Geology of the Yankton Area South Dakota and Nebraska

GEOLOGICAL SURVEY PROFESSIONAL PAPER 328

Prepared as part of the program of the Department of the Interior for the development of the Missouri River basin

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CONTENTS

ILLUSTRATIONS

[Plates 1–3, 10, and 13 in pocket]

TABLES

GEOLOGY OF THE YANKTON AREA, SOUTH DAKOTA AND NEBRASKA

By HOWARD E. SIMPSON

ABSTRACT

The Yankton area is in southeastern South Dakota and northeastern Nebraska; it consists of two 15-minute quadrangles and parts of four others, and includes 584 square miles. The striking geomorphic feature is the east-trending Missouri River trench which bisects the area; the Loess Hills lie to the south, and the James Valley lowland to the north. The lowland is broken by three drift-mantled bedrock ridges separated by broad, arcuate, drift-filled depressions. The western edge of the lowland is marked in South Dakota by the gently sloping flank of the Coteau du Missouri, and in Nebraska by a prominent escarpment which is an extension of the coteau.

Pre-Pleistocene strata range in age from Precambrian through Pliocene, and are chiefly of Late Cretaceous age. The rocks that crop out consist of argillaceous limestone, shale and claystone, marl, sand, and partly indurated gravel. All are of marine origin except the sand and gravel. Together they constitute three surface formations: the Niobrara formation and Pierre shale of Late Cretaceous age, and the Ogallala formation of Pliocene age. Beneath these formations are others known only locally from well cuttings, logs, and cores. They consist predominantly of marine shale and continental sandstone and minor amounts of marine limestone and siltstone. These strata constitute the Dakota sandstone of Early Cretaceous age, and the Graneros shale, Greenhorn limestone and Carlile shale of Late Cretaceous age. Of these, the Dakota sandstone contains members which may be equivalents of the Lakota sandstone and the Fuson shale. Pre-Cretaceous formations are the Sioux quartzite of Precambrian age, and an unnamed crystalline rock of inferred Precambrian age.

Deposits of Pleistocene and Recent age mantle the bedrock formations except along the walls of the Missouri River trench. Continental glaciers invaded the area during the Kansan and Illinoian stages, and the Iowan, Cary, and Mankato substages of the Wisconsin stage. Each glacier deposited till and stratified drift. Glacial deposits are separated stratigraphically by nonglacial deposits and buried soil profiles. The nonglacial deposits include Loveland, Leighton and Willman's Farmdale, Iowan and Tazewell, Cary, and Mankato loesses, and gravelly sand of western origin correlated with the Grand Island formation of late Kansan age. Buried soils identified are of Sangamon, Farmdale, and Cary-Mankato age. Recent deposits are of post-Cary age in part, but are chiefly post-Mankato; they include landslide deposits, swale deposits, undifferentiated alluvium and colluvium, terrace alluvium and tributary correlatives, flood plain alluvium, alluvial fan deposits, and eolian sand.

Principal structural features of the bedrock strata include joints, faults of small displacement, and minor warps. The most distinctive characteristics, however, is the nearly horizontal attitude of the Cretaceous formations which dip about 4 feet per mile a little north of west. The joints constitute two almost vertical sets, a principal set that strikes N. 62° W., and a secondary set that strikes north. Faults are generally normal in relative movement, but at least one is a strike-slip fault, and one is an apparent thrust fault; the maximum displacement is about 4 feet. Local differences as great as 35 feet in the altitude of the contact of the Niobrara formation and Pierre shale may have been caused by gentle warping or folding, or by differential erosion or sedimentation.

Modern landforms in the vicinity of Yankton are the result chiefly of geologic processes which have been active in post-Pliocene time. In general, Pleistocene time has been characterized by deposition during glacial stages and erosion during intervals between. As a result available evidence pertaining to landform development before the Cary substage has largely been destroyed, or mantled by late Wisconsin deposits. In contrast changes during the Cary and Mankato substages and the Recent epoch are well recorded by the same deposits.

Geormorphic development of the area is primarily a series of drainage changes. Each glacier that entered or crossed the area blocked valleys of the existing drainage system and forced the rivers to abandon their courses and cut new channels along or beyond the glacier margin. Most of these channels were occupied only temporarily and now are broad, shallow valleys in the upland south of the Missouri River trench. The old drift-filled courses not reoccupied by streams on recession of the ice are represented by broad, elongate shallow depressions; the ridges that lie between these old courses thus are segments of former drainage divides.

Probably the most significant geomorphic event was the formation of the Missouri River by glacial diversion during the Illinoian stage. At this time an ancient Niobrara River, then the master stream of the Yankton area, was diverted from its pre-Illinoian course. At the glacial maximum the water escaped along the ice front through a channel of late Kansan age. Apparently the channel was deepened enough to prevent return of the river to its earlier course when the ice receded. The Missouri River was diverted in turn by Iowan and Cary glaciers but returned to the trench after each retreated. During the Mankato sustage the ice again entered the trench but this time failed to force the river from it.

Geologic history inferred from the pre-Pleistocene formations is largely restricted to Cretaceous time, for little is known of the Precambrian rocks; Paleozoic, Triassic, and Jurassic strata are absent, and Tertiary strata are represented by a single formation. During the latter part of the Early Cretaceous epoch continental sediments accumulated on the eroded surface of Precambrian rocks. In early Late Cretaceous time an encroaching epeiric sea covered the region, and several hundred feet of marine sediments were deposited before the sea withdrew. Laminae in certain calcareous strata suggest that conditions of upwelling comparable to those that occur today off the southern California coast existed from time to time. Fluvial sediments subsequently were deposited during Tertiary time on the eroded surface of Cretaceous rocks. These were mantled in turn by till and outwash of at least five Pleistocene glaciers. During the recession of each ice sheet, silt derived from outwash was deposited as loess on the uplands and terraces by predominantly northwesterly winds. During interglacial intervals weathering produced soil profiles, and erosion tended to strip both soils and prior deposits from the upland. Time since the retreat of the last glacier has been characterized by a multiple sequence of alluvial filling and dissection within the Missouri River trench and by the accumulation of landslide deposits, swale deposits, and colluvium elsewhere.

Natural resources of economic value consist chiefly of construction materials which may be divided into two groups: those presently available, and those that require thorough investigation before development. The first group includes materials for earth fill, asphaltic paving filler, concrete aggregate, plaster sand, and road metal, and riprap and building stone for certain types of construction. The second group includes limestone and shale for portland cement, shale for expanded light-weight aggregate, and loess for sintered light-weight aggregate. Other natural resources include water, and rich agricultural soils developed on alluvium, loess, and till. Water is obtained from three chief sources: the Missouri River, alluvial fills occupying the Missouri and James River trenches and preglacial valleys, and artesian supplies from sandstone members of the Dakota. No evidence of significant metallic or fuel resources is known, nor did readings with a geiger counter indicate the presence of radioactive materials.

INTRODUCTION

Knowledge of bedrock formations underlying the northern Great Plains has advanced steadily since Meek and Hayden first subdivided the Cretaceous strata of Nebraska Territory in 1862. Surficial deposits generally have been ignored or lumped together although they compose a ubiquitous mantle which effectively conceals the bedrock over hundreds of square miles. Since 1946 extensive detailed mapping of both the bedrock and surficial deposits has been accomplished in this region as a result of the program of the Department of Interior for the development of the Missouri River drainage basin. This report is a product of the U.S. Geological Survey's participation in that program.

The Yankton area is of geologic interest for several reasons: (1) members of the Niobrara formation have not been differentiated previously on field evidence, (2) glaciers representing several stages and substages entered or crossed the area and left a nearly unbroken record of post-Kansan glaciation, and (3) Pleistocene deposits and abandoned glacial diversion channels permit reconstruction of the preglacial drainage pattern and the post-Kansan drainage history, and indicate the date of origin of the Missouri River in southeastern South Dakota.

The purpose of the investigation was: (1) to compile a detailed geologic map of both bedrock formations and surficial deposits, (2) to subdivide exposed bedrock formations into their respective members, (3) to identify and describe surficial deposits and correlate them with deposits of known age in adjacent States, (4) to reconstruct geologic history, and (5) to study and evaluate exposed rocks so that potentially valuable resources might be effectively explored and utilized.

An additional purpose was to provide geologic information concerning the area surrounding the Gavin Point Dam. This dam is one of several constructed across the Missouri River and its larger tributaries by the Corps of Engineers, U.S. Army, and the Bureau of Reclamation. The dam lies about 4 miles west of Yankton, and is rolled-earth embankment approximately 9,600 feet long and 72 feet high, with the spillway, powerhouse, and intake channel at the south abutment. The reservoir will extend upstream 37 miles to a point about halfway between Springfield, S. Dak., and Niobrara, Nebr. The dam will regulate discharge into the lower Missouri River, and will generate 100,000 kilowatts.

LOCATION AND SIZE OF AREA

The Yankton area is partly Yankton and Bon Homme Counties, S. Dak., and partly in Cedar and Knox Counties, Nebr. It includes two 15-minute quadrangles and parts of four others, as shown in figure 1. The name "Yankton area" is informally applied to the total area of 584 square miles. In order to interpret properly many of the features observed, it was necessary to make a reconnaissance study of Pleistocene deposits that lie chiefly to the west and south of the area; this reconnaissance covered an additional 475 square miles.

PREVIOUS GEOLOGIC INVESTIGATIONS

Early geologic investigations that accompanied settlement of this and other western regions were all of reconnaissance nature. The earliest observations in the Yankton area were recorded by Merriwether Lewis and William Clark (1904, v. 1, p. 124-139) in the journal of the Lewis and Clark Expedition; they referred to bluffs of "*White* Clay Marl or Chalk" at various localities. On the return journey Lewis and Clark collected a few fossils at the Great Bend of the Missouri River in central South Dakota, which led Morton (1830, p. 247, and 1841, p. 106) to conclude that strata exposed along the upper Missouri were of Cretaceous age. In 1855 James Hall and F. B. Meek described fossils collected by Meek and F. V.

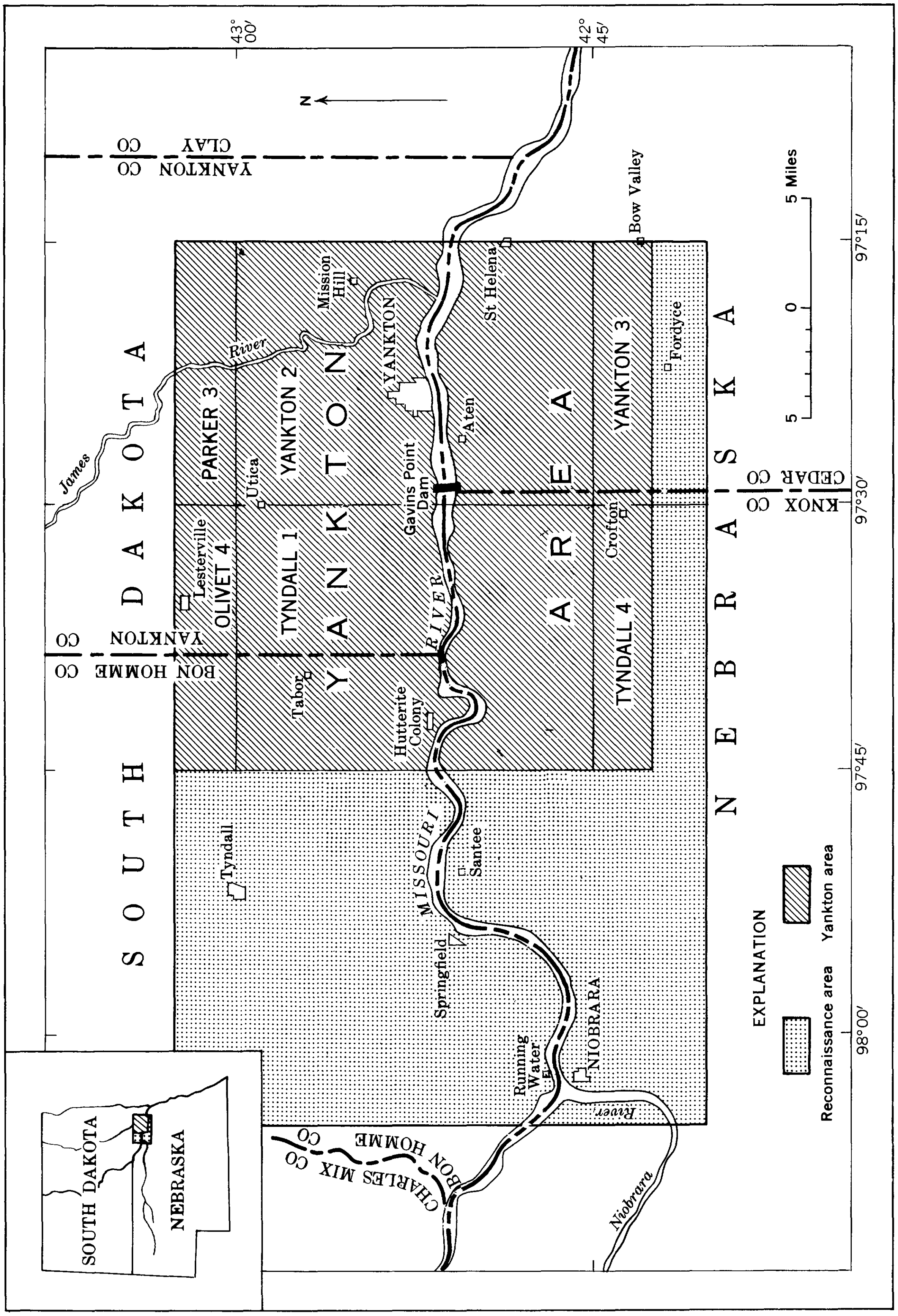

FIGURE 1.—Index map of the Yankton area, South Dakota and Nebraska; significant quadrangles are identified by name and number.

Hayden in 1853 along the upper Missouri River, and made (p. 405) the initial five-fold division of Cretaceous beds which essentially is followed still. The first published reference to surficial geology and Pleistocene history was by G. K. Warren (1869) as a result of an expedition to investigate the upper Mississippi, the Minnesota, and Wisconsin Rivers. He concluded (p. 311) that the southwestern limit of glacial drift was the Missouri River, which originated as a marginal stream, and that the James River and others originated similarly during retreat of the glacier.

During the last half of the past century, agricultural expansion and the increasing population of the region drew attention to a growing need for adequate, dependable water supplies. To meet this need geologists turned to the study of glacial deposits as well as bedrock formations, for both were potential sources. About 1880 this expansion of geologic interest changed the emphasis from exploration to economic geology, an emphasis that has accompanied the growth and development of the region.

In the early 1880's J. E. Todd began a reconnaissance study of both the bedrock formations and surficial deposits in southeastern South Dakota, and between 1885 and 1923 published several reports containing references to the Yankton area. These reports include geologic folios (Todd, 1903a, 1903b) at a scale of 1:125,000 for the Olivet and Parker quadrangles, South Dakota, the first published geologic maps for any part of the Yankton area at a scale larger than 1:1,000,000. Todd's reports are significant because they include almost the only data on Pleistocene deposits in southeastern South Dakota and northeastern Nebraska published before 1950, and because the framework he established is mainly correct today.

N. H. Darton published four reports between 1896 and 1909 that discussed geology and underground water resources of southeastern South Dakota. Some of these reports include logs obtained from well drillers, and, with the exception of recent test drilling at the Gavins Point Dam, constitute the chief source of subsurface data in the vicinity of Yankton.

By about 1920, geologists were keeping pace with the need for additional supplies of ground water and turned to the location and development of other natural resources. Most of the resulting reports are concerned with the stratigraphy of the region, and a few papers are directly concerned with, and contain results of, specific investigations in the vicinity of Yankton. These include publications chiefly of the South Dakota Geological Survey (Bolin, 1952; Caddes, 1947; Curtiss, 1950; Petsch, 1946; Rothrock, 1925, 1931), the Nebraska Geological Survey (Loetterle, 1937, Lugn, 1935), and the University of Nebraska State Museum (Schultz, Leuninghoener, and Frankforter, 1951). In addition there are unpublished theses written by N. C. Georgeson for the University of Iowa, and by L. W. Hewitt and J. J. Schulte for the University of Nebraska.

Since about 1945 geologic reports have begun to reflect in purpose or content a growing interest in effective land utilization of the region. The present report is an expression of this interest, as are reports by Warren and Crandell (1952), and Crandell (1958) and unpublished dissertations for Yale University by Crandell in 1951 and H. E. Simpson in 1952.

FIELDWORK

This report is the result of fieldwork during the years 1947 through 1952.

Natural and artificial exposures are numerous in the area, but commonly are insufficient in number and inadequate for detailed study owing to a widespread mantle of colluvium. A hand auger was used to obtain additional information, and more than 4,000 holes 2 to 5 feet deep were augered in the course of the investigation. To obtain information from greater depth, 6 holes were bored at selected localities to depths as great as 75 feet with a truck-mounted power auger.

Geologic data were plotted on aerial photographs which provided stereoscopic coverage at a scale of 1:20,000, and which were obtained from the Agricultural Adjustment Administration; the data were subsequently transferred to a planimetric base compiled at 1:48,000 from Bureau of Land Management township plats. Altitudes and heights generally were determined to within 3 feet of accuracy by altimeter. Drainage and culture were taken from the photographs with only slight modification; changes since the date of photography (1940 and 1941) are of little significance to the present investigation.

Published topographic maps covering parts of the area include two Missouri River strip maps prepared by the Corps of Engineers: the Rulo, Nebr., to Yankton, S. Dak., series, scale 1:24,000, and the Gavins Point, S. Dak., to Stanton, N. Dak., series, scales 1:24,000 and 1:12,000. Four topographic quadrangle maps published by the U.S. Geological Survey are also available. These are the 30-minute Olivet and Parker quadrangles, South Dakota, and the 7½-minute Niobrara and Verdigre NE quadrangles, Nebraska.

ACKNOWLEDGMENTS

During the course of both field and office work the writer conferred with scientists of various State and Federal agencies. These conferences yielded technical data, general information, and suggestions that have contributed to the report. This friendly cooperation is sincerely appreciated, and recognition is due several agencies and many individuals.

I am particularly indebted to R. F. Flint, D. R. Crandell, W. E. Benson, R. W. Lemke, and C. R. Warren, all of the U.S. Geological Survey, who have been of great help in the discussion of common problems. Helpful suggestions also resulted from conferences with E. C. Reed (Nebraska Geological Survey), C. B. Schultz and W. D. Frankforter (University of Nebraska State Museum), James Thorp (then Division of Soil Survey, Department of Agriculture), M. M. Leighton, (Illinois Geological Survey), and E. M. Swift (Corps of Engineers, Gavins Point Project). During 1951 R. E. White, geologist, was assigned to the project for 8 months; White mapped the upper and lower contacts of the Pierre shale along the Missouri River in Knox County, Nebr., and helped in compilation of office data. Summer field assistants included R. B. O'Sullivan (1947), C. K. Ham (1948), F. C. Witmer (1950), and John Weber (1951). To all, and to Elizabeth Simpson, my sincere thanks.

GEOGRAPHY

The topography of the Yankton area, which lies at the western margin of the Central Lowland (Fenneman, 1928; see also Flint, 1955, fig. 1, and Condra, 1946, p. 42) may be characterized as a gently rolling surface which rises slowly westward. The surface is broken by two deep stream-cut trenches and several low, moderately rolling ridges. The general surface is from 1,300 to 1,375 feet above sea level, and altitudes range from minimums of 1,155 to 1,190 feet along the Missouri River to a maximum of nearly 1,800 feet 3 miles south of the river; local relief is commonly less than 20 feet.

The most striking feature is the steep-walled Missouri River trench which bisects the area from west to east. The topographic floor of the trench is composed of a flood plain and remnants of two fill terraces. The flood plain is scarred by abandoned meanders, low scarps, and marshy chutes. The lower, or "bottom land," terrace is 15 to 25 feet above low-water profile, the higher terrace 40 to 60 feet. The surfaces of both terraces are uneven and slope gently upward to the trench walls. In addition to the terrace segments mapped, remnants of both too small to map are found at the mouths of some tributary streams.

Dissected bluffs 100 feet high composed of yellowish limestone are present along much of the Missouri River trench in the vicinity of Yankton. These bluffs stand vertically only where the river is, or recently has been, undercutting the limestone; elsewhere the bluffs form triangular facets with slopes as low as 45°. Terrain adjacent to the trench is deeply eroded, and the mature topography is known locally as "breaks."

The principal tributary of the Missouri River within the Yankton area is the James River which occupies a flat-floored trench. The floor is graded to the bottom land terrace of the Missouri River, and is in part marked by low natural levees. The trench walls are from 100 to 135 feet high, and are almost undissected. Small remnants of both strath and fill terraces are present within the trench.

