¼ sec. 01, T. 96 N., R. 56 W.
MLN 6	NE¼ NE¼ NE¼ NE¼ sec. 04, T. 96 N., R. 55 W.
MLN 7	NW¼ NW¼ NW¼ NW¼ sec. 06, T. 96 N., R. 54 W.
MLN 8	NE¼ NE¼ NE¼ NE¼ sec. 04, T. 96 N., R. 54 W.
MLN 9	NE¼ NE¼ NE¼ NE¼ sec. 01, T. 96 N., R. 54 W.
FIGURE 7, CROSS SECTION B-B'	
MLN 10	NW¼ SW¼ NW¼ NW¼ sec. 19, T. 96 N., R. 57 W.
MLN 11	SE¼ SE¼ SE¼ SE¼ sec. 17, T. 96 N., R. 57 W.
MLN 12	SE¼ SE¼ SE¼ SE¼ sec. 16, T. 96 N., R. 57 W.
MLN 13	NW¼ NE¼ NE¼ NE¼ sec. 22, T. 96 N., R. 57 W.
MLN 14	SW¼ SE¼ SE¼ SE¼ sec. 14, T. 96 N., R. 57 W.
MLN 15	SW¼ SW¼ SE¼ SE¼ sec. 13, T. 96 N., R. 57 W.
MLN 16*	NW¼ NW¼ sec. 21, T. 96 N., R. 56 W.
MLN 17	SW¼ SW¼ SW¼ SW¼ sec. 15, T. 96 N., R. 56 W.
MLN 18	SE¼ SE¼ SE¼ SW¼ sec. 14, T. 96 N., R. 56 W.
MLN 19	SE¼ SW¼ SW¼ SW¼ sec. 18, T. 96 N., R. 55 W.
MLN 20	SW¼ NW¼ NW¼ NW¼ sec. 22, T. 96 N., R. 55 W.
MLN 21	NW¼ NE¼ NE¼ NE¼ sec. 24, T. 96 N., R. 55 W.
MLN 22	NW¼ NW¼ NE¼ NE¼ sec. 21, T. 96 N., R. 54 W.
MLN 23	SE¼ SE¼ SE¼ SE¼ sec. 13, T. 96 N., R. 54 W.
MLN 24	SW¼ SW¼ SE¼ SE¼ sec. 16, T. 96 N., R. 53 W.

MAP LOCATION NUMBER	LEGAL DESCRIPTION
FIGURE 8, CROSS SECTION C-C'	
MLN 25	SW¼ SW¼ SW¼ SW¼ sec. 31, T. 96 N., R. 57 W.
MLN 26	NE¼ NE¼ NE¼ NE¼ sec. 04, T. 95 N., R. 57 W.
MLN 27	NW¼ NW¼ NW¼ NW¼ sec. 03, T. 95 N., R. 57 W.
MLN 28	NW¼ NW¼ NE¼ NW¼ sec. 01, T. 95 N., R. 57 W.
MLN 29	SW¼ SW¼ SW¼ SW¼ sec. 31, T. 96 N., R. 56 W.
MLN 30	SW¼ SE¼ SE¼ SE¼ sec. 31, T. 96 N., R. 56 W.
MLN 31	NE¼ NE¼ NE¼ NE¼ sec. 04, T. 95 N., R. 56 W.
MLN 32	NW¼ NW¼ NW¼ NW¼ sec. 03, T. 95 N., R. 56 W.
MLN 33	NE¼ SE¼ SW¼ SE¼ sec. 35, T. 96 N., R. 56 W.
MLN 34	SE¼ SW¼ SE¼ SE¼ sec. 36, T. 96 N., R. 56 W.
MLN 35	SE¼ SE¼ SE¼ SE¼ sec. 33, T. 96 N., R. 55 W.
MLN 36	SW¼ SE¼ SE¼ SE¼ sec. 36, T. 96 N., R. 55 W.
MLN 37	SW¼ SE¼ SE¼ SW¼ sec. 33, T. 96 N., R. 54 W.
MLN 38	SE¼ SE¼ SE¼ SE¼ sec. 34, T. 96 N., R. 54 W.
MLN 39	SW¼ SW¼ SW¼ SE¼ sec. 36, T. 96 N., R. 54 W.
FIGURE 9, CROSS SECTION D-D'	
MLN 40	SW¼ SW¼ SW¼ SW¼ sec. 18, T. 95 N., R. 57 W.
MLN 41	SW¼ NW¼ SW¼ NW¼ sec. 20, T. 95 N., R. 57 W.
MLN 42	SW¼ SW¼ SW¼ SW¼ sec. 09, T. 95 N., R. 57 W.
MLN 43	SW¼ SW¼ SW¼ SE¼ sec. 22, T. 95 N., R. 57 W.
MLN 44	SW¼ SW¼ NW¼ SW¼ sec. 14, T. 95 N., R. 57 W.
MLN 45	NE¼ NE¼ NE¼ NE¼ sec. 26, T. 95 N., R. 57 W.
MLN 46	SE¼ SE¼ SE¼ NE¼ sec. 13, T. 95 N., R. 57 W.
MLN 47	NE¼ NE¼ NE¼ NE¼ sec. 18, T. 95 N., R. 56 W.
MLN 48	SE¼ NE¼ NE¼ SE¼ sec. 17, T. 95 N., R. 56 W.
MLN 49	SE¼ SW¼ SW¼ SW¼ sec. 16, T. 95 N., R. 56 W.
MLN 50	NW¼ NW¼ NE¼ NE¼ sec. 21, T. 95 N., R. 56 W.
MLN 51	NE¼ NE¼ NE¼ NE¼ sec. 21, T. 95 N., R. 56 W.
MLN 52	SE¼ SE¼ SE¼ SE¼ sec. 15, T. 95 N., R. 56 W.
MLN 53	NE¼ NE¼ NE¼ NE¼ sec. 24, T. 95 N., R. 56 W.
MLN 54	NE¼ NE¼ NE¼ NE¼ sec. 21, T. 95 N., R. 55 W.
MLN 55	NW¼ NW¼ NW¼ NW¼ sec. 19, T. 95 N., R. 54 W.
MLN 56	NW¼ SW¼ NW¼ NW¼ sec. 20, T. 95 N., R. 54 W.
MLN 57*	NW¼ NW¼ NW¼ NW¼ sec. 22, T. 95 N., R. 54 W.
MLN 58	NW¼ NW¼ NW¼ NW¼ sec. 24, T. 95 N., R. 54 W.
MLN 59	SW¼ SW¼ SW¼ SW¼ sec. 18, T. 95 N., R. 53 W.

MAP LOCATION NUMBER	LEGAL DESCRIPTION
FIGURE 10, CROSS SECTION E-E'	
MLN 60	SW¼ SW¼ SW¼ SW¼ sec. 30, T. 95 N., R. 57 W.
MLN 61	SE¼ SE¼ NE¼ SE¼ sec. 33, T. 95 N., R. 57 W.
MLN 62	NE¼ NE¼ NE¼ NE¼ sec. 03, T. 94 N., R. 57 W.
MLN 63	NW¼ NE¼ NE¼ NW¼ sec. 02, T. 94 N., R. 57 W.
MLN 64	NW¼ NW¼ NW¼ NE¼ sec. 01, T. 94 N., R. 57 W.
MLN 65	NW¼ NW¼ NW¼ NW¼ sec. 06, T. 94 N., R. 56 W.
MLN 66	NE¼ NE¼ NE¼ NE¼ sec. 06, T. 94 N., R. 56 W.
MLN 67	SW¼ SW¼ SW¼ SW¼ sec. 33, T. 95 N., R. 56 W.
MLN 68	NE¼ NE¼ NE¼ NE¼ sec. 04, T. 94 N., R. 56 W.
MLN 69	SE¼ SE¼ NE¼ SE¼ sec. 35, T. 95 N., R. 56 W.
MLN 70	SW¼ SW¼ SW¼ SW¼ sec. 31, T. 95 N., R. 55 W.
MLN 71	NW¼ NW¼ NE¼ NW¼ sec. 05, T. 94 N., R. 55 W.
MLN 72	SE¼ SW¼ SE¼ SE¼ sec. 32, T. 95 N., R. 55 W.
MLN 73	NE¼ SE¼ SE¼ SE¼ sec. 33, T. 95 N., R. 55 W.
MLN 74	NW¼ NW¼ NW¼ NW¼ sec. 01, T. 94 N., R. 55 W.
MLN 75	NE¼ NE¼ NE¼ NE¼ sec. 01, T. 94 N., R. 55 W.
MLN 131	NE¼ NE¼ NE¼ NE¼ sec. 06, T. 94 N., R. 54 W.
MLN 76	SW¼ SW¼ SW¼ SW¼ sec. 34, T. 95 N., R. 54 W.
MLN 77	NW¼ NW¼ NW¼ NW¼ sec. 06, T. 94 N., R. 53 W.
FIGURE 11, CROSS SECTION F-F'	
MLN 78	SW¼ SW¼ SW¼ SW¼ sec. 18, T. 94 N., R. 57 W.
MLN 79	SE¼ SE¼ SE¼ SE¼ sec. 16, T. 94 N., R. 57 W.
MLN 80	SW¼ SW¼ SW¼ SW¼ sec. 15, T. 94 N., R. 57 W.
MLN 81	NW¼ SW¼ SW¼ SW¼ sec. 18, T. 94 N., R. 56 W.
MLN 82	NE¼ NE¼ NE¼ NE¼ sec. 21, T. 94 N., R. 56 W.
MLN 83	SW¼ SW¼ SE¼ SE¼ sec. 15, T. 94 N., R. 56 W.
MLN 84	SW¼ SW¼ SW¼ SW¼ sec. 13, T. 94 N., R. 56 W.
MLN 85	NE¼ NE¼ NE¼ NE¼ sec. 24, T. 94 N., R. 56 W.
MLN 86	SE¼ NE¼ NE¼ NE¼ sec. 19, T. 94 N., R. 55 W.
MLN 87	SW¼ SW¼ SE¼ NE¼ sec. 17, T. 94 N., R. 55 W.
MLN 88	SE¼ SE¼ SW¼ SW¼ sec. 15, T. 94 N., R. 55 W.
MLN 89	NE¼ NE¼ NE¼ NW¼ sec. 23, T. 94 N., R. 55 W.
MLN 90	SE¼ SE¼ SE¼ SW¼ sec. 13, T. 94 N., R. 55 W.
MLN 91	SE¼ SE¼ SE¼ SE¼ sec. 18, T. 94 N., R. 54 W.
MLN 92	SW¼ SW¼ SW¼ SW¼ sec. 16, T. 94 N., R. 54 W.
MLN 93	SE¼ SE¼ SE¼ SE¼ sec. 16, T. 94 N., R. 54 W.
MLN 94	SE¼ SE¼ SE¼ SE¼ sec. 13, T. 94 N., R. 54 W.

MAP LOCATION NUMBER	LEGAL DESCRIPTION
FIGURE 12, CROSS SECTION G-G'	
MLN 95	NW¼ NW¼ NW¼ NW¼ sec. 05, T. 93 N., R. 57 W.
MLN 96	SE¼ SE¼ SE¼ SE¼ sec. 33, T. 94 N., R. 57 W.
MLN 97*	NE¼ NE¼ NE¼ NE¼ sec. 03, T. 93 N., R. 57 W.
MLN 98	NE¼ NE¼ NE¼ NE¼ sec. 01, T. 93 N., R. 57 W.
MLN 99	SE¼ NE¼ NE¼ NE¼ sec. 06, T. 93 N., R. 56 W.
MLN 100	NE¼ NE¼ NE¼ NE¼ sec. 04, T. 93 N., R. 56 W.
MLN 101	SE¼ SE¼ SE¼ SW¼ sec. 35, T. 94 N., R. 56 W.
MLN 102	NW¼ NW¼ SE¼ SE¼ sec. 36, T. 94 N., R. 56 W.
MLN 103	NE¼ NE¼ NW¼ NE¼ sec. 06, T. 93 N., R. 55 W.
MLN 104	SE¼ SE¼ NE¼ SE¼ sec. 02, T. 93 N., R. 55 W.
MLN 105	SE¼ SE¼ NE¼ SE¼ sec. 36, T. 94 N., R. 55 W.
MLN 106	NE¼ NE¼ NE¼ NE¼ sec. 35, T. 94 N., R. 54 W.
FIGURE 13, CROSS SECTION H-H'	
MLN 107	SE¼ NW¼ SW¼ SW¼ sec. 07, T. 93 N., R. 57 W.
MLN 108	SW¼ SW¼ NW¼ SW¼ sec. 10, T. 93 N., R. 57 W.
MLN 109*	SW¼ SW¼ SW¼ NW¼ sec. 07, T. 93 N., R. 56 W.
MLN 110	SW¼ SW¼ SW¼ SW¼ sec. 10, T. 93 N., R. 56 W.
MLN 111	SE¼ NE¼ NE¼ NE¼ sec. 14, T. 93 N., R. 56 W.
MLN 112*	SE¼ SE¼ SE¼ NW¼ sec. 13, T. 93 N., R. 56 W.
MLN 113*	NE¼ NE¼ NW¼ SW¼ sec. 18, T. 93 N., R. 55 W.
MLN 114	NE¼ NE¼ sec. 16, T. 93 N., R. 55 W.
MLN 115	NE¼ NE¼ sec. 20, T. 93 N., R. 54 W.
MLN 116	NE¼ NE¼ NE¼ NE¼ sec. 22, T. 93 N., R. 54 W.
MLN 117	SW¼ SW¼ SE¼ NE¼ sec. 35, T. 93 N., R. 54 W.
MLN 118	NW¼ NW¼ NW¼ NW¼ sec. 06, T. 92 N., R. 53 W.
FIGURE 14, CROSS SECTION I-I'	
MLN 119	NE¼ SE¼ SE¼ NE¼ sec. 07, T. 94 N., R. 57 W.
MLN 120	NW¼ NW¼ SW¼ SW¼ sec. 10, T. 94 N., R. 57 W.
MLN 121	NW¼ NW¼ SW¼ SW¼ sec. 12, T. 94 N., R. 57 W.
MLN 122	SE¼ NE¼ NE¼ SE¼ sec. 12, T. 94 N., R. 57 W.
MLN 123	SW¼ SW¼ SW¼ SW¼ sec. 07, T. 94 N., R. 56 W.
MLN 124	NE¼ NE¼ NE¼ NE¼ sec. 18, T. 94 N., R. 56 W.
MLN 125	SW¼ SW¼ SW¼ SE¼ sec. 08, T. 94 N., R. 56 W.
MLN 126	SW¼ SW¼ SW¼ SW¼ sec. 09, T. 94 N., R. 56 W.
MLN 127	NW¼ NE¼ NE¼ NE¼ sec. 16, T. 94 N., R. 56 W.
MLN 128	SW¼ SW¼ SW¼ SW¼ sec. 11, T. 94 N., R. 56 W.
MLN 129	NW¼ NW¼ SW¼ SW¼ sec. 07, T. 94 N., R. 55 W.