Terrain north of the Missouri River trench constitutes part of the James River lowland, a gently rolling till plain at an altitude of 1,300 to 1,400 feet. Near Yankton the plain is marked by three major ridges. Turkey Ridge is the easternmost of the three and trends southeast. It is 10 miles wide and 40 miles long, and the crest is more than 1,680 feet in altitude, or about 300 to 400 feet above the adjacent terrain. The extreme northwest corner of the Yankton area encloses a small part of this ridge. James Ridge, the second, lies about 7 miles west of Turkey Ridge and is separated from it by the James River and its trench. The ridge is approximately 9 miles long and 2 miles wide, and like Turkey Ridge trends southeast The maximum altitude is just over 1,500 feet, 150 to 200 feet above the general surface. The southern half of this ridge is within the Yankton area. The third, or Yankton Ridge, is 5 miles south of James Ridge and lies along and parallel to the northern margin of the Missouri River trench. The ridge is 15 miles long, 5 miles wide, and is semielliptical in plan. The crest, at 1,670 feet altitude, is 300 to 400 feet above the general surface and nearly 500 feet above the floor of the adjacent trench. This ridge lies entirely within the Yankton area.

Other features of the lowland floor include several minor ridges, innumerable shallow depressions, and secondary drainage characterized by subparallel alinement with the various ridges. The minor ridges are commonly less than 25 feet high and 2 miles in length but attain maximums of 100 feet in height and 12 miles in length. These ridges are generally alined in festooned chains that can be traced for many miles. The depressions are irregular in plan, have gently sloping sides, and closures of 2 to 5 feet; a few are linked by infrequently used spillways into crude chains.

South of the Missouri River maturely dissected terrain known as the Devils Nest is bordered on the south and west by a rolling upland at an altitude of 1,700 to 1,800 feet, and on the south and east by a moderately rolling surface of somewhat lower altitude. The upland surface is separated from the Devils Nest by a northeast-facing escarpment that trends southeast and loses prominence in that direction. The foot of the escarpment is marked by a broad, shallow, arcuate depression that trends southeast to the village of Crofton, then northeast to the Missouri River trench. From approximately this junction down stream to the vicinity of St. Helena the bluffs of the trench are capped by remnants of a locally prominent strath terrace. The general westward increase in altitude described north of the Missouri River is much less apparent south of the trench, and locally is absent owing chiefly to local drainage.

SURFACE DRAINAGE

Of the many streams only the Missouri and the James warrant the term "river", and of these only the Missouri, the master stream, may be considered large. To the north most streams flow directly into the Missouri River, and only a few discharge into its principal tributary, the James River. To the south drainage from the Devils Nest and terrain immediately east flows directly into the master stream. Creeks southeast of the Devils Nest empty into West Bow Creek, which joins the Missouri River just east of the limits of the Yankton area. Southwest of the escarpment the terrain is drained by the north branch of the Elkhorn River, which flows southeast to enter the Platte River near Omaha, Nebr.

The Missouri River is a broad, shallow river carrying a suspended load of yellowish-brown silt and clay, and a bed load of light-colored fine sand. Between Niobrara and Springfield, as well as downstream from Yankton, the river follows a smoothly curving course; between Springfield and Yankton, however, it swings from one side of the trench to the other in broad, open meanderlike curves, impinging against and undercutting the limestone bluffs. The migration of these meanders since 1860 is illustrated in plate 2, which shows four successive positions of the principal channel of the Missouri River. The gradient of the river surface is 0.85 feet per mile. During 21 years of record prior to September, 1952, the discharge has ranged from 2,700 to 480,000 cubic feet per second, with an average of 26,980 cubic feet per second (U.S. Geol. Survey, 1955, p. 411).

At low-water stage in December the river is as little as 500 to 600 feet wide and 4 to 8 feet deep. Broad scrolls of mud are exposed along the banks on the inner downstream side of curves, and mud bars as large as half a mile wide and a mile long divide the river into 2 or 3 channels. In April during high-water stage the river may be about 6 times as wide, and the water surface as much as 16 feet higher. The scrolls and bars of mud are then under water, and the current scours deeply into loose flood plain and channel alluvium. Additional channels across the flood plain are occupied temporarily, but when discharge diminishes they serve as drainage ditches. The scrolls reappear, slowly grow, and attain maximum size again at low-water stage.

The James River is a small, sluggish stream. During 22 years of record prior to September, 1952, there are many days for which no flow is recorded, and the maximum discharge attained was 10,800 cubic feet per second; the average discharge is 367 cubic feet per second (U.S. Geol. Survey, 1955, p. 427). The surface gradient is 0.75 feet per mile. The stream carries a bed load of silt and clay and occupies a meander belt the width of the trench floor. Open meanders are common, but there are a few distorted loops, and a few segments of the course are relatively straight. At only one point in the area are trench walls steepened by the stream. Possibly the most striking feature of the river's course is the great semicircular curve nearly 3 miles in diameter where the James follows an abandoned meander of the Missouri River across the floor of the Missouri River trench to confluence with the master stream.

At low-water stage in the fall, the river is 75 to 250 feet wide, and an estimated 3 to 6 feet deep. In the spring during high-water stage the surface has been as much as 15 feet higher. The width changes little, however, unless overbank flooding occurs; this requires a rise of from 5 to 10 feet. Mud flats are absent and scrolls are few and narrow, even during low water. There are, however, some small "deltaic fans" built out into the river channel by short intermittent tributaries; composed of sand and silt, the exposed part is similar to an alluvial fan.

Few other streams in the area are perennial; among them are Antelope, Beaver (Nebr.),[1] Wiegand, and Devils Nest Creeks. All other streams are intermittent, flowing only in the spring or after heavy rains. Other bodies of surface water include springs, ponds, and a small artificial lake.

[1] Beaver Creek, Nebr., can be distinguished generally from Beaver Creek, S. Dak., by context.

Nearly all creeks are fed by small springs. Some are perennial, but as summer progresses the yield of many becomes so small that discharge is carried off within alluvium occupying the bottoms of the draws rather than on the surface. Most springs issue just above the contact of Pleistocene gravel and underlying till or shale. In areas where sand and gravel lie at the surface or where they are overlain by permeable silts, the number of springs is greatest and the annual yield largest; springs are rare in areas of till, and the discharge is small. Very few springs were observed in the Ogalalla formation; all are of small yield, and some are perennial. Those found mark the contact of this formation and the underlying Pierre shale. Springs within the Pierre shale are few and the yield is small; some are perennial. The Niobrara formation produces a few very small seeps from joints; some are perennial and some intermittent.

A perennial spring just above a contact of till and overlying gravel on the east side of the road near the center of the SW¼NE¼ sec. 17, T. 95 N., R. 55 W., Yankton County, presently is depositing calcium carbonate as soft travertine.

North of the Missouri River there are innumerable natural depressions. Most of these are flat-bottomed depressions in the till plain, but a few are shallow, narrow, channel scars in the Missouri River flood plain. The till-plain depressions generally contain shallow ponds resulting from melting snow in spring and from heavy rains in summer. Most of these are intermittent, although a few are perennial owing to inflow from farm wells or other artificial sources. Flood plain scars contain water if the water table is sufficiently high; they commonly hold water in the spring and early summer but become marshy or dry by late summer or fall.

South of the Missouri River there are fewer natural ponds. Nearly all are in flood plain scars and are similar to those described above.

In both South Dakota and Nebraska stock ponds are very numerous. One or more small earth-fill dams have been built across the larger draws in most fields, and others are being added each year. The embankment is generally constructed of alluvium and colluvium scraped from the bottom of the draw behind the dam site.

No natural lakes are present; Beaver Lake in sec. 27, T. 95 N., R. 56 W. is artifically dammed.

SOILS

Agricultural soil may be defined as the natural medium for the growth of land plants (U.S. Department of Agriculture, 1951, p. 6). Soils have distinctive characteristics which permit their classification; these characteristics result in part from the geologic materials on which the soil is formed, and in part on a variety of factors such as climate and topography. Geologically soils are of two kinds: those which immediately underlie the surface of the earth, and those which have been buried by younger deposits. In both cases a single soil profile may be the product of more than one environment and more than one soil-forming period.

SURFACE SOILS

Surface soils[2] in the Yankton area include representatives of the three soil orders: Zonal soils, Intrazonal soils, and Azonal soils. A brief description of the soil profiles, their occurrence, and their geologic significance follows.

Pedologists subdivide a soil profile into horizons, which are layers of soil approximately parallel to the soil surface, with individual characteristics produced by soil-forming processes. The A horizon is the horizon of maximum biological activity, eluviation (the removal of materials dissolved or suspended in water), or both, and is generally referred to as the humified horizon. The B horizon is the site of illuviation (accumulation of suspended material from A) or of maximum clay accumulation. The C horizon is the weathered parent material of the soil, and commonly contains the layers of secondary calcium carbonate and calcium sulfate found in some soils. The D horizon is any stratum below that may have significance to the overlying horizons and includes unweathered parent material (U.S. Dept. Agr., 1951, p. 173-181).

Zonal soils are represented by the great soil group known as Chernozem soils. The typical Chernozem soil in the vicinity of Yankton has formed under a tall grass cover on well-drained, nearly level terrain underlain by loess or till. The surficial layer (the A, humified, or eluviated horizon) is dark grayish brown to black, 6 to 15 inches thick, granular, and friable. Beneath this is oxidized parent material (C horizon) from which at least part of the overlying horizon has developed; it is a medium grayish brown, friable, and of columnar (loess) or massive (till) structure. Within this horizon there is a lighter colored horizon, called the Cca horizon, caused by the accumulation of secondary calcium carbonate. This horizon is a few inches to 3 feet thick and is from several inches to about 5 feet below the ground surface.

2 For an explanation of soils, including their description, classification, definition, and origin, see:
U.S. Department of Agriculture, 1951, Soil Survey manual: Handb. 18, Government Printing Office, Washington, D.C.
——1938, Soils and men: 1938 Yearbook of Agriculture, Government Printing Office, Washington, D.C.

The absence of an illuvial (B) horizon of obvious secondary clay enrichment is an indication of the immaturity of the modern soil profile. If clay enrichment is present it is effectively masked by humification and calcification.

Chernozem soils are characterized by a Cca horizon of calcium carbonate accumulation, and are thus classed as pedocals. The carbonate commonly occurs as numerous soft, irregular concretionary nodules, generally an eighth to a quarter of an inch in diameter. Locally the material is present as blebs and stringers, and rarely as a soft whitish deposit suggestive of incipient caliche. Calcium carbonate commonly is present also as a coating on the lower surfaces of stones within the soil. The origin of the Cca horizon is not understood clearly. Flint (1949a, p. 298) stated that:

> * * * the chief process involved [in its formation] appears to be evaporation. In subhumid regions much downward percolating water evaporates before it reaches the water table. Evaporation seems to occur in two distinct ways: (1) by ordinary evaporation within permeable soil, aided under suitable conditions by capillarity and in the drier regions by desiccation cracks; and (2) by transpiration of soil moisture by plants, the roots of which, even in subhumid regions, may penetrate several feet below the surface.

When available in the parent material, calcium sulfate may also be transported and redeposited in the C horizon by the same processes and at similar or greater depths to form a Ccs horizon characterized by selenite in single crystals, swallow-tail twins, and rosettes. Locally erosion has exposed the Cca or Ccs horizons, and slopes below them are littered with calcium carbonate nodules or selenite crystals. In the vicinity of Yankton the crystals have been observed only on slopes of weathered Pierre shale and on silt of the Ogallala formation.

Intrazonal soils are represented by the great soils group known as Wiesenboden (Humic-gley, or Meadow soils) which form in poorly drained depressions in the till-plain surface. The surface horizon is dark gray to nearly black owing to the humic content, a few inches to about one foot thick, and clayey; when dry it is granular, and when wet, highly plastic. Below this layer is a gleyed horizon that is clayey, highly plastic when wet, and a few to several inches thick. It is characterized by mottled light and dark gray coloring, and according to Robinson (1949, p. 354), marks the limits of fluctuation of the water table. Beneath the gleyed horizon is a horizon of grayish to greenish gray clay, the color of which is primarily caused by ferrous compounds rather than humus.

Azonal soils are represented by three great soil groups, the Lithosols, Alluvial soils, and Dune-sand soils (Regosols). Lithosols are shallow soils developed on rock formations and are found near Yankton on steep slopes where rapid erosion prevents the formation of a thick zonal profile. They are found most commonly in areas of exposed bedrock along the sides of draws and ravines and consist chiefly of partly weathered Pierre shale and argillaceous limestone of the Niobrara formation. Alluvial soils underlie the surface of flood plains and low stream terraces and are formed of sediment deposited during recent flooding. The sediment is composed principally of material derived from erosion of the upland, and, except for increased humic content, is mainly unaltered. The Dune-sand soil is a leached, slightly humified horizon 4 to 8 inches thick formed on sand dunes within the Missouri River trench.

RELATION TO GEOLOGY

A soil map bears a direct relation to a geologic map of a given area; this relation is limited, however, by local variations in several soil-forming factors, even on closely similar parent material. The relation near Yankton is somewhat obscure, for the only detailed soil maps available represent Cedar County (Roberts, R. C., and others, 1928) and Knox County, Nebr., (Hayes, F. A., 1930), and bear a class 2 rating[3]. The relation is generalized in the table below, which shows soil series mapped in areas of various parent materials and topography. The importance of topography is indicated by the change of soil series with a change of topography. For example, loess of Wisconsin age in areas of rolling terrain is characterized by the Crofton and Moody series, in areas of undulating terrain by the Hall, Marshall, and Moody series, and in nearly level areas by the Shelby series. The importance of parent material is shown by formation of the Cass series on alluvium and the Shelby series on nearly level loess. The relation of soils to Pleistocene deposits and topography for terrain north of the Missouri River trench is well represented by a table prepared by F. C. Westin and others (*in* Flint, 1955, p. 21).

Apparent discrepancies between geologic and soil maps are largely the result of different mapping techniques. The top of the modern soil profile is the land surface, but in geologic mapping, materials in the upper 2 to 5 feet commonly are unmapped because

[3] Soil maps are rated by the Division of Soil Survey, Bureau of Plant Industry, U.S. Department of Agriculture (Highway Research Board, 1949, p. 4). On class 2 maps major boundaries are likely to be well defined, but individual areas of less than 10 acres are not apt to be differentiated, and names contained are not always in accord with recent correlation; mapping was probably done without the aid of aerial photography.

Generalized relation of parent materials, geologic map units, and topography, to soil series south of the Missouri River; based on comparison of the geologic map (plate 1) with county soils maps[1]

Parent material	Map unit	Topography		
		Rolling	Undulating	Nearly level
		Soil series		
Eolian sand	Dune sand	Sarpy	Cass	
Recent alluvium (Sandy, silty, and gravelly substrata)	Flood plain alluvium			Cass Lamoure Knox Sarpy
	Tributary alluvium			Cass Bloomington Boyd Butler Hall Lamoure Judson Sogn Wabash
	Terrace alluvium			Cass Hall Lamoure Wabash Sarpy
Pleistocane alluvium	Grand Island formation	Dickinson		
Outwash (Sandy and gravelly substrata)	Cary outwash		Bloomington Boyd Dickinson Hall Marshall Moody Shelby Waukesha	
Alluvium and colluvium (Silty and sandy substrata)	Alluvium and colluvium			Cass Judson Lamoure Wabash
(Differs locally)	Landslide deposits [2]			
Till	Ground moraine (Iowan substage)	Crofton Shelby Sogn		
Silt	Wisconsin loess, undifferentiated	Crofton Moody	Hall Marshall Moody	Shelby
	Ogallala formation	Shelby	Boyd Dickinson Moody	
Shale	Pierre shale [3]	Knox Boyd	Boyd	Dickinson Butler
Argillaceous limestone	Niobrara formation [4]	Boyd	Boyd Hall Moody Sogn	Bloomington

[1] Hayes, F. A., and others (1930) and Roberts, R. C., and others (1928).
[2] Series designation chiefly dependent on parent material displaced by sliding.
[3] Shale is overlain by about 2 feet of loess in areas of Butler and Dickinson series.
[4] Limestone is overlain by about 3 feet of alluvium and loess in areas of Bloomington, Hall, and Moody series.

they are altered by weathering, disturbed, are of minor geologic significance, or are impractical to map. For example, much of the area underlain by Cary outwash south of the Missouri River is characterized by the Dickinson soil series; this soil series has also been mapped in small areas underlain by Pierre shale. In most of these areas, however, the shale is actually overlain by a veneer of outwash sand too thin to be mapped geologically.

The influence of time as a variable factor in formation of the surficial soil profile is neither expressed nor expectable in the table, because in South Dakota Flint (1955, p. 20) found the Barnes soil series on drift sheets of the four Wisconsin substages where the lithology and texture of the parent materials were similar.

BURIED SOILS

Most buried soils in the Yankton area are Zonal soils, for representatives of the Intrazonal and Azonal soil orders are rare. Physical characteristics of the buried soils are the same as those of their surface equivalents and permit classification in the same manner. Three principal buried soil profiles in the vicinity of Yankton are classed as Chernozems, and represent 3 periods of weathering. Difference in the maturity of these profiles is useful in correlation of these soils from one exposure to the next. This facilitates correlation of the geologic deposits on which the profiles formed.

CLIMATE, VEGETATION, AND INDUSTRY

The normal climate of the Yankton area is dry-subhumid, although during the growing season it is moist-subhumid (Thornwaite, 1941, p. 3). Winters of this continental climate are long and cold, springs short and rainy, summers long and moderately hot and rainy, and falls short and dry. Daily temperature changes are commonly rapid. The coldest month is January, the warmest, July. The extreme temperature range is —34°F to 111°F; the average annual temperature is 46.3°F. The average annual precipitation is 24.63 inches, with December the driest month (0.33 inches) and June the wettest (5.67 inches). About four-fifths of the annual precipitation falls during the months of April through September. Relative humidity measured at 2:00 p.m. local time ranges from about 42 percent in April to 60 percent in January. There are approximately 135 clear days yearly. A light breeze is customary during the summer, and periods of high winds in both summer and winter are of short duration. The prevailing wind direction is from the northwest during the months of October through April, and from the southeast the rest of the year. Wind distribution is shown in figure 2. The first snow, which generally melts, occurs about

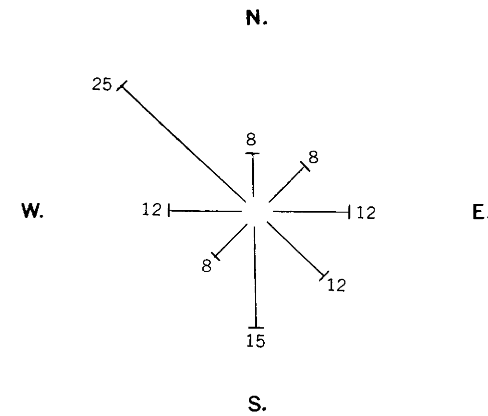

FIGURE 2.—Wind direction at Yankton, S. Dak., in percent of time.

November 1st; during the winter the average annual total accumulation of unmelted snow is about 30 inches, and the ground remains snow-covered for a period of approximately 60 days[4]. Winds locally pile snow into drifts several feet deep which may temporarily block traffic 1 to 2 days, but on open fields snow rarely accumulates to depths greater than several inches. The depth of frozen ground is dependent in part on the thickness of the snow mantle; generally it freezes to a depth of a few inches in late November, 4 to 7 feet during the winter months, and thaws in March. Low temperatures, wind, snow, and frozen ground preclude or sharply limit most out-of-doors work during December, January, and February.

Native vegetation of the upland consists largely of wheatgrasses on finer textured soils, and needlegrasses on sandier soils. Moisture-loving grasses are found on the floor of the Missouri River trench and its tributaries, and the heavy soils in undrained depressions support rushes and sedges. Stands of cottonwood and boxelder and scattered about the floors of the trench and larger tributaries, and thickets of willow cover much of the Missouri River flood plain. Along the lower slopes of the trench walls and in the smaller tributaries are growths of burr oak.

Farming is the chief industry. On the upland and in the valley bottoms farmsteads are protected by tree shelters planted, for the most part, by the original homesteaders. These shelters generally consist of indigenous cottonwood and boxelder, but include

[4] Climatic data above is abstracted from: Kincer, 1928; Day, 1922; Reed, 1918, the U.S. Weather Bureau, 1930, 1931 et seq., and 1942, and written communications from J. D. Magnuson and A. D. Murphy of the Huron, S. Dak., office of that agency (weather records have been kept in Yankton since 1873).

walnut, American elm, and ash. Most of the upland area and large portions of the alluvial bottom lands are cultivated. The major crops are corn, oats, and alfalfa. Hogs and cattle raised on uncultivated or dissected terrain or shipped in from the west are fattened for market on the corn and alfalfa.

Yankton has a population of about 8,500, and the eight other communities in the Yankton area range from approximately 35 to 750; the rural population is estimated at 10 to 12 persons per square mile except in the Devils Nest where the average is probably 3 to 5. Yankton is accessible by Federal and State highways, railroads, and air service. The Missouri River between Yankton and Sioux City, Iowa, is not now navigable but may become so in the future.