MAP LOCATION NUMBER	LEGAL DESCRIPTION
FIGURE 15, CROSS SECTION J-J'	
MLN 108	SW¼ SW¼ NW¼ SW¼ sec. 10, T. 93 N., R. 57 W.
MLN 97*	NE¼ NE¼ NE¼ NE¼ sec. 03, T. 93 N., R. 57 W.
MLN 81	NW¼ SW¼ SW¼ SW¼ sec. 18, T. 94 N., R. 56 W.
MLN 126	SW¼ SW¼ SW¼ SW¼ sec. 09, T. 94 N., R. 56 W.
MLN 68	NE¼ NE¼ NE¼ NE¼ sec. 04, T. 94 N., R. 56 W.
MLN 69	SE¼ SE¼ NE¼ SE¼ sec. 35, T. 95 N., R. 56 W.
MLN 53	NE¼ NE¼ NE¼ NE¼ sec. 24, T. 95 N., R. 56 W.
MLN 130	SW¼ SW¼ SW¼ SW¼ sec. 07, T. 95 N., R. 55 W.
MLN 34	SE¼ SW¼ SE¼ SE¼ sec. 36, T. 96 N., R. 56 W.
MLN 35	SE¼ SE¼ SE¼ SE¼ sec. 33, T. 96 N., R. 55 W.
MLN 21	NW¼ NE¼ NE¼ NE¼ sec. 24, T. 96 N., R. 55 W.
MLN 8	NE¼ NE¼ NE¼ NE¼ sec. 04, T. 96 N., R. 54 W.

APPENDIX B

Commercially drilled wells and test holes not used in cross sections

The following list contains legal descriptions of private wells and test holes drilled by commercial drillers referred to in the text. Logs are available from the computer files at the South Dakota Geological Survey. Those with map location numbers (MLN) are also listed in appendix A.

WELL OR TEST HOLE	LEGAL DESCRIPTION
SDGS No. 1 Holzbauer Test	SE¼ NE¼ NE¼ SW¼ sec. 12, T. 93 N., R. 55 W.
Yankton Police Station (MLN 113)	NE¼ NE¼ NW¼ SW¼ sec. 18, T. 93 N., R. 55 W.
Yankton City Well *	SW¼ SW¼ NE¼ sec. 13, T. 93 N., R. 56 W.
Yankton West Park (MLN 112)	SE¼ SE¼ SE¼ NW¼ sec. 13, T. 93 N., R. 56 W.
Highway Contractor Well	NW¼ NE¼ NE¼ NE¼ sec. 03, T. 93 N., R. 57 W.
English Ski Jump	NE¼ NW¼ NE¼ SW¼ sec. 13, T. 93 N., R. 57 W.
Utica Town Well	NE¼ NE¼ sec. 07, T. 94 N., R. 56 W.
Merle Johnson Well	SW¼ SE¼ sec. 10, T. 95 N., R. 54 W.
Oscar Rempfer Well (MLN 16)	NW¼ NW¼ sec. 21, T. 96 N., R. 56 W.
Rittershaus No. 1 Test	NE¼ SW¼ sec. 29, T. 96 N., R. 56 W.
Leonard Gunderson Well	NE¼ SE¼ sec. 03, T. 96 N., R. 57 W.

* Referred to by Simpson (1960)

APPENDIX C

Descriptions of measured geologic sections in the Pierre Shale

WAKONDA LIME QUARRY

NE¼ NW¼ NW¼ SE¼ sec. 35, T. 95 N., R. 54 W.

Age	Formation	Member	Thickness in centimeters	Description	Comments
Quaternary	---	---		Till	
Cretaceous	Pierre	Mobridge	4.5	Marl, very light color to white; distinct contacts	
			≅ 56.5	Shale, light-gray to medium-dark-gray; noncalcareous to very highly calcareous at base with a mottled pattern, otherwise calcareous throughout; weathers with a platy to blocky fracture; contains 2-4 cm somewhat distinct light marl at 84.0 cm above base of member, and another poorly defined ≅ 7 cm marl ≅ 111.5 cm above base of member	Same as the 71.0 cm interval below, but with more distinct bedding at top
			≅ 0.5	Bentonite	
			71.0	Shale, light-gray to medium-dark-gray; noncalcareous to very highly calcareous at base with a mottled pattern, otherwise calcareous throughout; weathers with a platy to blocky fracture	
		Virgin Creek	5.5	Bentonite, yellowish-gray; noncalcareous; small to moderate amount of biotite at base with largest flakes up to 1 mm across, sharp basal and gradational upper contacts	
			16.5	Shale, dark-gray to grayish-black, noncalcareous; weathers with a blocky fracture; mottled with lighter-colored (very pale-orange) bentonite	
			2.0	Bentonite, very light-gray to light-gray, noncalcareous; small to moderate amount of very fine biotite flakes; basal contact sharp, upper contact gradational	
			25.5	Shale, grayish-black with lighter colored streaks and smears (probably weathering phenomena, or possibly bioturbation), noncalcareous; weathers with a blocky fracture	

WAKONDA LIME QUARRY – continued

Age	Formation	Member	Thickness in centimeters	Description	Comments
Cretaceous	Pierre	Virgin Creek (continued)	6.5	Bentonite, light-gray, noncalcareous; moderate amount of fine to very fine biotite flakes at base; weathered very little; some iron staining; jarosite and gypsum absent; basal contact sharp, upper contact gradational; shale inclusions with worm burrows near top	
			17.0	Shale, grayish-black mottled with light-brownish-gray, noncalcareous; weathers with a platy to blocky fracture; scattered laminar areas (worm burrows?, fecal pellets?; no calcite)	
			5.0	Bentonite, yellowish-gray, mottled with dark shale near the top which may be worm burrows, noncalcareous; moderately abundant biotite flakes at base; sharp basal and upper contacts	
			30.5	Shale, dark-gray mottled with light-olive-gray, noncalcareous; weathers with a platy to blocky fracture; some iron staining along joints (mostly) and bedding planes; very little jarosite and gypsum	
			2.5	Bentonite, pale-olive, noncalcareous; sharp basal contact, slightly gradational upper contact; weathered little; minor small biotite flakes at base	
			18.0	Shale, dark-gray to grayish-black, noncalcareous; fissile	
			7.5	Bentonite, pale-olive; noncalcareous; few small biotite flakes at base; minor iron staining; minor gypsum; bottom contact sharp, upper contact somewhat gradational	