STRATIGRAPHY

The Yankton area is underlain by sedimentary rocks which range in age from Precambrian to Recent. The several formations and deposits have been studied and mapped in detail, and have been found to be separable logically, for the purpose of description, into 3 principal divisions: formations and deposits of pre-Pleistocene, Pleistocene, and Recent age, respectively. The rocks are described below, and their areal distribution is shown on the accompanying geologic map (pl. 1).

A subheading "Engineering characteristics" is included for each formation wholly or partly exposed to bring together information of particular significance to engineers, such as ease of excavation, suitability for graded roadways and crosscountry movement (trafficability), and stability of natural and artificial slopes. The information is largely based on field observations of the behavior of the several formations, but includes some results of laboratory testing. Such information on engineering properties of the strata, although useful, cannot replace detailed field and laboratory investigation for the proper construction of large engineering projects.

PRE-PLEISTOCENE ROCKS

Pre-Pleistocene rocks in the vicinity of Yankton range in age from Precambrian to Pliocene (table 1). For the purpose of description they are classified as pre-Cretaceous, Cretaceous, and Tertiary in age. The known strata consist of about 825 feet of claystone, shale, argillaceous limestone, marl, and orthoquartzite, all of known or inferred marine origin, and about 450 feet of sandstone, orthoquartzite, and unconsolidated sand and gravel of known or inferred continental origin.

Earlier writers have used various terms to indicate the lithology of pre-Pleistocene formations in southeastern South Dakota and northeastern Nebraska. In order to avoid confusion definitions are given below for certain rock terms as used in this report. These definitions are in accord essentially with those of Twenhofel (1937, 1939), Grim (1942, 1953), Schrock (1948), Pettijohn (1949), Dapples, Krumbein, and Sloss (1950), and Rodgers (1954).

Clay is an unindurated earth consisting of minerals that are mostly hydrous aluminum silicates or hydrous magnesium silicates, or particles of grain sizes finer than silt, or both, that develops plasticity when mixed with a small amount of water.

Mudstone is partly indurated clay or clay and silt that lacks fissility or lamination; it is coherent when dry, but incoherent when wet.

Claystone is partly indurated clay or clay and a little silt that lacks fissility or lamination; it is coherent both wet and dry.

Shale is indurated clay or clay and a little silt that possesses fissility or lamination; it is coherent both wet and dry.

Siltstone is partly indurated silt or silt and a little clay that lacks fissility or lamination; it is coherent both wet and dry.

Calcareous clay, calcareous mudstone, calcareous claystone, and *calcareous shale* contain calcium carbonate ranging in amount from that barely detectable by testing for carbon dioxide with a 10 percent solution of hydrochloric acid, to 25 percent by weight in an insoluble residue test.

Marl is an unindurated or partly indurated earth consisting of clay or clay and silt, and 25 to 50 percent calcite and dolomite, of which calcite is the more abundant.

Limestone is an indurated sedimentary rock consisting of more than 50 percent calcite and dolomite, of which calcite is the more abundant.

Argillaceous limestone is an indurated or partly indurated sedimentary rock consisting of from 10 to 50 percent clay or clay and silt, and from 50 to 90 percent calcite and dolomite, of which calcite is the more abundant.

Chalk is an unindurated or partly indurated earthy rock consisting of some clay or clay and a little silt, and a large amount of calcareous microbiotic remains.

Orthoquartzite is an indurated sedimentary rock chiefly composed of silica-cemented quartz sand.

The ease with which these rocks are broken may be represented for the purpose of this report by a subjective scale ranging from loose through weak

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TABLE 1.—*Pre-Pleistocene rocks in the Yankton area*

	System	Series	Formation	Member	Lithology	Thickness (feet)	Color symbol
Unexposed	Tertiary	Pliocene	Ogallala		Sand, silty clay interbedded with a little volcanic ash, and orthoquartzite: sand grayish orange, fine to coarse, partly crossbedded; silty clay pale yellowish green to pale red, calcareous, massive, contains vertebrate bone fragments; or orthoquartzite pale yellowish green, indurated.	125+	5 *YR* 7/4 5 *G* 7/1 to 10 *R* 6/2 10 *GY* 7/2
	Cretaceous	Upper Cretaceous	Pierre shale	Mobridge	Marl: weathers dark to pale yellowish orange, beds 1 to 6 inches thick, soft, weak.	18	10 *YR* 8/6 to 10 *YR* 6/6
				Virgin Creek	Mudstone, with thin layers of iron oxide cemented silt yielding numerous brown scales: light or medium-light gray, slightly calcareous to concalcareous, bedding not observed, soft, weak.	25	*N* 6 to *N* 4
				DeGrey and Verendrye	Shale, interbedded with a little claystone: lower part contains thin bentonite layers, upper part contains a few laminae of iron oxide cemented silt and numerous oolitic phosphatic nodules; fissile, soft, weak.	75	*N* 5
				Crow Creek	Marl: weathers to very pale orange, beds 1 to 2 inches thick, soft, weak.	6	10 *YR* 8/2
				Gregory	Shale and claystone, interbedded with thin bentonite layers, marl, and sand: shale and claystone weather pale grayish orange, contain iron-manganese concretions, fissile to thin bedded, soft, weak; marl weathers pale grayish orange, thin bedded, soft, weak, contains root fragments; sand pale grayish green, locally iron stained, loose, contains fish remains.	42–43	*N* 5 and 10 *YR* 8/2
				Sharon Springs	Shale: medium dark gray, characterized by flakes of carphosiderite(?), upper part nonbituminous and contains thin bentonite beds, lower part bituminous and contains disseminated bentonite; fissile, soft, weak.	1–11	*N* 4
			Niobrara	Smoky Hill chalk	Limestone, argillaceous: medium bluish gray, weathers dark yellowish orange, gypsum layers mark many bedding planes, beds generally 6 inches to 2 feet thick with 6-foot maximum, soft, subfirm, *Ostrea congesta* Conrad as colonial clusters along many bedding planes.	100+	5 *B* 5/1 and 5 *Y* 8/4 to 10 *YR* 6/6
				Fort Hays limestone	Limestone, argillaceous: like unit above but beds generally thicker than 6 feet, *Ostrea* colonies lacking.	80 ±	As above
Exposed			Carlile shale	Sage Breaks(?)	Shale: medium gray, slightly calcareous to noncalcareous, fissile, soft, weak.	5–22	*N* 7 to *N* 4
				Codell sandstone	Siltstone, clayey, with a few partings of silty shale: light to dark gray, bedding in part thick and in part crossbedded, moderately soft, moderately weak.	5–13	*N* 7 to *N* 3
				Blue Hill shale	Shale, interbedded with thin silty layers and in upper part a thin lens of crystalline limestone: medium gray, contains scattered grains and small nodules of pyrite and small phosphatic concretions, also contains *Inoceramus*(?) fragments and thin lamine of crushed calcareous fossil material, fissile, soft, weak.	146–177	*N* 5
				Fairport chalky shale	Shale: medium to dark gray, calcareous, contains numerous laminae of crushed calcareous fossil material, fissile, soft weak.	54–67	*N* 5 to *N* 3
			Greenhorn limestone		Limestone, interbedded with argillaceous limestone, marl, calcareous shale, and two very thin layers of bentonite: light to medium dark gray, open joints contain yellow-stained calcite, contains *Inoceramus labiatus* (Schlotheim), fissile to nonfissile, weak to moderately strong.		*N* 7 to *N* 4
			Graneros shale		Shale, interbedded with thin layers of silt and sand in lower part, and a few scattered thin layers of bentonite and carbonaceous material: medium dark gray, contains scattered crystals of pyrite, fragments of plant rootlets, and compressed *Inoceramus*(?), fissile, soft, weak; coarseness increases slightly eastward.	128–164	*N* 4
		Lower Cretaceous	Dakota sandstone	Upper sandstone	Sandstone, interbedded with claystone, shale, and numerous thin layers of black carbonaceous material: sandstone yellowish, white, probably cemented in part by calcium carbonate; claystone and shale medium to dark gray; coarseness decreases slightly eastward.	46–85	5 *Y* 9/1
				Middle shale	Shale and claystone, interbedded with thin layers of sandstone and black carbonaceous material: contains fragments of plant rootlets and, at or near top, manganese carbonate concretions; coarseness may increase slightly eastward; probably equivalent to Fuson shale.	25–52	*N* 4
				Lower sandstone.	Sandstone, lithologically like upper sandstone of this formation, but color medium to medium dark gray; probably equivalent to Lakota sandstone.	216–313	5 *Y* 9/1
		Precambrian	?		Gabbro(?): greenish, weathered(?), contains secondary calcite.	?	?
			Sioux quartzite		Orthoquartzite: grayish orange pink, fine to coarse grained.	20	5 *YR* 7/2

(broken easily in the hands), firm (broken with difficulty in the hands), and hard (broken easily with a hammer), to very hard (broken with difficulty with a hammer).

Color names represent dry material, and are taken from Goddard and others (1948); colors of damp material are somewhat darker.

Of the total known thickness of strata, nearly half are naturally exposed in the area. Knowledge of the unexposed, or subsurface, strata is restricted almost completely to data obtained from recent drill holes. Logs of a few older wells are recorded in various publications of Darton (1896, 1897, 1909) and Todd (1895, 1900), and logs of two recent wells have been published by Baker (1948, p. 7; 1951, p. 1).

Since 1947 the Corps of Engineers has conducted an extensive testdrilling program at the Gavins Point dam site. One hole[5] penetrated the upper part of the Dakota sandstone of Early Cretaceous age, and two[6] entered the Graneros shale of Late Cretaceous age. In addition, numerous holes entered the lower members of the Carlile shale after passing through immediately overlying alluvium in the Missouri River trench; others penetrated the surface and the top few feet of that shale. I was able to examine several of these cores in the field while drilling was in progress.

Other recent unpublished logs are available from the South Dakota Geological Survey and include water wells and oil tests drilled in the vicinity of Yankton by private and municipal interests. In 1950 the New England Distillery Co. drilled a third water well at 2nd Street and Walnut Avenue in Yankton, into the upper part of the Lakota(?)sandstone equivalent in the Dakota sandstone. The cuttings of this well were sampled and logged by the writer and F. C. Witmer, and a summary was filed with the South Dakota State Geological Survey in Vermillion. During 1952 and 1953 private interests drilled two oil tests near Springfield[7] and a third midway between Springfield and Yankton[8]. The first of these encountered Sioux quartzite, but the others bottomed in the lower part of the Lakota(?) equivalent. Cuttings were sampled and logged by the State Geological Survey for all three holes, and an electric log was made of the first by the State survey, and of the second by a private firm. In addition two municipal water wells drilled during 1953 in Utica (NE cor. sec. 7, T. 94 N., R. 56 W., Yankton County) and at the West Side Park pond in Yankton (SW cor. NE¼ sec. 13, T. 93 N., R. 56 W., Yankton County) were logged electrically by the State survey; these wells reached the Lakota(?) sandstone equivalent. An electric log was made also by the State survey of the Corps of Engineers administration building water well at the Gavins Point Dam. The first four electric logs are reproduced and correlated in plate 3, and the thickness of the several formations and their members or informal subunits, together with the altitudes of the principal contacts, are given in table 2.

Because strata making up the subsurface formations consist largely of interbedded sandstone, siltstone, and shale, the positions of their boundaries as determined from churn-drill cuttings are generally inaccurate. The cuttings show, however, details of the lithology of the beds, whereas the electric logs, together with core logs, indicate the position of contacts and other features of the strata which permit correlation and more accurate placement of formational contacts.

Outside the Yankton area all but one of the subsurface formations are well known from many exposures. In southeastern South Dakota, northeastern Nebraska, and northwestern Iowa, strata that are unexposed near Yankton crop out extensively along the principal streams and their tributaries. The best exposures of Cretaceous rocks are in the walls of the Missouri River trench from St. Helena downstream to about 10 miles south of Sioux City, Iowa, and along the Big Sioux River from its mouth to the vicinity of Corson, Minnehaha County, S. Dak. Outcrops of the Sioux quartzite of Precambrian age are scattered over much of east-central South Dakota; the best of these is along Split Rock Creek northeast of Sioux Falls, Minnehaha County. No exposures of the crystalline rock are known, but similar rock crops out in conjunction with the Sioux quartzite along the same creek.

The pre-Pleistocene strata are correlated with formations widely recognized in the western interior of the United States. Correlation is based on standard stratigraphic field methods, but no attempt was made to collect or study the microfauna. Comprehensive correlation charts of Cretaceous formations in the western interior are found in Cobban and Reeside (1952), and of Tertiary formations in Wood and others, (1941).

The strata are described systematically from oldest to youngest.

[5] Administration building water well: near cor. SE¼SW¼ sec. 7, T. 33 N., R. 1 W., Cedar County.

[6] 1. Core hole 18: SW cor. NW¼ sec. 15, T. 33 N., R. 1 W., Cedar County.
2. Core hole 129; near NE cor. SE¼SE¼ sec. 17, 93 N., R. 56 W., Yankton County.

[7] 1. Bon Oil Co.—Nick Jelsma No. 1, SE¼SE¼ sec. 10, T. 93 N., N 60 W., Bon Homme County.
2. Bon Oil Co.—Isaac and Byrne No. 1, SW¼ sec. 8, T. 93 N., R. 59 W., Bon Homme County.

[8] 3. Oil Ventures Co.—Schultz No. 1, SE¼SW¼ sec. 4, T. 93 N., R. 57 W., Bon Homme County.

TABLE 2.—*Thicknesses of subsurface formations, with altitudes of principal contacts*

[Based chiefly on electric logs shown in plate 3]

Formation	Member or informal subdivision	Bon Oil Co.—Nick Jelsma No. 1	Bon Oil Co.—Nick and Byrne No. 1	Utica municipal water well	Yankton municipal water well
		Altitude of contact, and thickness of member or subdivision, and formation, all in feet.			
		1,133	1,172		1,162
Carlile shale	Sage Breaks(?) member	22	8	....	5
	Codell sandstone member	5	9	....	9
	Blue Hill shale member	177	213	....	146
	Fairport chalky shale member	54	58	....	67
		258	288		277
		875	884	916	935
Greenhorn limestone		25	26	24	30
		850	858	792	905
Graneros shale	Upper part	18	20	26	25
	Middle part	27	16	38	26
	Lower part	83	98	99	92
		128	134	163	143
		723	724	729	762
Dakota sandstone	Upper sandstone member:				
	Upper part	18	25	19	35
	Middle part	10	18	25	24
	Lower part	19	17	19	25
		47	60	63	84
		676	664	666	677
	Fuson(?) shale equivalent:				
	Upper part	25	20	33	20
	Lower part	27	24	7	5
		52	44	40	25
		624	620	626	653
	Lakota(?) sandstone equivalent:				
	Upper part	141	104	>23	>82
	Lower part	76–78	34	?	?
		217–219	138	>23	>82
		[2] 405–407	.....	.....	475 ±[4]–339 ±[5]
Sioux quartzite		[3] >20	?	?	[5] >49

[1] Corps of Engineers drillhole No. Y-32, about 200 yards south of the hole logged electrically.

[2] From drill hole cuttings.

[3] From drilling log.

[4] Darton, N. H. (1909, p. 146): State mental hospital water well, 2 miles north and 1 mile east of drill hole.

[5] Todd, J. E. (1898, p. 100–101): Yankton municipal water well, exact location unknown but probably within 1,000 yards of this drill hole.

PRE-CRETACEOUS ROCKS

Two formations of pre-Cretaceous age are present in the Yankton area. One is the Sioux quartzite, locally called "Sioux Falls granite." The other is a crystalline rock about which very little is known, for it is reported in only one well for which no cuttings are available.

In 1898 Todd (p. 101) recorded as follows the lithology of the bottom 124 feet of a Yankton town well drilled in 1896:

	Thickness (feet)	*To depth (feet)*	*Altitude of lower contact (feet)*[1]
Fine sand	196	805	410
Clay	2	----	408
Sand	62	----	346
Last flow from 850 feet, soft water.			
Greenish clay	7	----	339
A hard tough greenish rock, sprinkled with quite calcareous white particles effervescing readily, the green easily fusing	[2] 49	[2] 929	286

[1] Altitudes of lower contacts as estimated by Simpson from Todd's data.
[2] There is a discrepancy of 4 feet in Todd's figures.

In regard to the "greenish rock" Todd stated that:

> This rock is of crystalline character, and from the tests applied appears to be mostly labradorite with some quartz and calcite or dolomite. At any rate it is a novelty in this region. Prof. W. H. Hobbs kindly reports it as containing felspar, quartz and magnetite.

Except for the presence of quartz, this rock may be similar to gabbro exposed at two localities just northeast of Sioux Falls (Todd, 1904; Beyer, 1897, p. 79-105) and encountered in a well north of Alexandria, S. Dak. (Todd, 1898, p. 98). The form and size of the igneous masses and their relation to the adjacent Sioux quartzite are unknown because all contacts are concealed.

SIOUX QUARTZITE

The lithologic character of the Sioux quartzite near Yankton was observed in thin sections made of cuttings from the Bon Oil Co—Nick Jelsma No. 1 oil test. The rock is a very hard, grayish orange pink orthoquartzite—a "sandstone" so firmly cemented that it breaks across grains instead of around them. The rock is generally dense, but it is in part somewhat permeable. It consists of fine coarse quartz sand with some unidentified silt- and clay-sized particles, cemented by silica. The cementing silica was deposited with the same optical orientation as the adjacent quartz grains, producing an interlocking secondary crystal growth, or enlargement. The cement is faintly stained surficially by red ferruginous oxides, and it is this staining that causes the characteristic of the rock. The original quartz grains are clear, rounded to moderately rounded, and moderate to high sphericity. Accessory minerals are rare and appear to be secondary. They consist chiefly of pyrite and ferruginous oxides which generally are present as individual grains but are in part interstitial.

In southeastern South Dakota the Sioux quartzite is known only in the deepest wells. Data published by Darton (1909, p. 146) show that the formation was cut in a well at the State Mental Hospital 3 miles north of Yankton at an altitude of about 475 feet (reported depth: 825 feet) and also in other wells in the region. Among these are municipal wells at Tyndall and at Scotland (7½ miles northwest of Lesterville). Using data obtained from these and other wells, Darton, Todd, and Hall (*in* Darton, 1909, pl. 10) contoured the eroded surface on which the Cretaceous strata lie; the relief of this buried surface in the Yankton area is at least 120 feet. In Nebraska no wells drilled near Yankton have reached the formation (Condra and Reed, 1943, p. 73–74), because none have been drilled deep enough.

The thickness of the Sioux quartzite is not known, for it has not been penetrated. Cuttings indicate that about 20 feet of the formation were drilled in the Bon Oil Co.,—Nick Jelsma No. 1 oil test, but a tremendous total thickness is indicated by a well about 50 miles west-northwest of Yankton, near Wagner, Charles Mix County, in which 3,787 feet of the orthoquartzite were drilled without reaching the base of the formation (Barkley, 1952, p. 23).

An accurate depth of penetration of the formation is commonly difficult to obtain owing to the lithologic character of the upper strata. Poorly cemented rock is known in surface exposures at various localities (W. B. Baldwin, written communication, 1951), and supposedly similar strata mark the unconformable contact of the Sioux quartzite with the overlying lower sandstone member of the Dakota sandstone both in the municipal water well at Scotland (Todd, 1898, p. 99-100) and in the Bon Oil Co.—Nick Jelsma No. 1 oil test. Because the poorly cemented quartzite is similar to the sandstone, determination of the upper contact is difficult.

For the purpose of this report the upper contact is arbitrarily drawn at the top of firmly cemented quartzite. This places it at an altitude of 405 to 407 feet in the Bon Oil Co.—Jelsma well; firm rock was not found either in the Scotland well or in other wells in the area. Premeable material which may belong with the Sioux quartzite is included with the superjacent sandstone. This arbitrary position of the contact is reasonable owing to the possible production of ground water (an important economic characteristic of the lower sandstone member (Lakota?) of the Dakota sandstone in the region) from permeable orthoquartzite, and to the difficulty of distinguishing it from Lakota(?)

Correlation of a sedimentary quartzite in the Yankton area with the Sioux quartzite exposed in eastern South Dakota and southwestern Minnesota is based solely on lithologic similarity. The nearest outcrop is near Parker, Turner County, about 40 miles north-northeast.

The formation was named by White (1870, p. 168) for exposures along the banks of the Big Sioux River, S., Dak. Several geologists have investigated the Sioux quartzite and, with only one exception (Hayden, 1876), have considered the formation to be of Precambrian (Huronian) age. Despite such general agreement there is little direct evidence of the age of the formation. Stratigraphic evidence (C. L. Baker *in* Baldwin, 1949, p. 9) proves it only to be Early Ordovician or older. Evidence of life is rare (Winchell, 1885), and questionable (Van Hise and Leith, 1909, p. 727). Although the fossils reported by Winchell, if valid, may suggest Cambrian age for the famous catlinite bed and younger strata, neither Cambrian nor Precambrian age is proven for any part of the formation. Reasons for the assignment of Huronian age have been summarized by W. B. Baldwin (written communication, 1951) in a dissertation for Columbia University. His report is the most comprehensive to date, and together with publications by Berg (1937, 1938) presents an excellent picture of the lithologic character, structure and distribution of the formation.

CRETACEOUS ROCKS

Rocks of Cretaceous age comprise six formations in the vicinity of Yankton. They are, from oldest to youngest, the Dakota sandstone of Early Cretaceous age, and the Graneros shale, Greenhorn limestone, Carlile shale, Niobrara formation, and Pierre shale of Late Cretaceous age.

Of these formations, the Graneros shale, Greenhorn limestone, Carlile shale, and Niobrara formation constitute the Colorado group. This group was originally defined by Hayden in 1876 (p. 45) and named for exposures along the east base of the Front, or Colorado, Range, and included in addition to the above the overlying Pierre shale. In 1878, however, White (p. 21–22, 30) restricted the name to exclude the Pierre shale, and his usage is generally accepted today.

The Niobrara formation and the overlying Pierre shale crop out extensively in southeastern South Dakota and northeastern Nebraska along the principal streams and in the flanks of bedrock ridges. Excellent exposures of the entire thickness of both formations are found along the walls of the Missouri River trench and in dissected terrain adjacent thereto on both sides of the river between St. Helena and the Bon Homme Hutterite (Mennonite, locally) Colony.

The two formations have been subdivided into their respective members on field evidence, and subdivision of the Niobrara formation is supported by laboratory data. On the accompanying geologic map, however, the formations are both shown as single units because the scale of mapping, steepness of slope, and thinness of members makes subdivision impractical.

Owing to the contrast between the light color of the marls and argillaceous limestone and the various somber hues of the several shale beds, contacts can be recognized easily at a distance. During the drier parts of the year the contact between the Cretaceous formations and overlying unconsolidated Tertiary and Pleistocene deposits is similarly apparent owing to a great moisture content in the Cretaceous strata that causes vegetation growing on these rocks to remain greener longer.

Except for the upper few feet of Carlile shale, that and all older formations are unexposed in the Yankton area. These strata do crop out, however, from St. Helena downstream along the Missouri River, and along the lower course of its tributary the Big Sioux River. The best description of these formations and their macrofauna is given by N. C. Georgesen (written communication, 1931), who examined that area and collected from it in preparing a Master's thesis at the University of Iowa. Because Georgesen was primarily interested in the Colorado group, Dakota strata are undifferentiated.

DAKOTA SANDSTONE

The Dakota sandstone is 287 to 423 feet thick in the vicinity of Yankton. It consists chiefly of fine to coarse, light-colored sand and sandstone interbedded with some gray shale and a little carbonaceous matter, and is characterized by the presence of a small amount of glauconite and nodules of manganese carbonate. The formation is subdivided into three members on the basis of lithologic character. They are a lower sandstone member thought to be equivalent to the Lakota sandstone of the Black Hills region, a middle shale member thought to be correlative with the Fuson shale of the same area, and an upper sandstone member.

The Dakota sandstone of this report is correlated with the type Dakota sandstone because of the sequence of lithology, proximity to the type locality, and the reported presence of Dakota sandstone at least as far west as west-central South Dakota (Gries, 1953, p. 447).

The Dakota group was named by Meek and Hayden (1861, p. 420-421) for exposures along the Missouri River trench in Dakota County, Nebr., opposite Sioux City, Iowa. In 1901 Darton (p. 526-532), working in the Black Hills, found in that area that the group as originally defined included strata of both Early and Late Cretaceous age, and so subdivided it. Tester (1931, p. 283-284), and Cobban and Reeside (1952, chart 106), have since concluded that the type Dakota sandstone is Early Cretaceous in age.

LOWER SANDSTONE MEMBER (LAKOTA(?) SANDSTONE EQUIVALENT)

The lower sandstone member ranges in thickness from 216 to 218 feet in the Bon Oil—Nick Jelsma No. 1 well to 314 feet beneath Yankton (see pl. 3). The increase in thickness can be accounted for by a valley in the pre-Dakota surface shown by Darton (1909, pl. 10). The altitude of the Sioux quartzite upper contact in a well at the State Mental Hospital (table 2) 3 miles north of Yankton implies a thinning in that direction, and Barkley (1952, p. 18) states that "at Elk Point and Jefferson [about 40 miles southeast of Yankton] well records show that the Lakota is pinched out by the Paleozoic section."

Well cuttings show that the member consists chiefly of fine to coarse angular sand which forms firm to loose yellowish-white sandstone interbedded with numerous thin layers of soft black carbonaceous material and medium to medium dark gray claystone or shale. Cuttings from the Scotland municipal water well indicate that layers near the base of the member locally have a grayish orange pink color and are firmly cemented by calcium carbonate. Todd (1898, p. 99–100) reported these basal strata to be 80 to 90 feet thick and concluded that about 25 feet of softer rock beneath constitute imperfectly cemented strata of Sioux quartzite. Examination of cuttings from the Bon Oil Co.,—Nick Jelsma No. 1 well indicates a somewhat similar condition in the lower part of that hole. These cuttings include numerous loose grains of grayish orange pink sand that may represent a less well cemented stratum of the Sioux quartzite or that may be residual or reworked from that formation.

Electric logs shown in plate 3 of both Bon Oil Co. drill holes indicate the Lakota(?) sandstone equivalent consists of two units. The lower unit has markedly greater electrical resistance than the upper, as shown by the right-hand (resistivity) curve of the two logs. The greater resistivity may be caused by fresh water in sandstone beds of differing permeability or by differential cementation of the beds by either calcium carbonate or silica.

No macrofossil fragments were observed in cuttings from the New England Distillery Co. well at Yankton.

The nature of the contact with the overlying middle shale member is not known. The contact, as drawn on available logs, ranges in altitude from 620 to 653 feet.

Correlation of the lowest member of the Dakota sandstone in the Yankton area with the Lakota sandstone as known in the Black Hills area is based solely on the lithologic sequence indicated by the electric logs in plate 3.

The name Lakota was first used by Darton (1899a, p. 387, 395-396) for strata he (1901, p. 34-35) subsequently concluded were of earliest Cretaceous age and constituted the basal beds of the Dakota group of Meek and Hayden (1861, p. 420-421). Later Darton and O'Hara (1909, p. 4) designated the type locality of the formation at Lakota Peak, Custer County, S. Dak.

MIDDLE SHALE MEMBER (FUSON(?) SHALE EQUIVALENT)

The middle shale member is from 25 to 52 feet thick in the vicinity of Yankton. It consists of medium dark gray shale and claystone interbedded with black carbonaceous material and fine yellowish-white sandstone similar to sandstone beds in the rocks immediately above and below. From the electric logs reproduced in plate 3 the shale member is estimated to consist of 90 percent clay-sized material in the Bon Oil Co—Nick Jelsma No. 1 well, 60 percent in the Bon—Isaac and Byrne No. 1 well, about 15 percent in the Utica well, and 10 percent at Yankton. The logs also indicate that the member thins eastward and generally is composed of two units. The lower unit is somewhat finer grained than the upper; the base of the upper bed is apparently marked by a layer of fine sand. The Fuson(?) is distinguished from rocks above and below by its greater amount of shale and claystone and by the presence of manganese carbonate (rhodonite) concretions at or near the top of the member. The nearest exposure of the unit (Barkley, 1952, p. 17) is 8 miles southeast of Sioux City, Iowa.

Macrofossil fragments were observed in cuttings from the New England Distillery well at Yankton; they consisted of plant fragments, apparently rootlets.

The nature of the upper contact is not known, but on available logs it is drawn at altitudes ranging from 664 to 678 feet (table 2).

Correlation of the middle shale member of the Dakota sandstone in the vicinity of Yankton with the Fuson shale as known in the Black Hills is based on the similarity of lithologic character and sequence. The most significant characteristic is the presence of manganese carbonate nodules in Fuson shale of the type area and equivalent(?) strata at Yankton. Baker (1948, p. 2) and Barkley (1952, p. 17) indicate that a shale containing similar nodules is known from well-cutting logs to occupy a comparable stratigraphic position in the region between the two localities. The similarity of the lithologic sequence is shown in plate 3.

Darton (1901, p. 530) named the Fuson shale for exposures in Fuson Canyon on the east side of the Black Hills. Previously the strata had been a part of the Dakota group of Meek and Hayden (1861, p. 420–421). The formation is of Early Cretaceous age.

UPPER SANDSTONE MEMBER

The upper sandstone member is from 47 to 84 feet thick near Yankton. Lithologically this member is similar to the lower sandstone member and is, apparently, best distinguished from it by the presence of a small amount of glauconite, and by the stratigraphic position of the upper sandstone above the horizon of manganiferous concretions that characterize the upper part of the subjacent middle shale member. The electric logs in plate 3 indicate that the upper member consists of three units. All three are sandy in the western drill hole, but the upper unit becomes somewhat finer grained eastward and the middle unit dominantly clayey. The lower unit remains sandy. The nearest exposure is in the southwest wall of the Missouri River trench near Ponca, Dixon County, Nebr., about 40 miles southeast of Yankton.

No macrofossils were observed in cuttings from the New England Distillery Co. well at Yankton.

The nature of the contact with the overlying Graneros shale is not known, but its altitude as drawn on the electric logs ranges from 723 to 762 feet (table 2).

The upper member of the Dakota sandstone of this report is the Dakota sandstone of the South Dakota Geological Survey and the Omadi sandstone of the Nebraska Geological Survey (Condra and Reed, 1943, p. 18).

GRANEROS SHALE

The Graneros shale ranges from 128 to 163 feet in thickness. Cuttings indicate the rock consists of a medium dark gray shale with layers of silt and sand a few inches to a few feet thick interbedded in the lower part. The strata contain many small scattered crystals of pyrite and include a few very thin layers of bentonite, laminae of calcareous fossil material, and, in the basal beds, a few thin carbonaceous layers. The electric logs in plate 3 indicate the formation consists of three units. The lowermost unit thickens slightly eastward and becomes somewhat sandier in that direction. The middle unit thickens a little toward the northeast; it consists chiefly of shale in the western drill holes but is somewhat sandier farther east. The uppermost unit contains some silty or sandy beds and is consistent in thickness. The nearest outcrop of the formation is in the southwest bluff of the Missouri River trench near Ponca, Nebr.

Macrofossils observed include many plant fragments (rootlets?), and numerous compressed clams similar to *Inoceramus* form distinct laminae of local extent at some horizons.

The contact with overlying Greenhorn limestone is conformable and gradational through a distance of about 2 feet. It ranges in altitude from 850 to 905 feet (table 2).

Correlation of these strata near Yankton with the Graneros shale as known elsewhere in the region is based on the similarity of lithologic character and sequence as observed in drill cores at the Gavins Point Dam.

In 1896 Gilbert (p. 564-565) subdivided the (Fort) Benton group of Meek and Hayden (1861, p. 421–422) into three formations; the lowest of these he named the Graneros shale. In 1897 he stated (p. 4) that the name was taken from exposures near Graneros and along Graneros Creek in Walsenburg quadrangle, Colorado. The strata are generally considered to be Early and Late Cretaceous in age, but Early Cretaceous equivalents farther west are not known to be represented as far east as the Yankton area. For this reason the formation is referred to in this report as Late Cretaceous in age.

GREENHORN LIMESTONE

The Greenhorn limestone is from 24 to 30 feet thick and is lithologically one of the most distinctive units among the subsurface strata. It is a firm, light gray to medium dark gray, argillaceous limestone interbedded with softer marl and a little calcareous shale, and two thin layers of bentonite. Open joints contain coarsely crystalline calcite with yellow ferruginous stains. The formation can be divided into two principal layers separated by a bed of softer rock, but because the formation is thin and the parting is only about 3 feet thick, it is not practical to do so. The nearest exposure is in the southwest bluff of the Missouri River trench near Ponca, Nebr.

Large fossil clams (pelecypods) are present throughout the Greenhorn limestone and are most numerous in the upper part; they have been identified as *Inoceramus labiatus* (Schlotheim).

The formation is overlain conformably by the Fairport chalky shale member of the Carlile shale. The contact is gradational through a distance of several inches and ranges in altitude from 875 feet in the Bon Oil Co.—Nick Jelsma No. 2 drillhole to 935 feet at Yankton (table 2).

Correlation of strata near Yankton with the Greenhorn limestone of Late Cretaceous age as it is known elsewhere in the region is based on the similarity of lithologic character and sequence as observed in drill cores at the Gavins Point Dam.

When Gilbert subdivided the (Fort) Benton group of Meek and Hayden (1861, p. 421-422) into three formations in 1896 (p. 564–565), he named the middle unit the Greenhorn limestone. The name, he stated, (1897, p. 4) was taken from exposures along Greenhorn Creek in Walsenburg and Peublo quadrangles, Colorado.

CARLILE SHALE

The Carlile shale is 227 to 288 feet thick and consists of partly calcareous, moderately firm, medium to dark-gray shale interbedded with a few thin layers of limestone, and, in the upper part, a distinctive bed of moderately firm, medium gray siltstone. The strata are subdivided into the following four members on the basis of lithologic character: Fairport chalky shale member at the base, Blue Hill shale member, Codell sandstone member, and Sage Breaks(?) member at the top.

Only the uppermost strata of the Carlile shale are exposed near Yankton. Near the center of the NW¼ sec. 24, T. 33 N., R. 1 E., just northwest of St. Helena, 5 feet of the Sage Breaks(?) member crop out in the south bluff of the Missouri River trench. Because the upper contact of the Carlile shale is 40 feet above the bottom land terrace at this locality, it is inferred that an additional 35 feet of the formation is concealed beneath a colluvial mantle in the slope below the outcrop. In the same bluff upstream from this locality the member is concealed owing to a gentle westward dip and a cover of colluvium; downstream for several miles progressively lower members crop out. In the north bluff of the Missouri River trench outcrops of the Carlile shale are absent owing to the presence of the James River trench, a concealing mantle of Pleistocene deposits, and the westward dip of the formation. In the Yankton area the formation is best known from drill cores at the Gavins Point Dam; in addition the upper 57 feet of the strata were exposed in the foundation excavation for the dam powerhouse.

Macrofossils are common in the Carlile shale, particularly in the lower part, but are generally so crushed as to be unidentifiable. The larger pieces recovered are apparently valve fragments of clams.

Strata near Yankton are correlated with the Carlile shale because of similarity of lithologic character and sequence. The most significant lithologic characteristic is the sandstone bed at or near the top of the formation; the lithologic sequence is indicated in plate 3. As localities where the four members have been recognized are 80 miles or more away, and as there are few or no intermediate supporting data available, there is some reason for making all correlations tentative. The striking similarity of the lithologic character and sequence with that of Upper Cetaceous strata throughout the western interior of the United States, however, favors firmer correlation.

The Carlile shale was named by Gilbert (p. 565) in 1896 for exposures in the vicinity of Carlile Spring and Carlile Station, just west of Pueblo, Colo. The strata originally constituted the uppermost part of the (Fort) Benton group of Meek and Hayden (1861, p. 419).

FAIRPORT CHALKY SHALE MEMBER

The thickness of the Fairport chalky shale member of the Carlile shale is believed to range from about 54 to 67 feet near Yankton. It is recognized in drill cores at the Gavins Point Dam, and in electric logs reproduced in plate 3. The rock consists of medium to dark-gray calcareous shale with scattered grains of pyrite. The most distinctive feature is a large amount of calcareous fossil material which forms many thin white laminae. The material generally is crushed so badly, however, that identification is impossible; some of the larger fragments are apparently of *Inoceramus.*

The contact with the overlying Blue Hill shale member is conformable and gradational through a vertical distance of several feet. It ranges in altitude from about 927 feet in wells near Springfield to 1,002 feet beneath Yankton.

These strata, originally referred to as the *Ostrea* shales by Logan (1897, p. 217-218) were formally named by Rubey and Bass in 1925 (p. 40-44) for exposures a few miles southwest of Fairport, Russell County, Kans.

BLUE HILL SHALE MEMBER

The Blue Hill shale member of the Carlile shale is inferred from electric logs to be from 146 to 177 feet thick. The rock consists of slightly calcareous medium-gray shale containing, along the bedding planes, scattered grains and small nodules of pyrite, some small phosphatic concretions, and thin laminae of calcareous fossils. The strata are less calcareous and contain fewer fossiliferous laminae than do the strata of the Fairport chalky shale member below. The lower part of the Blue Hill shale member contains a quarter-inch-thick bed of gypsum which is probably of local extent. In the upper part silty laminae are interbedded with the shale, and a single lens of limestone of small extent is present near the Gavins Point Dam. This lens is 3 to 18 inches thick and composed of hard, fine-grained, medium light gray limestone. Slightly lighter nodules within it have been fractured, the parts separated a quarter of an inch, and the intervening space filled by a darker limestone cement. The lens shows distinctly in the Bon Oil Co., —Isaac and Byrne No. 1 electric log, reproduced in plate 3, as a sharp peak in the resistivity curves at about 1,100 feet altitude. The formation is known best from drill logs at the Gavins Point Dam and from electric logs; in addition the uppermost 43 feet of the member was temporarily exposed in the excavation for the dam powerhouse.

Macrofossils are somewhat more numerous in the lower part of the formation than in the upper. They apparently consist of *Inoceramus* fragments which are crushed, as in the member below.

The contact with the overlying Codell sandstone member is conformable and gradational through a vertical distance of several inches. It ranges in altitude from 1,106 to 1,148 feet, or from 14 to 29 feet below the contact of the Carlile shale with the overlying formation.

The name Blue Hill shale, taken (Rubey and Bass, 1925, p. 39) from the Blue Hills in Mitchell County, Kans., was given by Logan (1897, p. 219-219) to the Victoria formation, or Victoria clays, of Craigin (1896, p. 50), The unit was raised to member rank by Dane and Pierce in 1933.

CODELL SANDSTONE MEMBER

The Codell sandstone member of the Carlile shale is 5 to 13 feet thick at the dam site and from 5 to 9 feet thick elsewhere in the vicinity of Yankton. The rock consists of firm to friable clayey siltstone containing a small amount of fine to very fine sand interbedded with a few thin partings of silty shale. The siltstone is in part thickly bedded and is also partly cross laminated. Individual laminae are less than an eighth of an inch thick and range from dark to light gray, depending on the amount of clay admixed. The silt and sand grains are chiefly quartz, but they include a moderate amount of mica and some feldspar. The member was temporarily exposed during excavation of the powerhouse foundation at the Gavins Point Dam. No macrofossils have been observed.

At the Gavins Point Dam the upper contact of the member averages about 1,142 feet and ranges from 1,133 to 1,162 feet in altitude; elsewhere in the area it is known to range from 1,111 to 1,164 feet. Almost everywhere the siltstone is overlain conformably and gradationally through a vertical distance of several inches by the Sage Breaks (?) member, and elsewhere unconformably by the Fort Hays limestone member of the Nobrara formation.

In 1926 Bass (p. 28, 64) named a sandy unit forming the upper part of the Blue Hill shale member the Codell sandstone bed; it was named for exposures near Codell in Ellis County, Kans. In 1933 the bed was raised to member rank by Dane and Pierce.

SAGE BREAKS (?) MEMBER

The Sage Breaks (?) member of the Carlile shale is as much as 6½ feet thick at the Gavins Point Dam but is locally absent; elsewhere it is from 5 to 22 feet thick. About 5 feet of Sage Breaks (?) strata are exposed in the south wall of the Missouri River trench northwest of St. Helena, at the location described on page 91, and about 10 feet were temporrarily exposed in the Gavins Point Dam powerhouse excavation. The strata consist of interbedded medium-gray noncalcareous and slightly calcareous shale. No macrofossils were observed.

The contact with the overlying Fort Hays limestone member of the Niobrara formation locally differs in nature. Drill cores in the vicinity of the Gavins Point Dam show the contact there is comformable and gradational through a vertical distance of 3 to 5 inches. In the outcrop northwest of St. Helena, however, the contact is abrupt and disconformable, with as much as 2 feet of relief. The altitude of the contact ranges from 1,133 to 1,208 feet.

The name Sage Breaks was assigned by Rubey (1930, p. 4) to strata which he believed to be the basal part of the Niobara formation but which Darton (1909, p. 55-56) had considered the uppermost part of the Carlile shale. The name was taken from exposures in the Sage Breaks, Weston County, Wyo. The member was reassigned to the Carlile shale by Cobban in 1951 (p. 2170, 2189-2190).

In the type area, the Sage Breaks member overlies the Turner sandy member, a correlative of the Codell sandstone member farther east and south. In the vicinity of Yankton, shale strata that overlie the Codell sandstone member are tentatively correlated with the Sage Breaks member because of the lithologic sequence.

ENGINEERING CHARACTERISTICS

The Carlile shale is the oldest formation in the vicinity of Yankton for which there is information pertaining to observed engineering characteristics. This information is limited, moreover, chiefly to the upper part of the formation as exposed during construction of the Gavins Point Dam, for there is only one natural exposure in the Yankton area (page 91). Engineering characteristics of the lower part of the formation may be similar, however, at least at the dam site, because cores and drilling rates in the lower part of the formation are similar to those of shale strata in the upper part.