WAKONDA LIME QUARRY – continued

Age	Formation	Member	Thickness in centimeters	Description	Comments
Cretaceous	Pierre	Virgin Creek (continued)	19.0	Shale, grayish-black to black, noncalcareous; weathers with a platy to blocky fracture; few fish remains present; some gypsum, jarosite, and iron staining, mostly along joints and some bedding planes; thin bentonite zones present	
		DeGrey	≅ 4.5	Shale, medium-dark-gray to dark-gray, noncalcareous; bentonitic; some gypsum, jarosite, and iron staining present, especially near bentonitic zones	
			≅ 6.0	Bentonite zone, pale-olive; bentonite interbedded with bentonitic shale; bentonite contains biotite	
			≅ 18.0	Shale, medium-dark-gray to dark-gray; noncalcareous; some gypsum, jarosite, and iron staining present	
			≅ 9.0	Bentonitic zone, pale-olive; bentonite interbedded with bentonitic shale; bentonite contains biotite	
			≅ 19.5	Shale, medium-dark-gray to dark-gray, noncalcareous; basal contact is sharp based on calcite content, but gradational based on color change; some gypsum, jarosite, and iron staining present, especially near bentonitic zones; Mosasaur bone fragments present	
		Crow Creek	271.0	Argillaceous micrite (“marl”), very pale-orange, highly calcareous at base; weathers with a platy to blocky fracture; contains numerous detrital grains in lowest 30 cm, which gradually disappear upward; some shale inclusions are as large as 5 x 5 mm; top is highly calcareous; shale clasts still present	

WAKONDA LIME QUARRY – continued

Age	Formation	Member	Thickness in centimeters	Description	Comments
Cretaceous	Pierre	Gregory	72.0	Shale, has a general greenish tinge background color, lighter color than underlying shale; generally noncalcareous so considered part of Gregory Member at present, but contains rare patches of minor calcite; weathers with a platy to blocky fracture; usually jarosite-, gypsum-, and iron-stained; top of member contains chunks with greenish grains that may have cleavage planes (phosphatic?); occur in zone 5.5 cm thick at very top of member; also contains white specks (dolomite?), possible fish remains, (black phosphate); possibly many other constituents; sharpest contact occurs at top of this zone; sample of upper 5.5 cm collected for analysis	
		Sharon Springs	60.0	Shale, noncalcareous; weathers with a platy to blocky fracture; gypsum, jarosite, and iron staining along bedding and joint surfaces; fish remains present (large amounts on some bedding planes, but others are nearly devoid of fish remains); contact with overlying Gregory Member gradational, picked where predominantly black shale changes upward into predominantly olive-black to light-brownish-gray to brownish-gray shale	
			10.0	Bentonite; noncalcareous; sharp basal contact, gradational upper contact; few biotite flakes near base; small amounts of gypsum, jarosite, and iron staining; upper contact picked at change from predominantly bentonite to predominantly shale	

WAKONDA LIME QUARRY – continued

Age	Formation	Member	Thickness in centimeters	Description	Comments
Cretaceous	Pierre	Sharon Springs (continued)	30.0	Shale; olive-black to brownish-black, noncalcareous; weathers with a platy to blocky fracture; some fish remains; jarosite, gypsum, and iron staining on bedding and joint surfaces	
			16.0	Bentonite, very pale-orange to pale-yellowish-orange; noncalcareous, minor jarosite, gypsum, and iron staining; sharp basal contact, gradational upper contact; no biotite seen at base; upper contact picked between predominantly bentonite and predominantly black shale	
			32.0	Shale, brownish-black to black, noncalcareous; platy weathering; some fish remains; iron staining, jarosite, and gypsum on joint surfaces; upper 10 cm is olive-gray and bentonitic with occasional very thin lenses of bentonite; shows blocky fractures from weathering	
			8.0	Bentonite, very pale-orange, noncalcareous; iron-stained at top and bottom; minor gypsum, no biotite seen at base; occasionally dark mottles (not pyrite)	
			20.5	Shale, dusky-yellowish-brown, noncalcareous; fissile to platy bedding, fish remains; minor jarosite and iron staining	
			1 – 3.5	Bentonite, freshest color is moderate-orange-pink, noncalcareous; pinches and swells, with some gypsum and minor jarosite staining, moderate iron staining	
			9.0	Shale; brownish-black, noncalcareous; weathers with a platy fracture; occasional fish remains; occasional jarosite staining on bedding planes and fracture surfaces	

WAKONDA LIME QUARRY – continued

Age	Formation	Member	Thickness in centimeters	Description	Comments
			15.0	Claystone, predominantly dark-yellowish-orange; limonite-stained; gypsum-cemented; containing 0 - 3 cm dominantly pinkish-gray bentonite mottled with medium-dark-gray to black detrital grains (MnO?)	
	Niobrara	---	---	---	Contact at 1,391 feet above sea level

NORTHWEST MARINDAHL LAKE

NW¼ NW¼ NW¼ NW¼ sec. 7, T. 95 N., R. 54 W.

Age	Formation	Member	Thickness in centimeters	Description	Comments
Quaternary	---	---	---	Till	
Cretaceous	Pierre	DeGrey	98.0	Shale, light-olive, mottled with olive-black, noncalcareous; weathers with a platy to blocky fracture; smeared yellowish-gray to light-olive-gray, noncalcareous bentonite seam with moderate, very small biotite flakes at top of exposure; smeared dusky-yellow to light-olive-brown, noncalcareous bentonite seam with a trace of very small biotite flakes at base of member. May be as much as 200 cm of shale, but badly slumped; initially thought only one bentonite seam was present	
		Crow Creek	100.0	Marl, very pale-orange, highly calcareous; minor iron staining; moderate number of shale clasts throughout (larger at bottom, maximum of 5 - 10 mm diameter); little detrital material at base except shale clasts	
		Gregory	112.0	Shale, dark-yellowish-brown to dusky-yellowish-brown, noncalcareous; fissile to platy; slight to moderate amount of jarosite and iron staining in lower half; little or no gypsum; upper 6.0 cm noncalcareous, but strongly mottled with mainly shades of yellow and orange; many detrital grains and white specks (thought to be dolomite, but none found in x-ray analysis, only 25 percent quartz)	
		Sharon Springs	47.0	Shale, olive-black mottled with dark-yellowish-brown at top; olive-black at base; noncalcareous; fissile to platy, few fish remains at base, none seen at top; slight iron staining; moderate jarosite and gypsum; upper contact picked at prominent color change	

NORTHWEST MARINDAHL LAKE – continued

Age	Formation	Member	Thickness in centimeters	Description	Comments
Cretaceous	Pierre	Sharon Springs (continued)	7.0 – 9.0	Bentonite, white except where jarosite-stained (moderate) and iron-stained (slight); no biotite noted; top contact somewhat undulatory (depositional?- or slump?-related); basal contact sharp	
			26.5	Shale, olive-black to brownish-black, noncalcareous; fissile (bottom) to platy (top); moderate jarosite staining, little or no iron staining; minor gypsum; some fish remains, but not as common as lower in section; basal 4 cm contains bentonitic shale inclusions	
			11.0	Bentonite, very pale-orange, noncalcareous; slight to moderate amount of jarosite; very minor gypsum; rare to occasional biotite flakes at base; sharp basal contact, gradational upper contact	
			29.0	Shale, olive-black to brownish-black, noncalcareous; minor iron, jarosite, and gypsum staining; fissile to platy (mostly fissile at base, mostly platy at top); fish remains present	
			17.5	Bentonite, grayish-yellow to yellowish-gray, noncalcareous; with highly bentonitic shale partings which are medium-gray to medium-dark-gray; slight to moderate jarosite and iron staining; little or no gypsum, biotite absent; contains noncalcareous shale streak 13.0 cm above base which pinches and swells from 0 to 6.0 cm thick; sharp basal contact, somewhat gradational upper contact	
			6.0	Shale, olive-black to brownish-black, noncalcareous; moderately to heavily iron-stained; some gypsum, minor jarosite; fissile to mostly platy; no fish scales observed	

NORTHWEST MARINDAHL LAKE – continued

Age	Formation	Member	Thickness in centimeters	Description	Comments
Cretaceous	Pierre	Sharon Springs (continued)	14.0	Shale, noncalcareous; highly iron-stained; heavily impregnated with gypsum	
	Niobrara	---	---	---	Contact at 1,352 feet above sea level

OLD CEMENT PLANT VALLEY

NE¼ SW¼ SW¼ NE¼ sec. 8, T. 93 N., R. 56 W.