The shale is somewhat firm; when moist a chunk of clay may be broken in the hands by exerting considerable force, and projecting corners are easily removed. When dry it breaks more readily along bedding planes than across them, and particles of silt and clay rub off on the fingers. The Codell sandstone member is somewhat firmer and lacks the shaly parting. The formation can be excavated both by hand and by power equipment. Blasting, although not necessary, is commonly utilized and particularly helpful in penetrating the siltstone bed at or a few feet below the upper contact. Permeability is extremely low and limited chiefly to very fine joints. These are very numerous in weathered parts of the formation and are common as much as 30 to 40 feet beneath or behind a surface exposed to weathering. Because the formation consists largely of clay and is generally moist or saturated, trafficability for heavy equipment is poor.

Observation of the few natural exposures of Carlile shale in and near the Yankton area shows that faces at a 70° angle have changed little during a 4-year period. This is due in part to shelter afforded the shale outcrops by vegetation and overhanging rock of the formation above. Comparison with the younger Pierre shale, which appears to be physically similar, suggests, however, that even under exposed conditions a slope of 45° would be little modified in a comparable period.

Physical characteristics of the upper part of the Carlile formation were obtained by the Corps of Engineers in their Soils and Materials Laboratory, Omaha, to determine suitability as a foundation material for the Gavins Point Dam powerhouse and spillway. Preconstruction tests yielded the data quoted (J. A. Trantina, district geologist, written communication, Dec. 21, 1954) in the table below. A distinction is not made in this table between the Sage Breaks(?) and Blue Hill shale members, which are referred to as the "clayey phase"; the "sandy phase" is the Codell sandstone member.

	Clayey phase	*Sandy phase*
Unconfined compression ---- psi	530	240
Cross grain shear strength ---- psi	50	50
Modulus of elasticity ---- psi	24,800	45,000
Dry density ---- lbs per cu ft	118	131
Moisture ---- percent	16	9
Specific gravity	2.69	2.69
Permeability ---- cm per sec	Impervious	10^{-5} to 10^{-9}

Carlile shale immediately beneath the Codell sandstone member caused some difficulty in foundation preparation for the Gavins Point Dam powerhouse, for slopes of about 75° failed subsequent to excavation. Available information does not clearly indicate the cause of the failure. It may have been differential wetting and drying with or without accompanying frost action, removal of confining overlying material (100 to 150 feet of rock and earth were removed), or both.

NIOBRARA FORMATION

The Niobrara formation is 182 feet thick in the NE¼NE¼ sec. 17, T. 93 N., R. 56 W., Yankton County, and Darton (1905, p. 184) reports a thickness of 205 feet at Santee, Knox County, Nebr. The rock is a medium bluish gray argillaceous lime stone that on exposure quickly weathers to grayish yellow, eventually becoming dark yellowish orange. It is soft and moderately firm, and when wet is highly plastic, especially weathered parts. Nonweathered material breaks into crudely chiplike or splintery pieces with a distinct but crude conchoidal fracture, but weathered rock breaks into irregular chunks.

Calculations based on insoluble-residue test data by Curtiss (1950, p. 53) show that calcium carbonate constitutes about 81 percent by weight of the formation. Most, if not all, of the carbonate is of organic origin. Calvin (1894, p. 153–154) estimated that Foraminifera constitute one-fourth to one-third the volume of the formation, and that rhabdoliths and coccoliths (extremely minute rods and plates, respectively, composed of calcium carbonate secreted by the biflagellate single-celled algae *Coccolithophoridae*) compose much of the matrix. Calvin found nearly all the foraminiferal shells to be filled with calcite and concluded that some of the comminuted debris is derived from the outer layer of *Inoceramus* valves.

The insoluble residue, about 19 percent by weight, consists of particles ranging in size from clay to fine sand. The clay minerals were found by X-ray refraction (USGS diffractogram 230,190, interpreted by A. J. Gude 3d) to be chiefly montmorillonite and illite; the remaining material consists of some quartz and feldspar and a little pyrite and phosphatic material. The residue is chiefly disseminated throughout the formation but composes a few very thin laminae.

Expression and distribution.—The Niobrara formation is the most distinctive lithologic unit in the region for it weathers a vivid yellow and commonly crops out in nearly vertical bluffs. Where it is overlain by a discontinuous mantle of younger material and the thickness of the exposed strata is slight, the outcrop forms a light yellow spalsh of color with a profile graded to the adjacent slope. The formation is present beneath the entire Yankton area with the exception of the James River and Missouri River trenches. It is best exposed along the walls of the Missouri River trench and in many valleys tributary thereto. Small scattered exposures are along Clay Creek on the southwest flank of Turkey Ridge, along Beaver Creek near the southeast end of James Ridge, and along many shallow draws in the area, notably those that drain southeast across Cedar County, Nebr. The Niobrara formation also lies at the surface of an area of about 5 square miles northwest of St. Helena, and a second area of about 2½ square miles lies 5 miles south of St. Helena. In these two areas the argillaceous limestone is generally mantled by 1 to 3 feet of alluvium and loess, although locally the thickness may be as great as 5 to 8 feet. Because this mantle is discontinuous and of irregular thickness the underlying bedrock has been mapped.

Paleontology.—Macrofossils found by the author include many disklike colonial groups of the index fossil *Ostrea congesta* Conrad, a few oysters of other, unidentified species, a clam (*Inoceramus?*), many scales, teeth, and bone fragments of unidentified species of fish, and a few rushes. A detailed study of the macrofauna of the formation as exposed in the Yankton area was made by N. C. Georgensen (written communication, 1931) for an unpublished thesis at the University of Iowa. In it Georgesen also made a brief study of the microfossils, an investigation that was repeated in greater detail over a larger area by Loetterle in 1937, and Bolin in 1952.

Subdivision. — Two members of the Niobrara formation have been recognized in Kansas for many years; the lower unit is called the Fort Hays limestone member, the upper the Smoky Hill chalk member.

Georgesen (written communication, 1931) concluded from his study of the formation as exposed along the Missouri River near Yankton that the unit was divisible into three members on faunal and lithologic evidence and that the subdivision is more dependent on microfauna than on macrofauna. He stated, however, that "***detailed work was not done on the microfauna ***," and proposed no formal names for his members.

In 1937 Loetterle made a detailed study of the microfauna of the Niobrara formation as exposed in central Kansas, eastern Nebraska, and southeastern South Dakota. He concluded (p. 13–14) that the formation can be divided into two members on both microfaunal and lithologic evidence, and extended formal names used in Kansas. Despite his statement that the basis of subdivision is partly lithologic, his description of the Smoky Hill chalk member is extremely brief, although valid for the Yankton area. No description of the Fort Hays limestone member is given.

In 1952 Bolin completed a detailed microfaunal study of the formation in southeastern and central South Dakota. He also recognized two members, and used the names extended by Loetterle. Bolin stated (p. 4–5):

> The results of this investigation indicate that it would be extremely difficult to recognize a lithologic subdivision of the Niobrara formation in this area. The lower part of the formation is somewhat harder, more dense, and has a slightly more bentonitic clay fraction than the upper part. These changes are very minor and would be a poor basis for subdividing the Niobrara into members. However, as they occur at the same horizon as the major microfaunal change, the Fort Hays-Smoky Hill contact is placed at this horizon. Since the main basis for subdivision is micropaleontologic rather than lithologic, it remains very difficult if not impossible to distinguish between the two members in the field without additional laboratory study.

In the Yankton area the formation may be readily divided into two members, primarily on the thickness of bedding. This method is practical, however, only where there are good, nonweathered exposures of several feet of strata; in shallow outcrops the bedding commonly is not exposed well enough or is modified by weathering. Detailed descriptions of the members follow.

Correlation and name.—Beds assigned to the Niobrara formation in the Yankton area have been correlated with those of the type locality a few miles upstream by direct tracing. Correlation is supported, moreover, by the similarity of the lithologic character and sequence and by index fossils.

The formation, originally Division No. 3 of Hall and Meek (1855, p. 405) was renamed the Niobrara Division by Meek and Hayden (1861, p. 422-424) for exposures along the Missouri River near the mouth of the Niobrara River in Knox County, Nebr.

FORT HAYS LIMESTONE MEMBER

The Fort Hays limestone member is 80 to 85 feet thick in the vicinity of the Gavins Point Dam and consists of thickly to massively bedded medium bluish gray limestone. H. L. Weil (written communication, Feb. 6, 1951), chief of the Corps of Engineers Soils and Materials Laboratory at Omaha, Nebr., states that at Pickstown, S. Dak., about 80 miles upstream, the rock:

> *** is extremely fine-grained, slightly porous, and slightly to highly absorptive. Although the rock is usually massive in appearance, subparallel microfossils and unidentified dark spots locally produce an elementary type of bedding. Locally, also, a faint 'salt-and-pepper' texture can be distinguished with difficulty. Thin section observation shows that microcrystalline carbonate and micro-grained clay particles form a matrix in which partially recrystallized microfossils filled with calcite are imbedded. Traces of phosphatic material are scattered through the rock. Insoluble residues appear medium gray in reflected light. They are composed principally of lightly stained clay minerals and smaller amounts of fine quartz and feldspar particles. The clay minerals of the insoluble residues are coarser grained than in the Smoky Hill member and usually show a parallel alignment. ***

This description is also valid for the member near Yankton.

Curtiss (1950, p. 53-55) collected four samples of this member from a drill core obtained about 4 miles southeast of the southern abutment of the Gavins Point Dam. The samples represented about 63 feet of core, or three-fourths of the thickness of the member. Insoluble-residue tests by Curtiss indicate the calcium carbonate contant ranges from 69.48 to 84.28 percent; only one sample contained less than 75 percent. Curtiss also obtained chemical analyses of the same samples, and computation show that the calcium carbonate content of the rock ranges from 77.53 to 87.05 percent. The average chemical analysis of the member, as computed from Curtiss' data and weighted for the thickness of section represented, follows:

	Percent		*Percent*
SiO_2	9.50	MgO	.85
Fe_2O_3	2.56	SO_3	.26
Al_2O_3	3.61	Volatiles	27.04
CaO	46.26	Moisture	1.41
			91.49

Computation indicates the average calcium carbonate content of the rock is 82.57 percent. The analysis is considered to be representative of the Fort Hays limestone member in the vicinity of Yankton.

The member is largely massive, and the few distinct beds observed are nearly all more than 6 feet thick and form the uppermost part of the member. Some partings between the beds are gypsiferous or bentonitic like those in the overlying Smoky Hill chalk member, but the partings are less than half an inch thick. The strata are broken by two sets of nearly vertical closed joints into large, roughly rectangular blocks. Ground water moving through the joints has produced a band of oxidized material several inches wide on either side. Roughly cylindrical pyritic concretions as large as 3 by 8 inches are in the lower 10 to 15 feet of strata near St. Helena. When weathered the concretions are concentrically banded and cause brown ferruginous spots several inches in diameter. The basal beds in which they occur are somewhat more siliceous and thus are harder than the overlying beds.

Expression and distribution.—The Fort Hays limestone member is exposed in the lower part of the nearly vertical bluffs that form the walls of the Missouri River trench. The lower half, which generally lies below the level of the trench floor, is readily accessible in the NW¼ sec. 24, T. 33 N., R. 1 E., Cedar County; here the basal contact is about 40 feet above the floor, and the upper half of the member has been removed by erosion. The upper half is most accessible in secs. 21 and 22, T. 93 N., R. 57 W., Yankton County, and in the vicinity of the Gavins Point Dam. The entire member was temporarily exposed in excavations for the dam powerhouse (pl. 4*A*). The beds are best distinguished by their thick to massive character.

Paleontology.—The very few macrofossils found in the member by the writer consist of a few oysters *(Ostrea congesta* Conrad), a clam *(Inoceramus?)*, and many bone fragments, teeth, and scales of fish. Microfossils are numerous and have been studied in detail by Loetterle (1937) and Bolin (1952).

Upper contact.—The upper limit of the Fort Hays limestone member is difficult to place owing to its transitional nature, its close lithologic similarity to strata that form the upper member of the Niobrara formation, and its inaccessibility in many of the better exposures. It is drawn somewhat arbitrarily at a decrease in thickness of bedding in the upper part of those massive strata generally separated by gypsum layers half an inch or less in thickness. Beds encompassing the contact are also characterized by a transition upward to lesser hardness, and, as shown in figure 3, lesser density and greater moisture content. In the field, however, these physical differences are difficult to ascertain. The contact is also marked by a transitional change in color of the nonweathered rock from lighter gray below to darker gray above. This change is undependable as a means of recognizing the contact because a second similar color change shown in plate 4*A* exists within strata here assigned to the Fort Hays limestone member, and because the change is apparent only on nonweathered surfaces, for within several weeks after exposure both members of the formation weather to the same light gray and the colors become indistinguishable.

The color transition and other features marking the contact were observed in a drill core (Corps of Engineers drill hole no. 166, SE cor. sec. 9, T. 93 N., R. 56 W., Yankton County) later used by Bolin for his study of microfossils in the Niobrara formation. In this core the transitional strata are about 10 feet thick. They are exposed, although neither readily apparent nor accessible, in steep bluffs adjacent to the Gavins Point Dam, and in secs. 17 and 18, T. 93 N., R. 57 N., Yankton County, and lie just below the floor of an abandoned quarry[9] adjacent to the drill-hole site.

Correlation and name.—Correlation of these strata with those of the type area is dependent partly on similarity of lithologic character and sequence, and partly on examination by the writer of scattered exposures of the formation in eastern Nebraska and central Kansas.

Mudge (1876, p. 218-219) originally gave the name Fort Hays division to strata that now constitute the lower member of the Niobrara formation and the three subjacent formations. According to the Kansas Geological Society (*in* Wilmarth, 1938, p. 756), the name was taken from old Fort Hays in western Kansas. Williston (1893, p. 108–109) later restricted the name to beds at the top of Mudge's division, and Craigin (1896, p. 51) subsequently assigned them to the Niobrara formation.

[9] The quarry and adjacent plant site, both abandoned, belonged to the former Western Portland Cement Co: the land is now privately owned.

SMOKY HILL CHALK MEMBER

The Smoky Hill chalk member is about 100 feet thick in the vicinity of the Gavins Point Dam and consists of medium bluish gray argillaceous limestone which is thinner bedded than that in the underlying member. At Pickstown, S. Dak., the rock, according to H. L. Weil (written communication, February 6, 1951) of the Corps of Engineers, is

> *** composed of *** soft chalk which is very fine grained, microscopically porous, and highly absorptive. Although the rock appears massive in unweathered specimens ***, elementary bedding is shown in vertical section by a parallel arrangement of numerous white microfossils. The microfossils are imbedded in a gray matrix so that the chalk usually has a marked 'salt and pepper' appearance. Traces of phosphatic matter and pyrite are scattered through the rock. *** The insoluble residues appear very dark gray or black in reflected light. They are almost opaque to transmitted light, but some extremely fine-grained, randomly oriented clay mineral flakes can be seen under the microscope ***.

This description is also valid for the member in the Yankton area.

Curtiss (1950, p. 50, 53) collected five samples of the Smoky Hill chalk member from a section exposed in the abandoned quarry in the NE cor. sec. 17, T. 93 N., R. 56 W., Yankton County. These samples represented 83 feet of section, or about four-fifths of the thickness of the member. Insoluble-residue tests by Curtiss showed the content of calcium carbonate to be from 77.38 to 89.91 percent, and chemical analyses of the same samples gave calculated results from 82.28 to 94.38 percent. Following the same procedure as for the Fort Hays limestone member, the average chemical analysis of the Smoky Hill chalk member was computed from Curtiss' data to be:

	Percent		*Percent*
SiO_2	5.04	MgO	.55
Fe_2O_3	3.89	SO_3	1.20
Al_2O_3	1.78	Volatiles	36.78
CaO	49.03	Moisture	2.09
			100.36

Calculation indicates the average calcium content of the rock is 87.51 percent. This analysis is considered to be representative of the Smoky Hill chalk member in the vicinity of Yankton.

Beds of the Smoky Hill chalk member are very similar to the underlying strata. The principal differences include the thickness of bedding and the distinctness of bedding planes. The upper 45 to 50 feet of the member is characterized by beds ranging in

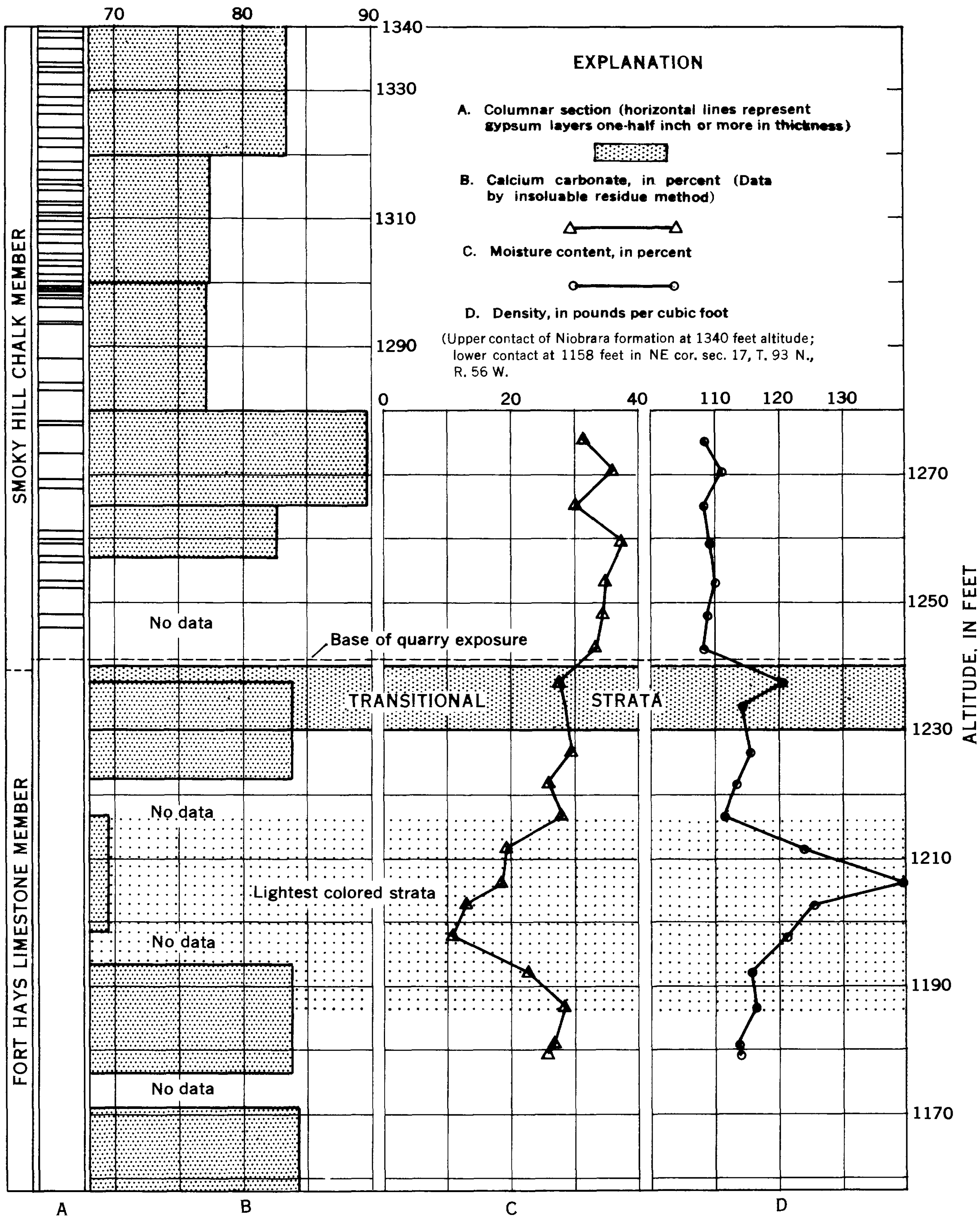

FIGURE 3.—Composite columnar section of the Niobrara formation, showing calcium carbonate content, moisture content, and density of certain parts. The position of the contact between the two members is marked by transitional strata, a change in the thickness of bedding, and the presence in the upper member of gypsum layers half an inch or more thick. The light-colored part of the lower member, illustrated in plate 4A, is indicated.

thickness from 6 inches to 2 feet (pl. 4*B*), but bedding in the lower part ranges from 1 to 6 feet. As strata in the underlying Fort Hays limestone member are even thicker, there is a decrease in thickness of strata from the base of the Niobrara formation to the top. In addition, beds constituting the upper 30 feet of the Smoky Hill chalk member locally weather a slightly redder color, are more soluble, and are more thoroughly jointed than other strata of the formation.