Age	Formation	Member	Thickness in centimeters	Description	Comments
Cretaceous?	---	---	---	---	Covered
Cretaceous	Pierre	DeGrey	≅ 3	Bentonite seam	
			230.0	Shale(?)	Mostly covered, probably slumped.
			15.0	Claystone, dark-brown; noncalcareous; grades upward into gray shale	Probably slumped.
		Crow Creek	122.0	Marl	Similar to the described exposures of this member in the Wakonda lime quarry and northwest Marindahl Lake sections.
		Gregory	19.0	Claystone, dark-yellowish-brown and light-olive-gray, noncalcareous; lower 2 cm darker because of presence of dark laminae, possibly caused by phlogopite; small specks <0.5 mm, white, reddish-brown, and tan, of unknown composition, plus quartz grains occur throughout; sharp basal contact, gradational upper contact	
		Sharon Springs	84.0	Shale, pale-brown to pale-yellowish-brown, noncalcareous; dry; fractures present	
			5.0	Bentonite, pinkish-gray, noncalcareous; with jarosite staining; basal 1 cm indurated with much gypsum present; lower contact sharp, upper contact undulatory	
			57.0	Shale, dusky-yellowish-brown, noncalcareous; blocky to fissile, fractured, damp; with jarosite and limonite staining; fish scales throughout; very thin, <0.5 cm, bentonite seams present	
			21.0	Bentonite; pinkish-gray, noncalcareous; highly fractured, highly stained with jarosite	

OLD CEMENT PLANT VALLEY – continued

Age	Formation	Member	Thickness in centimeters	Description	Comments
Cretaceous	Pierre	Sharon Springs (continued)	13.0	Shale, olive-gray to dark-yellowish-brown, noncalcareous; highly fractured, blocky; fish scales present; fractures filled with veins which are indurated, gypsiferous, jarosite- and probably limonite-stained	
			12.0	Bentonite, noncalcareous, highly fractured; pinkish-gray with jarosite-stained fracture surfaces, plus about half the upper 4 cm with jarosite staining; basal and upper contacts undulatory	
			35.0	Shale, dusky-yellowish-brown, noncalcareous; highly fractured, blocky to laminated; fish scales present; fractures filled with veins which are indurated, gypsiferous, jarosite- and probably limonite-stained; damp	
			29.5	Claystone, olive-gray to dark-yellowish-brown, noncalcareous; highly fractured, blocky to laminated; fish scales present; fractures filled with veins which are indurated, gypsiferous, jarosite- and probably limonite-stained; upper contact is approximate	
			2.0	Bentonite, grayish-yellow to dusky-yellow, noncalcareous; extremely thin laminae of shale present; basal contact sharp, upper contact undulatory and interbedded with shale	

OLD CEMENT PLANT VALLEY – continued

Age	Formation	Member	Thickness in centimeters	Description	Comments
Cretaceous	Pierre	Sharon Springs (continued)	103.0	Claystone, dusky-yellowish-brown, noncalcareous; blocky, highly fractured, fish scales throughout; fractures filled with veins composed of noncalcareous clay or possibly altered bentonite with some gypsum, dusky-yellow; jarosite- and probably limonite-stained; basal indurated zone at bottom of 1.5 m deep pit could not be penetrated by shovel, but presumably lies above Pierre/Niobrara contact; indurated material is noncalcareous, gypsiferous, yellowish-brown, jarosite-stained; contact located in auxiliary pit, allowing total thickness of unit to be determined	
	Niobrara	---	---	---	Elevation of contact with overlying Pierre Shale estimated to be 1,330 feet above sea level (measured up from estimated position of 1,250-foot contour at bottom of valley)

LAKE PORT LOCALITY

(Composite Section)

Age	Formation	Member	Thickness in centimeters	Description	Comments
Upper, secondary trench in the NE¼ SE¼ SW¼ NE¼ NE¼ sec. 11, T. 93 N., R. 57 W.					
Quaternary	---	---	---	Till.	
Cretaceous	Pierre	Mobridge	≅ 250	Marl; includes cap of 10 to 30 cm of highly weathered mudstone(?)	See Lake Port Supplement for detailed description
Cretaceous	Pierre	Virgin Creek	1.5 – 2.0	Bentonite, light-olive-gray, noncalcareous; slight to moderate biotite throughout; moderately to highly weathered; moderately to highly iron-stained; both contacts sharp	
			69.0	Mudstone, mostly olive-gray to olive-black (wet surface) with some light-gray, noncalcareous to highly calcareous (from many white specks); blocky to very blocky, some weathering with conchoidal fracture; slight iron staining and moderate manganese staining	
			---	Bentonite streak	Same as the one at top of described portion of slumped block at the NW¼ SE¼ NW¼ NE¼ NE¼ sec. 11, T. 93 N., R. 57 W., see below
An intact slumped block (rotation is evident) in the NW¼ SE¼ NW¼ NE¼ NE¼ sec. 11 (≅ 12 m north of main exposure)					
Cretaceous	Pierre	Virgin Creek	0 – 0.3	Bentonite streak	Upper exposures badly disturbed
			32.0	Mudstone; blocky to very blocky; weathering with a conchoidal fracture; lowermost 8.0 cm is medium- to dark-gray, noncalcareous to slightly calcareous, with some stringers of highly calcareous marl in worm burrows(?); middle 8.0 cm is very light-gray, highly calcareous marl; uppermost 16.0 cm is pinkish-gray to very light-gray to medium-dark-gray, noncalcareous to highly calcareous, with slight to moderate iron staining and moderate manganese staining	This interval probably correlates to the 67.5 cm mudstone in the Lake Port Supplement

LAKE PORT LOCALITY – continued

Age	Formation	Member	Thickness in centimeters	Description	Comments
Cretaceous	Pierre	Virgin Creek (continued)	0 – 1.0	Bentonite streak, pinkish-gray, noncalcareous; 0.5 cm average thickness; slight but fresh iron staining; no biotite; bottom and top contacts are sharp	
			16.5	Mudstone, medium-light-gray to medium-dark-gray, noncalcareous but with moderately calcareous streaks and blebs; blocky; weathers in part with conchoidal fracture; with moderate iron and slight to moderate manganese staining	
			0 – 1.5	Bentonite, light- to very light-gray, noncalcareous; average thickness about 1 cm; with very slight iron staining (only slightly weathered); bottom contact sharp, top contact slightly gradational	
			19.0	Mudstone; weathers with blocky to conchoidal fracture; noncalcareous at base, moderately to highly calcareous in middle, and non-calcareous to slightly calcareous at top; occasional concretions at about middle of interval, probably composed of heavily iron-stained marl; medium-dark-gray at base, light-gray in middle, and medium-light-gray to medium-gray at top; moderate manganese staining, slight to moderate iron staining; few bivalves	
			1.0 – 1.5	Bentonitic mudstone, light-gray to medium-light-gray, noncalcareous; some very small biotite flakes at base; *Inoceramus* prisms at top, at least locally; top and bottom contacts are sharp, based on color	
			36.5	Mudstone, medium-light-gray to medium-dark-gray, noncalcareous to slightly calcareous, very calcareous in pockets of bivalve remains; weathers with blocky to conchoidal fractures; moderate manganese and slight iron staining	