Bedding planes within the Smoky Hill chalk member commonly are marked distinctly by gypsiferous layers and large disklike colonial groups of oysters. The gypsum layers are 1 to 5 inches thick and contain small amounts of bentonite, other clayey matter, and calcium carbonate. The layers have sharp, slightly irregular contacts and are a little more resistant to weathering than the adjacent argillaceous limestone. The gypsum crystals are generally acicular, of simple habit, loosely cemented, translucent, and ½ to 1 inch in length; they are oriented perpendicular to the bedding plane. In some layers the crystals are granular, white, and of sugary texture, in others a little crudely banded gypsum was observed. Several of the thicker layers of acicular crystals have contacts marked by an accumulation as much as half an inch thick of sugary crystals, but such crystals also occur in the middle part of a few layers. The bentonite is grayish green to grayish yellow and is present chiefly in layers in the upper part of the member. Commonly it is disseminated to varying degrees, but locally it is in small lenses about an inch thick and a few inches across; these are generally interrupted by stringers of gypsum. The other clayey matter is bluish-gray mudstone believed to consist of insoluble material. The calcium carbonate is somewhat disseminated, white, and powdery. Iron oxides stain several of the layers, notably those with sugary texture, and particularly the layer immediately underlying the upper contact of the formation.

The gypsum layers probably are of secondary origin. Oxidation of pyrite in the strata is believed to have produced acid sulfate water. Movement of the water along bedding planes probably caused replacement of the carbonate radical in the limestone with a sulfate ion in solution, yielding gypsum. This process accounts for several features of the gypsum layers: (1) their occurrence along bedding planes in the limestone, (2) the sugary, acicular, and banded nature of the gypsum, (3) orientation of the acicular crystals, (4) the commonly greater permeability of the middle part of a layer, and (5) the presence of clay, residual in origin owing to leaching of the carbonate radical. Recrystallization of the gypsum subsequent to its formation is suggested by the large size of some acicular crystals, stringers of gypsum that penetrate clay bodies, and crudely banded gypsum, but evidence is inconclusive.

Some of the limestone strata display when nonweathered, laminae characterized by color banding as illustrated in plate 5*A*. The individual laminae commonly alternate in color value between medium dark bluish gray and light bluish gray. The difference is apparently owing to a greater amount of calcareous material in the light-colored laminae; also, the median grain size is a little coarser in these same laminae. Contacts between laminae are generally distinct but rarely sharp. Individual laminae range in thickness from about one-eighth to three-eighths of an inch. Conditions of sedimentation were clearly cyclic, and they may have been periodic; no evidence of a greater cycle of sedimentation was obvious.

Joints locally are numerous in the Smoky Hill chalk member. They commonly are half an inch to an inch wide, bordered by sharp but somewhat irregular contacts, and filled with secondary gypsum like that marking the bedding planes. The filled joints are found throughout the member and locally are so numerous as to resemble, together with the bedding-plane layers which they post-date, a coarse "boxwork" illustrated in plates 4*B* and 5*B*.

Expression and distribution.—The Smoky Hill chalk member is well exposed in both bluffs of the Missouri River trench upstream from Yankton. An excellent, easily accessible exposure of nearly the entire thickness is found in the quarry in the NE¼-NE¼ sec. 17, T. 93 N., R. 56 W., Yankton County, and is illustrated in plate 4*B*. Most other exposures of the member are either on gentler slopes and so are partly mantled by thoroughly weathered or colluvial material or are steep and relatively inaccessible. The Smoky Hill is distinguished from the Fort Hays limestone member below by the thinner bedding, the presence of gypsum layers and fossil oyster colonies along the bedding planes, and locally the somewhat redder weathered color, greater solubility, and more thorough jointing of the Smoky Hill chalk member.

Paleontology.—Fossils are numerous in the Smoky Hill chalk member. Macrofossils include *Ostrea congesta* Conrad, which is generally present as colonial clusters in rough calcareous disks about 1 to 1½ inches thick, and from a few inches to several feet across. A few shells are found as separate individuals or attached to other shells. The colonies have

A. The Fort Hays limestone member, Niobrara formation, as it was exposed in the south end of the Gavins Point Dam powerhouse excavation. The light-colored strata marking the middle part of the member are clearly visible in the freshly sawed face. Photograph by Corps of Engineers, U. S. Army.

B. Smoky Hill chalk member, Niobrara formation, exposed in the face of an abandoned quarry in the NE cor. sec. 17, T. 93 N., R. 56 W., Yankton County. Note thickness of bedding, solution pits, and joints; the face is about 80 feet high.

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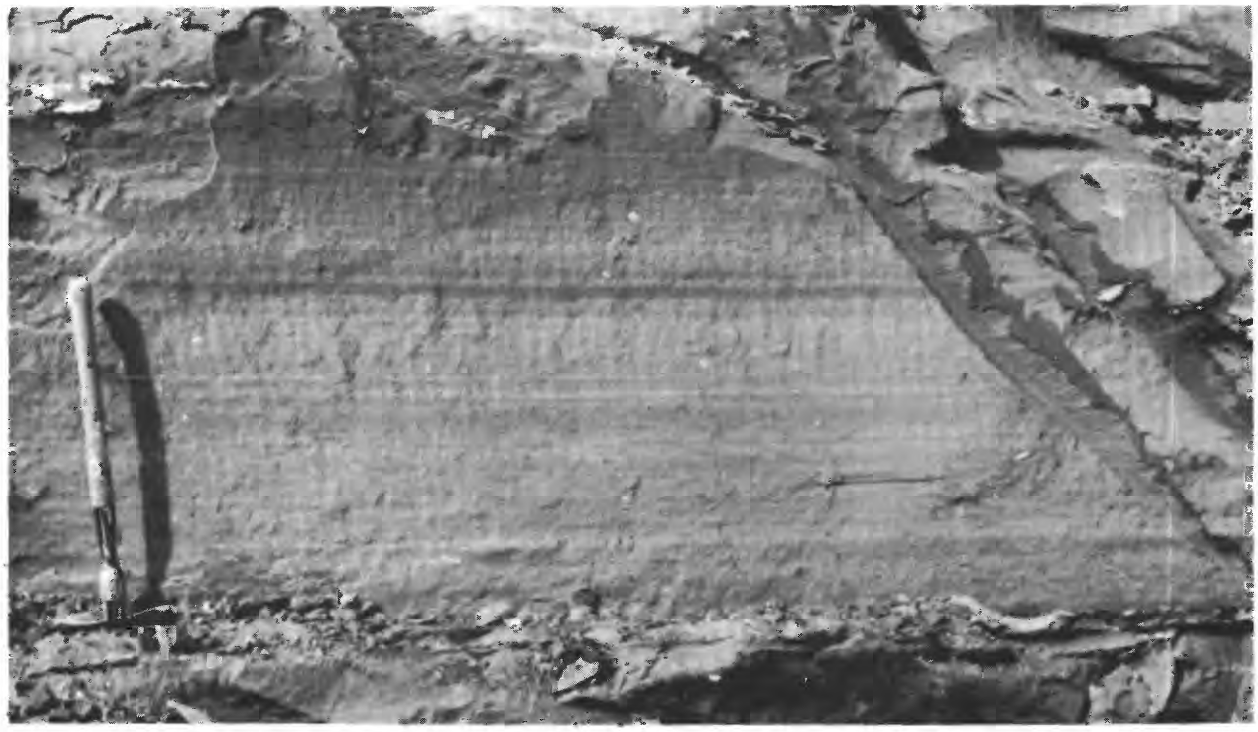


A. Laminae in the lower part of the Smoky Hill chalk member, Niobrara formation, distinguished chiefly by differences in composition and color; exposed in the Gavins Point Dam powerhouse excavation.

B. Coarse "boxwork" of gypsum-filled bedding planes and joints in the Smoky Hill chalk member, Niobrara formation; exposed in the SE cor. NE¼NW¼ sec. 23, T. 93 N., R. 57 W., Yankton County.

been observed only along bedding-plane partings, and are commonly associated with gypsum layers. The thin lenses of limestone to which the oysters are attached occupy slight depressions in the underlying bed. During hiatuses in deposition of the member, calcium carbonate mud collected in slight depressions on the sea floor, and lithified. Owing to the firmness and composition of the resulting lenses, they afforded more favorable sites for growth of oysters than adjacent, more clayey parts of the bottom.

The presence of oyster colonies along the bedding planes and associated with the gypsum layers indicate intervals of nondeposition or very nearly so. This opinion is based on the fact that modern oysters live only in essentially nondepositional environments, and on the assumption that Cretaceous oysters required an environment similar to that of modern genera.

Other macrofossils include fragments of rushes, and many scales, teeth, and bone fragments of fishes. Microfossils are numerous and have been described by Loetterle (1937) and Bolin (1952).

Upper contact.—The upper limit of the Smoky Hill chalk member, and, therefore, of the Niobrara formation, is conformable, abrupt, and marked by a gypsiferous layer 1 to 5 inches thick and characterized by strong ferruginous staining. The layer is illustrated in plate 6*A*. The altitude of the contact at 24 outcrops from 1 to 13 miles apart on both sides of the Missouri River between St. Helena and Niobrara and ranges from 1,402 feet near St. Helena to 1,278 feet near Niobrara (Simpson, 1952, fig. 7). The maximum altitude observed was 1,473 feet in the center of sec. 35, T. 95 N., R. 54 W., Yankton County.

Correlation and name.—Strata assigned to this member in the vicinity of Yankton are correlated with those of the type locality chiefly on the similarity of lithologic character and sequence and partly on examination of scattered exposures of the formation in eastern Nebraska and central Kansas.

The member was named by Craigin in 1896 (p. 51) for exposures along the Smoky Hill River in western Kansas.

ENGINEERING CHARACTERISTICS

The rock is nearly firm, and a piece may be broken in the hands by exerting considerable force. It breaks with a crude conchoidal fracture forming irregular, somewhat slabby or splintery pieces. Excavation of the Niobrara formation is possible both by hand and by power equipment; blasting, although not necessary, is advantageous. Power shovels can cut to within 1 foot of a limit with little overbreakage, and smooth faces are readily cut to close tolerances with truck-mounted coal saws. The Corps of Engineers mounts saws on a circular, rotating mechanism for tunnel cutting. Permeability is very low and limited chiefly to joints; these are most numerous in the Smoky Hill chalk member but are more open in the Fort Hays limestone member. Owing to its clay content the rock is plastic when wet, particularly weathered parts, and dusts off readily when dry. Trafficability may be poor in wet weather.

Natural slopes of 70° to 90° stand for years with little recession and no slumping or sliding. Any retreat of such a slope is largely the result of frost action. Faces newly cut in unweathered rock are very susceptible to frost action and become fractured to a depth of about 1 foot in the first year. From a few observations, however, it is inferred that this rate of breakage will decrease during subsequent years if the broken material is not removed.

Physical characteristics of the formation were determined by the Corps of Engineers Soils and Materials Laboratory, Omaha, to ascertain its suitability as foundation material for the Gavins Point Dam powerhouse and spillway, and as fill material in the rolled-earth embankment that will eventually constitute most of the dam. Preconstruction tests yielded data quoted in the following table (communication, J. A. Trantina, district geologist, December 21, 1954). No distinction between the two members of the formation has been made.

Physical characteristics of the Niobrara formation

Unconfined compression	psi	750
Crossgrain shear strength	psi	110
Modulus of elasticity	psi	142,500
Dry density	lb per cu ft	95
Moisture	percent	28
Specific gravity		2.69

Preliminary and progress tests have shown that the Niobrara formation can be used satisfactorily for the impermeable part of a dam embankment.

PIERRE SHALE

The Pierre shale is as much as 180 feet thick a few miles west of Yankton, but owing to erosion the top of the formation is missing and the original thickness is unknown. The strata consist of shale, claystone, calcareous mudstone, and marl, of which shale is estimated to constitute about one half. The marl is light gray when nonweathered and weathers yellowish orange; the other rock types are gray both nonweathered and weathered. The rock is composed chiefly of montmorillonite, although calcium car-

A. Contact of the Niobrara formation with the overlying Sharon Springs member, Pierre shale, in the NE¼NW¼ sec. 23, T. 93 N., R. 58 W., Bon Homme County. At this locality the ferruginous gypsum layer (see arrows) marking the contact is conspicuous; the homogeneous beds above the contact are 18 inches thick.

B. The Gregory member, Pierre shale, as it crops out in the NE¼NE¼ sec. 17, T. 93 N., R. 56 W., Yankton County. The contact between the two units of the member is well exposed; the nature of the color change is characteristic of that between successive members of the formation.

bonate is dominant in the marls which are strikingly similar to the Niobrara formation below. All the rock types are soft and somewhat firm to firm; when wet they are highly plastic. The shale splits into small slabby pieces or flakes, but the others break into irregular chunks.

Expression and distribution.—The Pierre shale is fairly conspicuous despite its somber color, for it underlies much of the rolling grass-covered land along both sides of the Missouri River trench. It is exposed atop the north bluff of the trench from about 2 miles west of Yankton to about 1 mile east of the Hutterite Colony, and on the south bluff almost continuously upstream from the west boundary of Cedar County. The best sections are found in the many landslide scarps and stream-cut banks that scar the sides of small ravines tributary to the trench. The thickness of individual members and the altitudes of their contacts are commonly difficult to ascertain, for the strata are so susceptible to landsliding that few well-exposed beds remain undisturbed. An accessible locality where the formation is fairly well exposed in place is a small spur near the SE cor. NW¼ sec. 18, T. 93 N., R. 57 W., Yankton County. Here the formation is about 160 feet thick. Another locality with a complete, but slumped, section, is on the east side of a gully in the NE¼NE¼ sec. 23, T. 93 N., R. 58 W., Bon Homme County, where the formation is about 180 feet thick. Poor outcrops extend west from St. Helena and lie northwest of Bow Valley, and scattered small sections are exposed in Turkey and James Ridges.

Paleontology. — The macrofauna of the Pierre shale near Yankton is sharply limited in variety and restricted to a very few rich zones. A single mosasaur skelton was exhumed, and large amounts of fish remains consisting of scales, teeth, and fragments of bones were found in some strata. The microfauna was not examined, but collections from the marl beds have been studied by J. J. Schulte (written communication, 1951).

Subdivision.—The Pierre shale is readily subdivisible on the basis of lithology, and various subdivisions of the formation in South Dakota have been made by several geologists associated with the State geological survey and with the U.S. Geological Survey. Their work is summarized in table 3.

Of the four zones or facies of the Sully member of Gries and Rothrock (1941), only the Crow Creek is recognized in the vicinity of Yankton. The Oacoma zone, which is characterized upstream from the Rosebud Bridge site[10] by the presence of many large iron-manganese concretions, loses its distinctive lithologic character a few miles downstream from the bridge site. In a thesis submitted to the University of Nebraska in 1952 J. J. Schulte stated that in Knox County:

> *** black iron manganese concretions are sparse *** about the size of marbles, and their presence is the only indication of the Oacoma zone ***.

The small, sparse nodules are not a valid basis for correlation, however, as Schulte also stated that similar concretions are found in the Verendrye shale zone of Searight. Whether beds that lie above the Crow Creek and below the Virgin Creek members of this report are correlative with Searight's Agency zone, Oacoma zone, or Verendrye zone is not known. The Sully member of the South Dakota Geological Survey, therefore, may be used in the Yankton area for a stratigraphic unit which is readily delimited in the field.

The use of Crandell's DeGrey and Verendrye (locally pronounced Ver-en'-dree) members rather than Sully member is also possible, although in the Yankton area their contact neither can be proven nor readily located in the field. Crandell's subdivision, however, seems to express somewhat better the tentatively inferred picture of sedimentation. For this reason the extension of Crandell's nomenclature into southeastern South Dakota is preferred. Although it is conceivable that either the DeGrey or Verendrye member is absent from the area, reconnaissance of sections as far upstream as the Rosebud Bridge site suggests both are present. Because the two members are so similar in appearance and their contact is not proven in the vicinity of Yankton, they are described together in this report.

Correlation and name.—Beds assigned to the Pierre shale have been correlated with those of the type locality by direct tracing, supported by similarity of lithologic character and sequence.

The Pierre shale, originally designated Division No. 4 by Hall and Meek (1855, p. 405), was named the Fort Pierre group by Meek and Hayden (p. 424-427) in 1861 for exposures at old Fort Pierre, a few miles north of the present town of Fort Pierre, Stanley County, S. Dak.

SHARON SPRINGS MEMBER

The Sharon Springs member is 11 feet thick in the NE cor. sec. 17, T. 93 N., R. 56 W., Yankton County, at the abandoned cement plant quarry. Westward

[10] The Rosebud, or "Wheeler," Bridge stood about 75 miles northwest of Yankton at Wheeler, 17 miles south of Platte, Charles Mix County, S. Dak. It was removed in 1953.

TABLE 3.—*Principal changes in stratigraphic subdivisions and nomenclature of the Pierre shale in South Dakota along the Missouri River trench*

<table>
<tr><th colspan="2">North-central, central, and southeastern South Dakota</th><th colspan="10">Central South Dakota</th><th colspan="2">Southeastern South Dakota</th></tr>
<tr><th colspan="2">Searight 1937</th><th colspan="2">Searight 1938</th><th colspan="2">Moxon and others 1939</th><th colspan="2">Gries and Rothrock 1941</th><th colspan="2">Gries 1942</th><th colspan="2">Crandell 1952, 1958</th><th colspan="2">Simpson (this report)</th></tr>
<tr><td colspan="2">Elk Butte member</td><td colspan="2">Elk Butte member</td><td colspan="2">Elk Butte member</td><td colspan="2">Elk Butte member</td><td colspan="2">Elk Butte member</td><td colspan="2">Elk Butte member</td><td colspan="2">(not present)</td></tr>
<tr><td colspan="2">Mobridge member</td><td colspan="2">Mobridge member</td><td colspan="2">Interior member</td><td colspan="2">Mobridge member</td><td colspan="2">Mobridge member</td><td colspan="2">Mobridge member</td><td colspan="2">Mobridge member</td></tr>
<tr><td colspan="2">Virgin Creek member</td><td colspan="2">Virgin Creek member</td><td colspan="2">Virgin Creek member</td><td colspan="2">Virgin Creek member</td><td colspan="2">Virgin Creek member</td><td colspan="2">Virgin Creek member</td><td colspan="2">Virgin Creek member</td></tr>
<tr><td rowspan="3">Sully member</td><td>Verendrye shale zone</td><td rowspan="4">Sully member</td><td>Verendrye shale zone</td><td rowspan="4">Sully member</td><td>Verendrye zone</td><td rowspan="4">Sully member</td><td>Verendrye beds</td><td rowspan="4">Sully member</td><td>Verendrye zone</td><td colspan="2">Verendrye member</td><td>Verendrye member</td><td rowspan="3">undifferentiated</td></tr>
<tr><td>Oacoma zone</td><td>Oacoma zone</td><td>Oacoma zone</td><td>Oacoma zone</td><td rowspan="2">Agency-Oacoma zone</td><td rowspan="2">DeGrey member [1]</td><td>Shale-and-bentonite facies</td><td rowspan="2">DeGrey member</td></tr>
<tr><td>Agency shale</td><td>Agency shale</td><td>Agency shale</td><td>Agency shale</td><td>Siliceous-shale facies</td></tr>
<tr><td rowspan="5">Gregory member</td><td>Upper</td><td>Gregory marl</td><td>Gregory marl</td><td>Crow Creek sand and marl</td><td>Crow Creek chalk and sand</td><td colspan="2">Crow Creek member</td><td colspan="2">Crow Creek member</td></tr>
<tr><td rowspan="4">Lower</td><td colspan="2" rowspan="4">Sharon Springs member</td><td rowspan="4">Sharon Springs member</td><td rowspan="2">Upper</td><td rowspan="2">Gregory member</td><td>Shale zone</td><td colspan="2" rowspan="2">Gregory member</td><td colspan="2" rowspan="2">Gregory member</td><td rowspan="2">Gregory member</td><td>Claystone and shale unit</td></tr>
<tr><td>Marl zone</td><td>Marl unit</td></tr>
<tr><td rowspan="2">Lower</td><td rowspan="2">Sharon Springs member</td><td>Upper</td><td colspan="2" rowspan="2">Sharon Springs member</td><td colspan="2" rowspan="2">Sharon Springs member</td><td rowspan="2">Sharon Springs member</td><td>Non-bituminous unit</td></tr>
<tr><td>Lower</td><td>Bituminous unit</td></tr>
</table>

[1] Crandell did not subdivide this member in his report of 1950.

it thins to 5½ feet in the NE¼NE¼ sec. 23, T. 93 N., R. 58 W., Bon Homme County, and to 1 foot in the NE¼NE¼ sec. 22, T. 33 N., R. 4 W., Knox County. Farther west it thickens again to 9½ feet in the center NE¼ sec. 24, T. 93 N., R. 61 W., Bon Homme County.

The member consists of fissile, bentonitic, medium dark gray shale that is in part bituminous. It is weak and soft, and when wet it is highly plastic. When weathered, the rock readily separates into small thin chips. Curtiss (1950, p. 56) sampled the member for chemical analysis at the abandoned cement plant quarry; the result is quoted below.