LAKE PORT LOCALITY – continued

Age	Formation	Member	Thickness in centimeters	Description	Comments
Cretaceous	Pierre	Virgin Creek (continued)	0 – 1.0	Bentonite streak, white to very light-gray, noncalcareous, no biotite; sharp basal contact, gradational upper contact	
			61.5	Mudstone, light-gray to medium-gray, noncalcareous at base and top, variably calcareous throughout rest of interval with occasional bivalve fragments and worm burrows (the lighter the color the more calcareous); weathers with blocky to conchoidal fractures; brownish-black at the base where wet; moderate manganese staining; very thin bentonite streak 11.0 cm below top	
			1.0 – 1.5	Bentonite	Same as 1.5 cm bentonite, 20.0 cm shale, and 6.5 cm bentonite at top of section in NW¼ SE¼ NW¼ NE¼ NE¼ sec. 11, T. 93 N., R. 57 W., see below.
			16.5	Shale	
			6.0	Bentonite, yellow staining	
Main exposure in large stream cut in the NW¼ SE¼ NW¼ NE¼ NE¼ sec. 11, T. 93 N., R. 57 W.					
Cretaceous	Pierre	Virgin Creek	1.5	Bentonite, greenish-gray to dark-greenish-gray (5 GY series), noncalcareous; slight iron staining; trace of biotite at base; top and bottom contacts sharp; no worm burrows or shale clasts	
			20.0	Shale, grayish-black to black, very slightly calcareous; blocky; some iron staining	
			6.5	Bentonite, light-gray to medium-light-gray (weathers pale- to dark-yellowish-orange), noncalcareous; moderately iron-stained; minor biotite at base; worm burrows and shale clasts in upper 2.5 cm; very sharp basal contact, sharp upper contact	Same unit as 7.0 cm bentonite bed at base of described section in Lake Port Supplement.
			30.5	Shale, brownish-black, noncalcareous; platy to blocky; slight iron staining; minute *Inoceramus* shell fragments (prisms)	

LAKE PORT LOCALITY – continued

Age	Formation	Member	Thickness in centimeters	Description	Comments
Cretaceous	Pierre	Virgin Creek (continued)	12.0	Shale, brownish-black; noncalcareous; platy on surface weathers to a blocky fracture underneath; *Inoceramus* prisms; bentonite streak at top	
			0 – 2.0	Bentonite, medium-gray, noncalcareous; no biotite seen, nor any worm burrows or shale clasts; sharp bottom and top contacts	
			2.5	Shale, brownish-black, noncalcareous; bentonitic; weathers with a platy to very fine blocky fracture; some *Inoceramus* shell fragments (prismatic carbonate)	
			2.6	Bentonite, light-olive-gray, noncalcareous; some biotite throughout; no worm burrows or shale clasts; very sharp basal contact, sharp upper contact	
			34.0	Shale, brownish-black, noncalcareous; weathers with a platy to very fine blocky fracture; some *Inoceramus* shell fragments (prismatic carbonate)	
			41.0	Shale, brownish-black, noncalcareous; with slight iron staining; weathers with a platy to blocky fracture; bentonite streak at top	
			8.5	Bentonite, pale-yellowish-brown, noncalcareous; with slight iron staining; shale clasts and worm burrows in upper 3.0 cm; moderate amount of very fine biotite at base; very sharp basal contact, upper contact gradational and irregular	
			3.5	Shale, brownish-black, noncalcareous; with slight iron staining; weathers with a conchoidal to blocky fracture	

LAKE PORT LOCALITY – continued

Age	Formation	Member	Thickness in centimeters	Description	Comments
Cretaceous	Pierre	Virgin Creek (continued)	1.2 – 2.3	Bentonite, noncalcareous; some iron staining; moderate amount of fine biotite at base; shale clasts and worm burrows throughout, but more numerous at top; very sharp but slightly undulatory basal contact, and gradational irregular upper contact	
			15.2	Shale, brownish-black, noncalcareous; with slight iron staining; weathers with a conchoidal to blocky fracture; bentonite streak 2.7 cm from top, 0 – 1.5 cm thick, noncalcareous, greenish-gray (5 GY 6/1)	
			1.0	Bentonite, yellowish-gray, noncalcareous; no biotite at base; contains shale clasts and worm burrows throughout; sharp basal contact, gradational irregular upper contact	
			3.5	Shale, brownish-black, noncalcareous; weathers with a conchoidal to blocky fracture; with slight iron staining	
			4.0	Bentonite, greenish-gray, noncalcareous; some biotite at base; contains occasional shale clasts and worm burrows throughout; very sharp basal contact, sharp upper contact	
			7.0	Shale, brownish-black, noncalcareous; weathers with a platy fracture; with slight iron staining	
			0 – 2.0	Bentonite, light-olive-gray, noncalcareous; some biotite flakes at base; shale blebs throughout, especially at top, some worm burrows; sharp basal contact, gradational and irregular upper contact	
			51.0	Shale, olive-black, noncalcareous; weathers with a blocky, often conchoidal fracture; with slight iron staining; rare to occasional limestone concretions at top; slight gypsum content	

LAKE PORT LOCALITY – continued

Age	Formation	Member	Thickness in centimeters	Description	Comments
Cretaceous	Pierre	Virgin Creek (continued)	57.5	Shale, grayish-black, noncalcareous; blocky to massive, some weathering with a conchoidal fracture; with slight iron staining; slight gypsum content; bentonite streak at top	
			2.5	Bentonite, greenish-gray, noncalcareous; some very fine biotite, especially at base; shale fragments throughout, becoming very numerous at the top; bottom contact sharp, top contact gradational	
			9.0	Shale, grayish-black to black, noncalcareous; massive	
			1.5	Bentonite, greenish-gray, noncalcareous; contains shale clasts, few flakes of biotite; top and basal contacts sharp but undulatory	Average thickness given
			5.5	Shale, grayish-black to black, noncalcareous; massive	
			6.0	Shale, grayish-black to black, noncalcareous; massive; noncalcareous bentonite streak at top	
			0 – 2.0	Bentonite streak, medium-light-gray to medium-gray, noncalcareous; contains shale fragments throughout, biotite was not seen	
			---	Shale, black, noncalcareous	Not measured, as partly below water line in pit at base of trench

LAKE PORT LOCALITY – continued

Age	Formation	Member	Thickness in centimeters	Description	Comments
Cretaceous	Pierre	?	268.0	---	Missing interval; contact between the DeGrey and Virgin Creek Members probably occurs in this interval. Thickness determined by measuring between the 2.5 cm bentonite described above and the 3.2 cm bentonite described below (in intermediate section at the NE¼ SE¼ SW¼ NE¼ NE¼ sec. 11, T. 93 N., R. 57 W.)
Intermediate section in vertical trench in stream cut at the NE¼ SE¼ SW¼ NE¼ NE¼ sec. 11, T. 93 N., R. 57 W.					
Quaternary	---	---	---	Till	
Cretaceous	Pierre	DeGrey	34.5	Shale, olive-gray with a few mottles of olive-black, noncalcareous; fissile to platy; weathered at top	
			40.5	Shale, olive-gray with a few mottles of olive-black, noncalcareous; fissile to platy; bentonite streak at top	
			3.2	Bentonite, dark shade of yellowish-gray, noncalcareous; with slight iron staining; biotite flakes uncommon; worm burrows in upper 2.0 cm, filled with dark overlying shale; top and bottom contacts sharp	
			88.0	Shale, mottled olive-gray and olive-black, noncalcareous; generally weathers with a platy fracture; with slight iron staining; two bentonite streaks, one 45.0 cm above base and is nonweathered, the second 54.0 cm above base of unit and is moderately to heavily jarosite- and iron-stained	
			0.8	Bentonite, pale-yellowish-brown to dark-yellowish-brown, noncalcareous; a few tiny biotite flakes; top and bottom contacts sharp	

LAKE PORT LOCALITY – continued

Age	Formation	Member	Thickness in centimeters	Description	Comments
Cretaceous	Pierre	DeGrey (continued)	47.0	Shale, olive-gray to olive-black, noncalcareous; platy to blocky; with slight iron staining; very slight amount of gypsum present	
			1.5	Bentonite, light shade of pale-yellowish-brown, noncalcareous; with slight iron staining; no biotite; worm burrows throughout; top and bottom contacts sharp	
			12.5	Shale, olive-black to brownish-black, noncalcareous; weathers with a blocky fracture; with slight iron staining	
			3.0	Bentonite, light-olive-gray, noncalcareous; with slight to moderate manganese staining and slight iron staining; numerous tiny biotite flakes concentrated near the middle; worm burrows throughout; sharp basal and top contacts	
			15.5	Shale, olive-black to brownish-black, noncalcareous; weathers with a blocky fracture; with slight iron staining	
			8.5	Bentonite, noncalcareous; some biotite at base, mostly very fine flakes; biotite-rich bentonite interbedded and interlensing with bentonite layers and lenses that are totally lacking biotite; biotite-rich bentonite is medium-light-gray and bentonite lacking biotite is light-olive-gray; appearance is confusing and not understood; worm burrows in upper 2.0 cm filled with dark overlying shale; basal and upper contacts sharp	
			15.5	Shale, medium-dark-gray to dark-gray, noncalcareous; blocky to massive; no weathering products	
		Crow Creek	---	---	Contact with Crow Creek Member

LAKE PORT LOCALITY – continued

Age	Formation	Member	Thickness in centimeters	Description	Comments
Description transferred downstream to vertical trench in stream cut at the SW¼ NW¼ NE¼ SE¼ NE¼ sec. 11, T. 93 N., R. 57 W.					
Quaternary	---	---	---	Till	
Cretaceous	Pierre	DeGrey	17.0	Shale, weathered, with a 2.5 cm bentonite seam running through middle of interval	
		Crow Creek	109.0	Marl, generally pale-yellowish-brown to grayish-orange, very calcareous; contains numerous shale particles, some up to 5 to 7 mm in diameter, but gradually disappear toward top of unit; with some iron staining; weathers with a blocky fracture and a nodular weathering pattern; upper 12.5 cm worm burrowed, with burrows filled with overlying DeGrey shale; sharp upper contact; rock samples with shale clasts and worm burrows collected	
			6.0	Marl, light-brownish-gray to brownish-gray, highly calcareous; with numerous detrital grains and white blebs, some red blebs; bottom contact sharp; upper contact gradational, picked where there is a marked decrease in white blebs. X-ray analysis: 22 percent quartz; 16 percent dolomite, 15 percent calcite, 45 percent clay, trace of gypsum	
		Gregory?	5.5	Shale, olive-gray to olive-black, noncalcareous; fissile to platy, no jarosite, but some gypsum present; no fish remains seen	
		Sharon Springs	1.0	Bentonite, grayish-orange, noncalcareous; no biotite; contains jarositic mass 0.85 cm thick; worm burrows throughout, containing dark shale; sharp lower and upper contacts	

LAKE PORT LOCALITY – continued

Age	Formation	Member	Thickness in centimeters	Description	Comments
Cretaceous	Pierre	Sharon Springs (continued)	25.0	Shale, brownish-black to olive-black, noncalcareous; fissile to platy; some jarosite and gypsum; slightly more fish remains than in shale units below	This interval is equivalent to the section described below (8 m downstream). The 3.0 to 3.5 cm thick bentonite is the same one as the 1.0 to 2.5 cm bentonite 8 m downstream (see below)
			3.0 – 3.5	Bentonite, very pale-orange, noncalcareous; no biotite noted; sharp upper and lower contacts	
			49.5	Shale, brownish-black, noncalcareous; fissile to platy; some jarosite and iron staining; some gypsum; fish remains are rare	
			0 – 1.5	Bentonite, noncalcareous, highly weathered with much gypsum and jarosite; too weathered to determine original color or biotite content; sharp top and basal contacts, where present; laterally changes abruptly into bentonitic shale	
			19.5	Shale, olive-black to brownish-black, noncalcareous; fissile to platy; with some iron staining; some gypsum and jarosite; very few fish remains present	
			7.5	Bentonite; yellowish-gray	
Description transferred about 8 m downstream to trench in stream cut; trench extended into pit below water level (water removed to reveal Pierre-Niobrara contact)					
Cretaceous	Pierre	Gregory?	3.5	Shale, light-olive-gray to olive-gray, noncalcareous; generally fissile, sometimes platy; minor gypsum, no jarosite; no fish remains	
		Sharon Springs	19.0	Shale, light-olive-gray, noncalcareous; fissile to platy; with moderate amounts of jarosite and gypsum on bedding planes and joint surfaces; fish remains present	

LAKE PORT LOCALITY – continued

Age	Formation	Member	Thickness in centimeters	Description	Comments
Cretaceous	Pierre	Sharon Springs (continued)	1.0 - 2.5	Bentonite; highly weathered with large amounts of jarosite, gypsum and iron staining; weathering too severe to note color or biotite content; sharp top and basal contacts	Range in thickness based on natural exposures 3 to 4 m on either side of trench; it is only 1.0 cm in the trench. This is the same bentonite as the 3.0 to 3.5 cm bentonite 8 m upstream (see above)
			52.0	Shale, olive-black to brownish-black, noncalcareous; platy to blocky moderate amounts of gypsum and jarosite along bedding planes; moderate fish remains	
			0.5 – 1.5	Bentonite, noncalcareous; pinches and swells, moderately to highly weathered with large amounts of jarosite and gypsum and some iron staining; too thin and weathered to note original color and biotite content	
			20.5	Shale, olive-black to brownish-black, noncalcareous; generally platy; jarosite and gypsum common on bedding planes and joint surfaces; moderate amount of fish remains	
			7.5	Bentonite, yellowish-gray, noncalcareous; with moderate jarosite and iron staining; little if any biotite at base; upper 3.0 cm contains burrows filled with dark shale; sharp upper and basal contacts	
			66.0	Shale, olive-black to brownish-black, noncalcareous; massive, but becomes platy and fissile in upper 24.0 cm; lower 13.0 cm moderately iron-stained, rest of unit occasionally iron-stained; jarosite staining prominent in upper 24.0 cm; some gypsum on joint surfaces and bedding planes, particularly in upper one-third of unit; occasional fish remains on bedding planes	