Chemical analysis of the Sharon Springs member of the Pierre shale, from the NE¼NE¼ sec. 17, T. 93 N., R. 56 W., Yankton County

	Percent		Percent
SiO_2	60.98	MgO	1.69
Fe_2O_3	3.20	SO_3	none
Al_2O_3	16.84	Volatiles	7.53
CaO	1.84	Moisture	5.14
			97.22

From this analysis calcium carbonate is calculated to make up 3.28 percent of the member. An X-ray diffractogram (USGS 230,191, interpreted by A. J. Gude 3d) shows that the shale is composed chiefly of montmorillonite, with some quartz.

Well-weathered exposures of the member are characterized by many conspicuous bright yellow scales composed of a secondary sulfate of iron. Gude concluded that an X-ray diffractogram (USGS 223,620) of the material gave a good pattern of "d" spacings that closely match the complete measurements for coquimbite[11] (Palache and others, 1951, p. 532-534), a hydrated ferric sulfate. Measurements for cyprusite,[12] a variety of carphosiderite, (Palache and others, 1951, p. 566-567), a basic hydrated ferric sulfate, are an incomplete match. Owing to the fine grain of the mineral the refractive indices are known only to lie between 1.75 and 1.79, and thus compare favorably with the indices of carphosiderite (0: 1.82, E: 1.73); the indices of coquimbite are 0: 1.53 and E: 1.57. Also, the mineral, like carphosiderite, is not soluble in cold water, although coquimbite is. Because the refractive indices of the mineral are like those of carphosiderite, and because it is not soluble in cold water, the mineral is tentatively identified as carphosiderite.

The strata are divisible into two units. The lower unit ranges from 1 to 5½ feet in thickness. Where the lower unit is less than 3 feet thick, the upper unit is absent. Beds of the lower unit are bituminous and contain considerable bentonite, which is chiefly disseminated throughout the unit but which does form a few very thin layers of short lateral extent. The lowermost 18 to 24 inches of strata contain large quantities of fish teeth, scales, and bone fragments. The contact of the lower with the upper unit is at the base of two conspicuous bentonite layers in the upper unit.

The upper unit is from 3 to 5½ feet thick. It is nonbituminous and largely lacks the disseminated bentonite of the lower unit; thin layers of bentonite are more numerous, thicker, and of greater lateral extent. Two layers 3 to 5 inches thick and 1 to 3 inches apart lie immediately above the base of the unit. Another distinctive feature is the local occurrence of phosphatic concretions half an inch in diameter in the upper 2 to 4 feet of strata. They are composed chiefly of microscopically crystalline apatite, with many minute crystals of pyrite. Chemical analysis of a single sample (USGS 141,021) by Ann Sweeney and Percy Moore indicate that the concretions contain 29.2 percent phosphate and 0.003 percent uranium. They are olive gray to light olive gray, with a thin yellowish-gray rind. Some are irregular in form; these are generally less than half an inch in diameter and have no apparent nuclei. Others are more cylindrical; they are as much as 2 inches long and either contain an elongate bone fragment or are tubelike, probably owing to the loss of such a nucleus. None of the concretions have an apparent preferred orientation. Strata that contain them are typically exposed in the SE cor. NE¼ sec. 11, T. 93 N., R. 57 W., Yankton County, in the east wall of a small creek valley, or may be exposed by a little digging in a road ditch about 50 yards west of the SE cor. sec. 19, T. 33 N., R. 1 W., Cedar County.

Expression and distribution.—The Sharon Springs member is generally well exposed, for it crops out in bare slopes intermediate in angle between bluffs of the Niobrara formation below and grassy, gentle slopes of the overlying beds. Locally, however, the member is obscured by colluvium. The strata underlie much of the area, and good to fair exposures are found in nearly all parts where Pierre shale is exposed. The most accessible exposure is at the abandoned quarry in the NE¼NE¼ sec. 17, T. 93 N., R. 56 W., Yankton County, but in this outcrop the member is incompletely exposed. Possibly the best exposure is in the NE¼NW¼ sec. 23, T. 93 N., R. 58 W., Bon Homme County.

Paleontology.—A fossil macrofauna consisting of a large quantity of fish scales, teeth, and bone frag-

[11] Coquimbite: ASTM card number 3-0536; (3.12/100, 5.09/90, 3.06/90).
[12] Cyprusite: ASTM card number 2-0597; (3.06/10, 4.9/70, 1.97/70).

ments is a characteristic feature of the basal beds of this member. Similar material in very small amounts is found in the rest of the strata. No other macrofossils were found, and the microfauna has not been studied.

Upper contact.—The upper limit of the member is readily identified in the field by a change in color from the somber hue of the Sharon Springs to the lighter color of marl at the base of the overlying Gregory member. Where the Sharon Springs is overlain by a thin sandy layer the contact is disconformable, but where it is overlain by marl it is conformable and sharp.

Correlation and name.—Searight (1938, p. 137) based his correlation wholly on lithologic similarity. Strata in the vicinity of Yankton are correlated with the lower part of the Sharon Springs member of Searight by similarity of lithologic character and sequence.

The name Sharon Springs member was first applied by Elias in 1931 (p. 56-65) to interbedded bituminous and nonbituminous strata at the base of the Pierre shale in Wallace County, Kans.; the name was apparently taken from the town of Sharon Springs in the same county. In 1938 Searight (p. 137) extended the name to similar strata in South Dakota, which originally made up part of his (1937, p. 10-21) Gregory member, and which lay between the Niobrara formation and the Crow Creek member of this report. Subsequent changes in usage are indicated in table 3.

GREGORY MEMBER

The Gregory member is from 41 to 43 feet thick and consists chiefly of grayish-orange marl, and medium-gray shale and claystone. A distinctive thin, sandy layer is present at the base of the member. The strata are weak and soft; when wet the shale and claystone are highly plastic, the marl less so. When weathered the shale beds separate into small thin chips, and the claystone amd marl break down to yield a structureless, mealy earth. The strata are readily divisible into three units: the lowermost unit consists of the thin sandy layer, the middle unit consists of marl beds, and the uppermost unit consists of shale and claystone beds.

The sandy unit is as much as 4 inches thick. It is generally pale grayish green when nonweathered and oxidizes to yellowish gray, with iron stains. Small phosphatic nodules identical with those described in the upper part of the underlying Sharon Springs member are found wherever the sandy unit is exposed. The layer comprises two facies. The most common facies consists chiefly of grayish-green glauconite, fish teeth, scales, and bone fragments, a very little bentonite, a few grains of yellowish-gray siltstone, and a few shale pebbles. The pebbles are as large as 3 mm thick and 1 cm in diameter and are generally rounded. The other facies consists principally of angular shale fragments, bentonite, calcium carbonate (both disseminated and as small concretionary particles), and numerous coarse grains of clear quartz. The quartz grains are well rounded and of high sphericity; some have a frosted surface. Both facies are separated from the marl above, as from the strata below, by a disconformity.

The sandy unit contains an unusual concentration of fossil fish material. This accumulation may represent: (1) a lag concentrate left from the winnowing out of the clay fraction from strata of the Sharon Springs member by submarine wave and current action, (2) a hiatus in the deposition of clay particles, (3) the death of an unusually large proportion of fish life, or (4) a great increase in the total amount of fish life. The disconformable nature of the layer and its localized occurrence disallow all but the first possibility. If the amount of material in the concentrate is then compared with the amount of similar material in the underlying strata, one infers that locally the erosion of at least 5 to 10 feet of shale was necessary to yield the amount of fossil material in the concentrate.

Exposures of the sandy layer are of small lateral extent, but their distribution indicates that the unit is discontinuous. For these reasons spatial relations between the facies is not known. The layer has no significant topographic expression because it is too thin; it is, moreover, generally covered by colluvium derived from overlying strata and must be exposed by a little digging. A good outcrop is near the SE. cor. sec. 11, T. 93 N., R. 57 W., Yankton County.

The middle, or marl unit, is from 7 to 9 feet thick, and is lithologically similar to the Smoky Hill chalk member of the Niobrara formation. No nonweathered rock was observed and the weathered rock is very pale orange. Locally a faint alternation of color bands suggests laminae and cyclic sedimentation comparable to that in the Smoky Hill. Curtiss (1950, p. 55) sampled the marl for chemical analysis; the result is quoted below.

Computation shows that calcium carbonate constitutes 45.17 percent of the rock. An X-ray diffractogram (USGS 230,192, interpreted by A. J. Gude 3d) indicates the rock consists chiefly of calcite, with some dolomite, quartz, montmorillonite, and illite. The contact of this unit with the overlying strata is shown in plate 6*B*. It is sharp, conformable, and distinct owing to the difference in color.

Chemical analysis of the marl unit in the Gregory member, Pierre shale, from the NE¼NE¼ sec. 17, T. 93 N., R. 65 W., Yankton County

	Percent		Percent
SiO_2	33.36	MgO	3.71
Fe_2O_3	3.20	SO_3	none
Al_2O_3	7.54	Volatiles	23.43
CaO	25.31	Moisture	3.22
			99.77

The uppermost unit is about 34 feet thick. It is composed of calcareous and noncalcareous claystone and shale, interbedded with a few thin silty layers. The strata are medium-gray on both weathered and nonweathered surfaces, with moderate yellow-brown oxidation stains along many very fine joints and partings. Bentonite beds are numerous and range from ¼ inch to 4 inches in thickness. Wormdrilled ellipsoidal concretions as much as 2 inches thick and 6 inches across are scattered through the strata. The nodules are composed chiefly of iron and manganese oxides, and the two longer dimensions are oriented parallel to the bedding. The beds bend up over the concretions indicating penecontemporaneity. In most outcrops of weathered rock secondary gypsum crystals as much as 6 inches long are numerous. Single crystals are most common, but many penetration- and swallow-tail-twins are found; in each case the b axis is oriented vertically. The crystals are believed to have resulted from the weathering of pyrite enclosed in the strata; this yielded calcium sulfate which was probably concentrated by soil-forming processes described in the introduction. Curtiss (1950, p. 41–42) sampled this claystone and shale unit for chemical analysis; the result is quoted below.

Chemical analysis of the claystone and shale unit in the Gregory member, Pierre shale, from the NE¼NE¼ sec. 17, T. 93 N., R. 56 W., Yankton County

	Percent		Percent
SiO_2	55.10	MgO	2.76
Fe_2O_3	1.36	SO_3	.45
Al_2O_3	20.38	Volatiles	9.24
CaO	1.74	Moisture	.51
			91.54

Calcium carbonate is calculated to constitute 3.11 percent of the material. An X-ray diffractogram (USGS 230,193, interpreted by A. J. Gude 3d) shows that the rock contains abundant montmorillonite and some illite, quartz, feldspar, calcite, and dolomite(?).

Expression and distribution.—The Gregory member is not well exposed, for its typical topographic expression is a grassy, gentle slope locally mantled by colluvium. Good exposures are largely limited to landslide scars and cut banks, and so are of rather short lateral extent. The marl beds are readily distinguished on most slopes by their proximity to the contact of the Niobrara formation and the Pierre shale, and by their light-colored soil from somber units of the Gregory above and the Sharon Springs member below. The shale and claystone beds of the upper unit are distinguished by their position between two marl units and by the lack of flakes or chips of ferruginous slit. An accessible, good outcrop of the member, not including the basal sandy unit, is in the quarry in the NE¼NE¼ sec. 17, T. 93 N., R. 56 W., Yankton County; it is illustrated in plate 6*B*. Other exposures are known in the vicinity of St. Helena and Turkey Ridge, but not James Ridge.

Paleontology.—Macrofossils observed are limited to fish teeth, scales, and bone fragments concentrated in the basal sandy layer and scattered through the remainder of the strata, and to plant fragments (rootlets?) which generally are concentrated in the lower 2 feet of the marl beds and are dispersed through younger layers. Locally the concentration may be somewhat higher stratigraphically. Microfossils in the member have been studied by Searight (1938, p. 135-137), and in the marl beds alone by J. J. Schulte (written communication, 1951).

Upper contact.—The upper limit of the member is characterized by a color change from the gray of the upper part of the Gregory member to a light color typical of the overlying Crow Creek member. The contact thus marked is conformable and gradational through a vertical distance of 18 to 24 inches. Because of this and because exposures are generally poor, the contact is drawn somewhat arbitrarily.

Correlation and name.—Strata assigned to the Gregory member in the Yankton area are correlated by direct tracing and comparison of lithologic character and sequence with the unit at its type locality.

The name, taken from exposures in Gregory County, S. Dak., at the site of the Rosebud Bridge (see p. 31) was applied by Searight (1937, p. 10-21) to beds between the Niobrara formation and the DeGrey and Verendrye members of this report. Subsequent changes in usage are indicated in table 3.

CROW CREEK MEMBER

The Crow Creek member is about 6 feet thick and consists of marl beds lithologically and physically similar to those that constitute the lower part of the Gregory member. Weathered rock is a very pale orange; no nonweathered rock was observed. In the Yankton area the Crow Creek member lacks the basal sandy layer that is characteristic of the unit in central South Dakota. Curtiss (1950, p. 55) sampled the Crow Creek member at the abandoned quarry and included the beds with the upper part of the Gregory member, although he recognized their difference lithologically. Chemical analysis of his sample is quoted below.

Chemical analysis of the Crow Creek member Pierre shale, from the NE¼NE¼ sec. 17, T. 93 N., R. 56 W., Yankton County

	Percent		*Percent*
SiO_2	26.66	MgO	1.66
Fe_2O_3	6.00	SO_3	none
Al_2O_3	8.12	Volatiles	23.78
CaO	28.85	Moisture	3.71
			98.78

Calculations indicate a calcium carbonate content of 51.49 percent.

Expression and distribution. — The Crow Creek member, like those above and below, is not well exposed for it underlies grassy, gentle slopes, locally mantled with colluvium. The only good outcrop known is in a cut bank in the NE¼NE¼ sec. 11, T. 93 N., R. 57 W., Yankton County, on the east side of a small tributary of the Missouri River; the exposure is illustrated in plate 7*A*. Typical exposures of the member are commonly recognized by the light color of the marly soil and locally, by a slight steepening of the slope. Outcrops are limited principally to the walls of the Missouri River trench west of Yankton and to the maturely dissected terrain adjacent to it.

Paleontology.—No macrofossils were found. The microfauna has been studied by Searight (1938) and Schulte (written communication, 1951).

Upper contact.—The upper limit of the member must be drawn somewhat arbitrarily, as the conformable contact is gradational through a vertical distance of 18 to 24 inches, and as exposures are generally poor. On grassy slopes the contact is indicated by the change from the lighter color of the marly soil to the darker color of the soil derived from the overlying shale and claystone.

Correlation and name.—Strata assigned to the Crow Creek member in the Yankton area are correlated with those of the type locality by direct tracing and similarity of lithologic character and sequence.

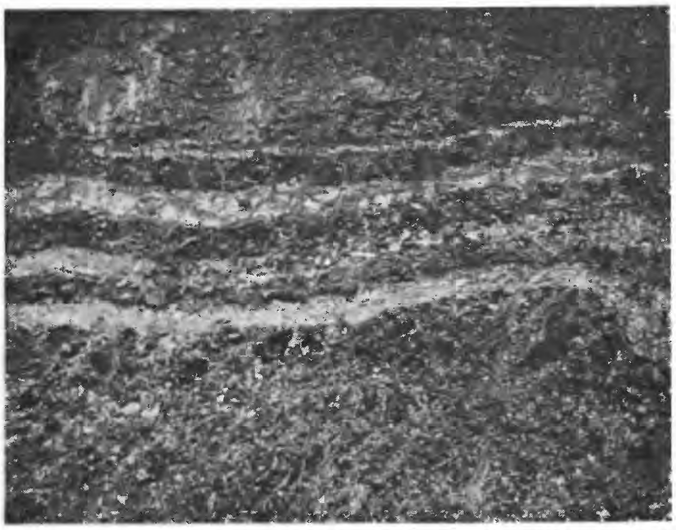
Marl beds with a sandy layer at the base originally constituted the upper part of the original Gregory member of Searight (1937, p. 13), but in 1938 Searight restricted the name to the marl and accompanying sandy layer and transferred them to the overlying Sully member. In 1941 Gries and Rothrock (p. 14-18) renamed the marl unit the Crow Creek in southwest Buffalo County, S. Dak. Subsequent changes in usage are summarized in table 3.

DeGREY AND VERENDRYE MEMBERS

The DeGrey and Verendrye members constitute a sequence about 75 feet thick composed of noncalcareous, medium-gray shale with some thin beds of claystone. The sequence can be divided roughly into two parts, depending on the amount of bentonite contained. The lower part, about 50 feet thick, contains several layers of bentonite ranging from a fraction of an inch to 4 inches in thickness. The upper part, which is about 25 feet thick, is nearly free of bentonite but contains a few thin layers of iron-oxide-cemented silt that yield distinctive reddish-brown scales on weathering. The unit is characterized by two distinctive features: a sequence of conspicuous bentonite layers at or near the top of the lower part, and several horizons marked by phosphatic oolites in the basal beds of the upper part.

The sequence of bentonite layers is illustrated in plate 7*B*. The first (basal) and third layers generally are considerably thicker than the second and fourth, and the four together, with the partings between, make up not more than a foot of strata. The minor lithologic differences between the shale above and below the sequence, together with the sequence, may mark a depositional break which may be correlative with the contact between the DeGrey and Verendrye members in central South Dakota. A composite section of the Pierre shale compiled by the Corps of Engineers in the vicinity of the Fort Randall Dam, 60 miles west-northwest of Yankton, shows several very thin beds of bentonite in the Oacoma zone of the South Dakota Geological Survey. Also, Gries (1942) and others of the South Dakota Survey describe the Oacoma strata as highly bentonitic. Crandell (1958) refers to the upper part of the DeGrey member as the "shale-and-bentonite facies." In each case available descriptions and data indicate fewer bentonitic beds in strata immediately above and below the Oacoma zone of the South Dakota Geological Survey or its correlative, the upper part of the DeGrey member. It is tentatively inferred, therefore, that the distinctive sequence of bentonite beds in the vicinity of Yankton may lie in the upper part of the DeGrey member and arbitrarily may be considered

A. Crow Creek member, Pierre shale, exposed in cut bank in the NE¼NE¼ sec. 11, T. 93 N., R. 57 W., Yankton County. This is the only clean outcrop of the member in the Yankton area; note the nature of the upper and lower contacts, marked by two arrows.



B. Distinctive sequence of four bentonite beds within the DeGrey and Verendrye members, Pierre shale; exposed in the NW¼NW¼ sec. 23, T. 93 N., R. 58 W., Bon Homme County.

C. Typical phosphatic, oolitic nodules in the DeGrey and Verendrye members, Pierre shale, in the NE¼NW¼ sec. 23, T. 93 N., R. 58 W., Bon Homme County. Only the longest nodule is in place. Film box is 3 inches long.

D. Iowan till, overlain by a little loess, exposed in the NW cor. SW¼ sec. 26, T. 33 N., R. 1 W., Cedar County. Note joints defined by oxidation and deposition of secondary minerals.

to mark the top of that member. Additional work is needed between Yankton and Chamberlain to prove or disprove the inference.

The phosphatic oolites are present principally as nodular masses but also as small groups and isolated individuals. Although oolites in the nodules are hard and the others are soft, all are physically similar. They are dark-gray prolate ellipsoids about a millimeter long and half a millimeter in diameter; they lack apparent nuclei or concentric structure and consist of microgranular apatite and traces of quartz. The soft oolites are commonly slightly flattened, probably by the weight of overlying strata. The groups of pellets contain 10 to 25 oolites, are separated by shale strata, and pore space between oolites of the group is commonly filled with secondary gypsum or calcite. Most commonly the oolites form porous syngenetic nodules, shown in plate 7*C*. These may consist of several hundred to a few thousand hard oolites which are generally less deformed than the soft ones. Some of the nodules are nearly spherical in form and others are elongate, but most are flattened ellipsoids with the long axes subparallel to the bedding. The nodules are generally 2 inches thick and as large as 8 inches across, but one measured 27 inches long. They have a yellowish-gray rind about a quarter of an inch thick and are commonly fractured in a septarian-like pattern. Oolites do not compose the entire mass of all nodules; relatively massive apatite composes part of some nodules, but rearly more than 25 percent. In most nodules interstices are partly filled with pyrite or gypsum; the gypsum is secondary, but the pyrite is probably primary. Chemical analysis (USGS 141,022 by Ann Sweeney and Percy Moore) of a single sample indicates the oolites contain 27.7 percent phosphate, and 0.005 percent uranium.

Expression and distribution.—Like the Crow Creek and Gregory members below them, the DeGrey and Verendrye members are not well exposed. The typical topographic expression is a grassy, gentle slope locally mantled by colluvium, and good exposures are limited to landslide scars and cut banks. The noncalcareous DeGrey and Verendrye are distinguished by their darker color from calcareous members above and below. The sequence of bentonite beds and the oolitic nodules have no affect on the expression of the unit. An excellent exposure of the strata in the NE¼NW¼ sec. 23, T. 93 N., R. 58 W., Bon Homme County, displays both the bentonite sequence and many oolitic nodules. Outcrops of the unit are limited largely to both walls of the Missouri River trench between Yankton and the Hutterite Colony.