LAKE PORT LOCALITY – continued

Age	Formation	Member	Thickness in centimeters	Description	Comments
Cretaceous	Pierre	Sharon Springs (continued)	6.0	Bentonite, medium-light-gray, mottled with olive-gray, noncalcareous; with very little weathering; few biotite flakes scattered throughout; contains alternating light and dark laminae; sharp upper and basal contacts	
			11.5	Shale, dusky-yellowish-brown, noncalcareous; massive; fish remains moderate in number	
			8.5	Bentonite, medium-gray to medium-dark-gray, noncalcareous; unweathered; rare biotite flakes scattered throughout, some pyrite; sharp upper and basal contacts	
	Niobrara	---	---	Chalk, olive-black, slightly to moderately calcareous; unweathered, massively bedded; with a few white specks (microfossils?); few fish remains	Elevation of contact is 1,342 feet above sea level

LAKE PORT SUPPLEMENT

NW¼ SW¼ SW¼ NE¼ NE¼ sec. 11, T. 93 N., R. 57 W.

Age	Formation	Member	Thickness in centimeters	Description	Comments
Quaternary	---	---	---	Till	
Cretaceous	Pierre	Mobridge	160+	Marl and mudstone, generally grayish-orange mottled with dark-yellowish-brown, but also very pale-orange, or dark shade of pale-yellowish-brown, or light-olive-gray to olive-gray, slightly to moderately calcareous; interbedded, with gradational contacts between the marl and the mudstone; pale-yellowish-orange to dark-yellowish-orange iron staining; weathers with a blocky fracture	
			< 1	Bentonite streak; highly weathered, very irregular; large gypsum content, moderate iron staining	
			17.5	Mudstone, predominantly pale-yellowish-brown to dark-yellowish-brown, slightly calcareous; blocky	
			< 1	Bentonite streak; highly weathered; large gypsum content, moderate iron staining	
			91.0	Marl, yellowish-gray to light-olive-gray to grayish-orange, medium-light-gray or medium-gray (somewhat mottled); slightly to highly calcareous; blocky; colors partly masked by iron staining	
			< 1	Bentonite streak; highly weathered; considerable gypsum and iron staining	
			19.0	Marl, light-olive-gray, moderately calcareous; blocky, some gypsum, slight iron staining	
			12.5	Marl, yellowish-gray, moderately calcareous; blocky, slight iron staining	

LAKE PORT SUPPLEMENT – continued

Age	Formation	Member	Thickness in centimeters	Description	Comments
Cretaceous	Pierre	Mobridge	97.5	Marl, very light-gray with some pockets of medium-light-gray to medium-gray, highly calcareous, but moderately so in pockets; (darker color is less calcareous); blocky; slight iron staining	
		Virgin Creek	1.5	Bentonite	
			81.0	Mudstone	
			< 1	Bentonite streak	
			61.5	Mudstone	
			< 1	Layer of *Inoceramus* fragments	
			9.5	Mudstone	
			0 – 1.0	Bentonite	
			67.5	Mudstone	See described section from Lake Port slumped block in the NW¼ SE¼ NW¼ NE¼ NE¼ sec. 11 (≅ 12 m north of main exposure)
			1.0	Bentonite	
			15.0	Mudstone	
			< 1	Bentonite streak	
			68.0	Shale and mudstone	
			2.0	Bentonite	
			27.0	Mudstone	
			7.0	Bentonite, unweathered to heavily iron-stained	Same bentonite as 6.5 cm bentonite upper part of the Lake Port main exposure in NW¼ SE¼ NW¼ NE¼ NE¼ sec. 11, T. 93 N., R. 57 W.

LESTERVILLE RECREATION AREA

SE¼ NE¼ SE¼ SW¼ sec. 16, T. 93 N., R. 57 W.

Age	Formation	Member	Thickness in centimeters	Description	Comments
Mobridge Member slumped down over the Virgin Creek Member and the upper part of the DeGrey Member to middle of the 2.5 cm bentonite					
Cretaceous	Pierre	DeGrey	16.0	Shale, dark-greenish-gray, noncalcareous; platy to blocky	Topsoil developed on DeGrey
			2.5	Bentonite, yellowish-gray, noncalcareous; no biotite noted, moderate amount of gypsum; bottom contact reasonably sharp, top contact gradational; contacts based on color change, as some shale appears to occur throughout	
			13.5	Shale, dark-greenish-gray, noncalcareous; platy to blocky; occasional iron staining and iron oxide blebs, jarosite and gypsum nodules.	
		Crow Creek	128.0	Marl, dark shade of very pale-orange, highly calcareous; contains shale clasts throughout, up to 5 mm in maximum diameter, but slightly less concentrated and smaller (2 mm) near top; shale clasts may have bluish tint; top 14.0 cm is worm-burrowed, burrows filled with shale of the DeGrey Member; sharp basal contact, and reasonably sharp upper contact	
		Gregory?	13.0	Shale, probably very pale-orange, upper 5.0 cm is calcareous, but lower 8.0 cm is noncalcareous; heavily weathered; manganese-stained, moderately iron-stained; moderate amount of gypsum; contains numerous detrital grains, grading out only slightly toward the top, mostly quartz grains and white specks, probably dolomite; "salt and pepper" appearance	
		Sharon Springs	14.0	Shale, olive-brownish-black, noncalcareous; fissile to platy; moderate jarosite and slight iron staining; slight gypsum; some fish remains	

LESTERVILLE RECREATION AREA – continued

Age	Formation	Member	Thickness in centimeters	Description	Comments
Cretaceous	Pierre	Sharon Springs (continued)	3.5	Bentonite, very pale-orange, noncalcareous; moderate jarosite staining, slight iron staining; no biotite noted; sharp top and bottom contacts	
			48.0	Shale, olive-black to brownish-black, noncalcareous; fissile at bottom, grading upward into platy or even blocky fracture from weathering at top; moderate jarosite and slight iron staining on bedding planes; little or no gypsum, few fish remains	
			1.0 – 1.5	Bentonite and bentonitic shale grading laterally into each other, pale-yellowish-orange to grayish-orange, noncalcareous; no biotite noted; sharp top and basal contacts	
			3.0	Shale, grayish-brown, noncalcareous; blocky; with little to very little iron and jarosite staining; little gypsum present; some fish remains	
			7.5	Shale, dark-yellowish-brown to dusky-yellowish-brown, noncalcareous; fissile; moderate iron staining along bedding planes, moderately iron-stained throughout; moderate gypsum; too weathered to permit determination of presence of fish remains	
			8.8	Bentonite, very pale orange, noncalcareous; heavily jarosite- and iron-stained at top, moderately so at bottom, only slightly so in middle; no biotite at base; both top and basal contacts are sharp; upper 6.0 cm contains black-shale-filled worm burrows, slight to moderate in number	
			6.0	Shale, noncalcareous; highly gypsiferous and weathered; some jarosite and iron staining; probably represents the lowermost shale in the member	

LESTERVILLE RECREATION AREA – continued

Age	Formation	Member	Thickness in centimeters	Description	Comments
Cretaceous	Niobrara	---	---	Chalk, very pale-orange, highly calcareous; with numerous white specks; weathers with a blocky fracture	Elevation of formation contact is 1,322 feet above sea level