Paleontology.—A complete though poorly preserved skeleton of a mosasaur was found in slumped beds tentatively assigned to the DeGrey member, in the NE¼NW¼ sec. 23, T. 93 N., R. 58 W., Bon Homme County. The specimen was identified by D. H. Dunkle (written communication, Oct. 5, 1948) of the U.S. National Museum as *Platecarpus* cf. *p. brachycephalus* Loomis. No other macrofossils were found.

Upper contact.—The contact with the overlying Virgin Creek member is conformable and gradational through a vertical distance of a few inches. On nearly all slopes its position is indicated chiefly by a change from the darker gray of strata belonging to the DeGrey and Verendrye to the lighter gray of the member above.

Correlation and name.—The undifferentiated DeGrey and Verendrye members are correlated tentatively with the DeGrey and Verendrye of other areas by direct tracing of contacts with the underlying Crow Creek member and the overlying Virgin Creek member and by similarity of lithologic sequence. Originally, beds of the DeGrey and Verendrye constituted the Agency shale and Oacoma zone and the Verendrye shale zone, respectively, all of the Sully member of Searight (1937, p. 21-25). In 1950 Crandell (p. 2341-2345) dropped the name Sully, introduced the name DeGrey, and raised the DeGrey and Verendrye units to member rank. Other changes in usage are shown in table 3. The DeGrey member was named for an exposure about 2¼ miles southeast of DeGrey post office, Hughes County, S. Dak., and the name Verendrye was taken from exposures at the monument to the early French explorer Verendrye at Fort Pierre in Stanley County, S. Dak.

VIRGIN CREEK MEMBER

The Virgin Creek member, which is about 25 feet thick, is apparently composed of light or medium light gray slightly calcareous to noncalcareous mudstone, containing several thin layers of iron-oxide-cemented silt. On weathering, these layers yield light-brown scales similar to those derived from the underlying undifferentiated DeGrey and Verendrye members. Scales from the Virgin Creek member, however, are more widely distributed and much more numerous. Outcrops of the Virgin Creek are also characterized by a thick mantle of weathered mudstone in which hand-auger holes 5 feet deep did not reach undisturbed strata. Detailed information on the physical characteristics of this member is lacking because there are no good exposures. A single section of transitional strata immediately below the upper contact suggests that the rock is soft, weak, and breaks into irregular pieces. When wet it is highly plastic.

Expression and distribution.—Owing to the rapidity with which newly exposed strata weather to an earthy mantle, there are no exposures of nonweathered Virgin Creek. Commonly the member underlies grassy, very gentle slopes mantled with colluvium and scarred by landslide deposits. It is distinguished by its slightly lighter color and greater number of iron-cemented scales from the darker shale and claystone of the unit below, and by its relatively darker color from the overlying marl. A typical slope is in the NE¼NW¼ sec. 23, T. 93 N., R. 58 W., Bon Homme County; similar slopes are present in the adjacent terrain and on the south side of the Missouri River trench.

Paleontology.—No macrofossils were found.

Upper contact.—The contact of the Virgin Creek member with the overlying Mobridge member is conformable and gradational through a vertical distance of 4 to 8 feet. The best exposure is at the locality cited above, where the contact is characterized by alternating beds of marl and calcareous mudstone. Generally, however, the contact is recognized only by a change in color from the light-gray mantle of the weathered Virgin Creek to yellowish orange of the overlying Mobridge member.

Correlation and name.—In the Yankton area strata assigned to this member are correlated chiefly on similarity of lithologic character and sequence and indirectly on tracing of the overlying member. Strata that constitute this member were named by Searight in 1937 (p. 35–43) for exposures in and near the valley of Virgin Creek at a locality 1½ miles south of Promise, northeastern Dewey County, S. Dak.

MOBRIDGE MEMBER

As much as 18 feet of strata represent the Mobridge member, but the upper part has been removed by erosion and the original thickness is not known. The rock is a marl that is even more similar in lithology to the argillaceous limestone of the Niobrara formation than are the Crow Creek member and the marl beds of the Gregory member. No nonweathered material was observed; weathered rock is dark to pale yellowish orange, soft, weak, and breaks into irregular chunks. When wet it is highly plastic. Individual beds are as much as 6 inches thick, and faint iron-stained color banding, believed to represent cyclic laminae, was observed locally. No laboratory data concerning the member are available.

Expression and distribution.—The Mobridge member is commonly well exposed in cut banks and in nearly bare slopes that rise more steeply than the gentler slopes of subjacent members of the Pierre shale or overlying Tertiary and Pleistocene deposits. The strata generally crop out near the heads of gullies on both sides of the Missouri River trench and are distinguished most readily by their weathered color, which is a somewhat darker orange than that of the older marl units. Probably the best exposure is in a gully that heads near the north side of sec. 2, T. 93 N., R. 57 W., Yankton County; an exposure of part of the member in a road cut in the SE cor. NW¼ sec. 18, T. 93 N., R. 57 W., Yankton County, is easily accessible.

Paleontology.—No macrofossils were observed.

Upper contact.—The Mobridge member is separated from sediments of post-Cretaceous age by a sharp unconformity. Generally the member is overlain by the Ogallala formation of Pliocene age; in the southwestern part of the area this contact is at an altitude of about 1,535 feet, and northward across the Missouri River trench it is at about 1,495 feet. Like other members of the Pierre shale, the Mobridge member is locally overlain by deposits of Pleistocene and Recent age. Owing to the erosional nature of this contact, its altitude differs from one locality to another. The position of the unconformity is clearly indicated by a change in color from that of the marl to the pale greenish gray, pale red, or yellowish brown of the overlying material, and by an increase in mean particle size.

Correlation and name.—Strata belonging to the Mobridge member in the vicinity of Yankton are correlated by direct tracing and similarity of lithology with beds in south-central South Dakota assigned to the Mobridge member by Searight in 1937 (p. 44).

The member was named by Searight in 1937 (p. 44-45) for an exposure in southeastern Corson County, S. Dak., near the west end of a bridge across the Missouri River at the town of Mobridge.

ENGINEERING CHARACTERISTICS

Rock types that constitute the Pierre shale are soft, and in part loose but chiefly weak to moderately firm. The shale beds separate into flakes and chips, and the claystone and marl beds into irregular chunks—the claystone with crudely curved fracture, the marl with nearly plane fracture. Excavation of all members is possible both by hand and by power equipment; blasting is not necessary but may speed excavation, especially in nonweathered rock. Because the formation consists largely of clay, trafficability for equipment of any kind is poor when the rock is wet. The rolling topography and sparse grass cover that characterize the formation facilitate runoff, but their effects are more than counterbalanced by dehydration cracks, landslide fissures, fine joints and partings, the surface texture of the rock, and the absorbent nature of at least part of the clay. Where runoff is channeled by the topography, erosion is rapid. Power equipment can cut close to a limit, and smooth faces are readily cut with coal saws. Permeability is extremely low and is limited chiefly to many hairline joints in weathered rock. All the strata are highly plastic, although the shale beds of the Sharon Springs member and the marl beds of the Gregory, Crow Creek, and Mobridge members are slightly less plastic, and the mudstone of the Virgin Creek member more plastic than the others.

Slopes underlain by Pierre shale are highly susceptible to landsliding. Stability of the several members differs, however, and relative stability based on the stratigraphic position of the foot of numerous landslides as observed subjectively is indicated below.

Sharon Springs member (most stable)
Gregory member, marl unit
Mobridge member
Crow Creek member
Gregory member, shaly unit
DeGrey and Verendrye members
Virgin Creek member (least stable)

The least stable strata are clearly those of the Virgin Creek member; on an absolute scale the interval between the Virgin Creek and the undifferentiated DeGray and Verendrye members would be much greater than the interval between any two other units of the scale above. Relative slope stability is also suggested by the height of nearly vertical stable exposures. Outcrops are seldom more than 4 to 5 feet high in strat of the Virgin Creek member, compared with 12 to 15 feet in other shaly units. The four most stable units in the table above cannot be compared satisfactorily on this basis to the three least stable units, for the four may be too thin to properly express relative stability in this fashion.

ENVIRONMENT OF DEPOSITION OF UPPER CRETACEOUS ROCKS

The regimen in which most if not all of the Upper Cretaceous strata were deposited was a marine epineritic environment. The water, although somewhat sheltered, was open and generally subject to free circulation. The sea bottom probably was not more than a few hundred feet deep and from time to time was agitated by waves and currents. Within this environment, factors controlling deposition varied enough so that part of the time clayey sediments predominated, and part of the time calcium carbonate predominated. Conditions that produced the Graneros shale thus were repeated in effect during deposition of most of the Carlile shale and the Pierre shale. Likewise, conditions under which the Greenhorn limestone was deposited were repeated during deposition of the Niobrara formation and marl beds of the Pierre shale. Beyond the immediate environment volcanoes spewed out ash, now altered to bentonite, which settled to the sea floor. These layers of bentonite suggest that eruptions began at least as early as deposition of the Greenhorn limestone and continued through accumulation of the Pierre shale.

The source of most fine-grained clastic sediments was probably to the west, but the coarse component is largely of eastern derivation. A western source of the fine-grained material is suggested by thickening of Cretaceous marine strata in that direction. It is quite possible, however, that part of the fine fraction was reworked from older fine grained strata to the north and east or was derived from a lowland mass along the eastern border of the epeiric sea. The large size of grains in the relatively coarse-grained beds of Cretaceous rocks indicates that a western source is unlikely for these grains. A general though slight increase in median grain size eastward, together with an increasing quantity of silt and sand, are inferred from electric logs. These inferences suggest derivation of the coarse fraction from the east, either from erosion of a land mass or reworking of earlier coarse-grained beds. Thus the coarse sediment may have been derived from some part of a granitic land mass that long before had supplied sand for the Sioux quartzite (W. B. Baldwin, written communication, 1951). The small amount of coarse clastic material yielded suggests that this old mass may have been of low relief.

Reworking of older beds including the Dakota sandstone is quite possible, for waves and currents deposited the coarse clastics. This is indicated by such features as cut-and-fill stratification in the Codell sandstone member of the Carlile shale, erosion of the shale beneath the coarse layer at the base of both the Gregory and Crow Creek members of the Pierre shale, and the size, shape, and distribution of oolitic nodules in the undifferentiated and DeGrey and Verendrye members of the Pierre. Crandell (1952, p. 1763–1765) concluded that a coarse layer at the base of the Crow Creek member of the Pierre shale in central and south-central South Dakota may have resulted from reworking of the Codell sandstone member of the Carlile shale owing to a Late Cretaceous uplift of an area in east-central South Dakota.

Various features within the Cretaceous rocks indicate that the depth of water in which the sediments accumulated was fairly shallow. Contemporary marine rushes live at depths of a few inches to a few feet, and oysters commonly live within tidal range, and rarely deeper than a few fathoms. The occurrence of rushes and oyster colonies in the Smoky Hill chalk member of the Niobrara formation thus indicates very shallow water for that member; neither indicator was found in other strata, either calcareous or clayey. Fragments of vegetation, however, indicate that some strata of both types accumulated within the zone of photosynthesis. The depth of this zone differs with several physical factors as well as with plant species, but the ordinary depth limit for vigorous photosynthetic activity in 25 fathoms, and the general base for marine algae is approximately 50 fathoms (Cloud, 1952, p. 2133). As some calcareous beds contain greater concentrations of vegetation fragments, these particular sediments may have accumulated at shallow depths, although the plants may have preferred the more calcareous environment. Most clayey strata contain no plant matter, a fact suggesting that they accumulated below the zone of photosynthesis. Among these are beds containing phosphatic oolites and oolitic nodules which are generally considered to have formed below the zone.

Oolites and oolitic nodules commonly form in the littoral zone where their shape is partly the result of rolling and turning by waves and currents, but they are also known to form at considerable depth in other places where rotation is not a factor. Oolites and oolitic nodules are of themselves, therefore, nonspecific as indicators of shallow depth. In the vicinity of Yankton, wave or current action is thought to have been effective in formation of the oolitic nodules owing to their flattened, narrow, elongate form and roughly subparallel orientation. This implies that effective wave or current action extended below the zone of photosynthesis.

Pyrite and undecomposed plant material suggest that at times the sea floor was partly anaerobic. Rubey (1930, p. 12-13) concluded from his study of fine-grained Upper Cretaceous sedimentary rocks in the Black Hills region, however, that the preservation of organic matter, pyrite, and calcium carbonate is favored by relatively shallow water and a rapid rate of accumulation. His reasoning seems to apply equally well to Cretaceous sedimentation in the vicinity of Yankton.

Evidence of the rate of sedimentation indicates the rate varied. Intervals of nondeposition are clearly indicated by the growth of oyster colonies found along bedding planes of the Niobrara formation. As some of these colonies consist of more than one layer of shells, colonies may indicate nondeposition for from one to several years. Accumulation of the DeGrey and Verendrye members was either slow enough or interrupted enough times, to permit growth of phosphatic oolites and oolitic nodules. In general, the dispersed scales and skeletal fragments of fish suggest that the rate of accumulation of the Niobrara formation and the Pierre shale was slow enough to allow scavengers and wave or current action to scatter oganic remains. Laminae in the Niobrara formation and the marl beds of the Pierre shale, however, may constitute a clue to the maximum rate of sedimentation: if we arbitrarily assume that the laminae are annular, then these layers attained a rate of as much as half an inch a year. That, then, would be the maximum rate. If a lamina actually represents accumulation during 10 years, or tens of years, the rate would be proportionately slower; if a lamina represents less than a year the rate would be faster, but this seems very improbable to the writer.

Cyclic laminae in the Smoky Hill chalk member of the Niobrara formation and the Gregory and Mobridge members of the Pierre shale pose a problem: What is their origin, and what period of time does a single cycle represent? Because the laminae of the Smoky Hill chalk member are apparent in only one exposure in the vicinity of Yankton and those in the Pierre shale are less distinct and poorly expoded, insufficient data are available for a definite answer to either question. Processes that may yield cyclic laminae have been discussed by a number of writers referred to by Rubey (1930, p. 40-41) and Bramlette (1946, p. 32-34). A likely hypothesis that does not appear and which may account for the laminae observed is based on upwelling of marine water.

In general the conditions could be likened to those associated with the California current. According to Sverdrup and others (1946, p. 724-727 and 785-787) upwelling which occurs annually off the southern California coast begins in March, slows in July, and ceases in the fall. It is the result of southerly transport of surface water by periodic north-northwest winds, and the displaced surface water is supplanted by water that rises from moderate depth, probably less than 200 meters (Sverdrup and Fleming, 1941, p. 334). Upwelling returns to the photosynthetic zone nutrient salts, including phosphate, which serve to fertilize the zone. The response is a luxuriant growth of phytoplankton. Somewhat comparable conditions are known to exist in various other localities about the world, including the western coasts of South America and Africa, and regions of divergence of the equatorial countercurrents.

In the Cretaceous sea there may have been times during which similar annual upwellings took place. If these upwellings introduced increased food supplies as they do today, they probably led to the growth of unusually large numbers of plankton. The plankton may be a positive factor in the precipitation and preservation of calcium carbonate in four ways (Rankama and Sahama, 1950, p. 464-469):

1. Phytoplankton of some kinds separate calcium carbonate to form internal hard parts; that is, coccoliths and rhabdoliths. Greater numbers of plants would result in greater numbers of hard parts to accumulate on the sea floor following death of the organisms.

2. Phytoplankton assimilate carbon dioxide in lhotosynthesis; as the amount of carbon dioxide is reduced, alkalinity is increased; and as the solubility of calcium carbonate is thus decreased, it may be chemically precipitated.

3. Some kinds of micro-organisms produce ammonia; this may cause precipitation of calcium carbonate by increasing alkalinity and reducing solubility.

4. Bacteria may cause decomposition of organisms containing calcium, and calcium carbonate may be formed by carbon dioxide yielded by decomposition. The plankton could prove a negative factor in the precipitation and preservation of calcium carbonate in two ways: carbon dioxide produced during decay of organisms, and through respiration by zooplankton and by larger animals that feed on them would tend to increase the solubility of calcium carbonate.

Times of upwelling, therefore, may have been times of more rapid deposition of calcium carbonate on the sea floor, both as organic hard parts, and as a chemical precipitate. During intervals between upwellings less food would mean fewer plankton, and, hypothetically, less precipitation of calcium carbonate. The annual cycle thus would produce cyclic laminae with the laminae of each pair alternating in calcium carbonate content. If a small amount of inorganic, clastic, sediment were continuously deposited, a banded argillaceous limestone like the Smoky Hill chalk member could result. Larger quantities of clastic sediment could result in a marl similar to the calcareous units of the Pierre shale.

Phosphate disseminated throughout the Niobrara formation and concentrated in oolites in the Pierre shale may also have been introduced by upwelling, (Kazakov, 1937, p. 110-113), but may have been derived "locally." In either case the source of the phosphate is basically the same: decomposition of organic material settling to the bottom from the photosynthetic layer.

The association of calcium carbonate with the phosphate may indicate indirectly that the phosphate had its origin in upwelling. Johnston and Williamson (1916, p. 731) showed that the solubility of calcite (calcium carbonate) varies inversely with the temperature of the water; in cool water the concentration of carbon dioxide keeps the water sufficiently acid to prevent a chemical precipitate from forming, and organic or clastic calcareous sediments would be dissolved unless their rate of accumulation was more rapid than the rate of solution. Conditions favoring the preservation of calcareous sediment most commonly exist in a shallow sea where the water is warm to the bottom. The shallow bottom aids in warming the water by reducing circulation, and a reduction of circulation opposes upwelling.

If the cyclic laminae are not annular but represent a period of tens or hundreds of years, the alternation in composition is more difficult to explain. The basic cause may then be an unidentified climatic cycle, but the immediate cause is unknown.

Any explanation of cyclic laminae must conform with the principal elements of the Cretaceous sequence. This sequence consists of three basic components. clayey, calcareous, and sandy units. Two hypotheses are suggested. The first requires continuous upwelling and alternating shallower and deeper water. The result is deposition of calcareous layers containing fine-grained phosphate during times of shallow water, and slower accumulation of noncalcareous sediments with growth of oolites during times of deeper water. Changes in depth of water required may be either eustatic or cause by vertical movements of the sea floor. The second involves multiannular periods of upwelling alternating with intervals without upwelling; depth of water may remain constant. The result would be deposition of calcareous sediments during periods of upwelling, and noncalcareous sediments during intervening intervals. This hypothesis requires changes either in climate or marine environment that alternately cause or permit upwelling and stop or obstruct it.

There is little basis for a preference between structural and climatic changes to explain the Cretaceous sequence. The Cretaceous sea receded from the continent and the Rocky Mountains began to grow in Late Cretaceous time, and structural shifts in the sea floor during accumulation of Upper Cretaceous strata can thus be accounted for. Structural changes are indicated by coarse layers at or near the base of the Niobrara formation and the marl beds of the Gregory and Crow Creek members of the Pierre shale. These coarse layers show strong current activity as might be caused by a change in conformation of the sea floor. The structural changes may be have been related either to slight uplift of an adjacent land area to the north and east, or to activity premonitory to the draining of the great Cretaceous sea and the growth of the Rocky Mountains to the west. Little is known, however, of the Cretaceous climate or of changes it underwent as the sea retreated and the mountains rose. As the possibility of a combination of climatic and structural changes cannot be eliminated, a choice between the preceding hypotheses cannot be made.

TERTIARY ROCKS

Several formations of Tertiary age crop out in western South Dakota and western Nebraska, but only one, the Ogallala formation of Pliocene age, is known to be present in the Yankton area. Another Tertiary formation may be exposed a short distance southwest, for in 1952 Schulte, in an unpublished thesis for the University of Nebraska, mapped a massive reddish clay about 9½ miles southwest of Verdigre, Knox County, and tentatively correlated the deposit with the Brule formation of middle and late Oligocene age.

OGALLALA FORMATION

The Ogallala formation attains a maximum thickness of about 125 feet in sec. 33, T. 33 N., R. 3 W., Knox County, but the original thickness of the formation is unknown as the uppermost beds have been removed by erosion. Eastward the unit thins and pinches out between the Pierre shale and overlying Pleistocene deposits about a mile south of Crofton, Knox County. North of the Missouri River the formation is generally less than 10 feet thick, although 12 feet is exposed in the NW¼NW¼ sec. 23, T. 93 N., R. 58 W., Bon Homme County.

The strata consist of light-colored fluvial silty clay, sand, fine gravel, and, locally, lenses of orthoquartzite. Of these, all except the orthoquartzite are unconsolidated. The formation may be divided into two subunits: the lower consists chiefly of sand, fine gravel, and orthoquartzite, and the upper unit is composed principally of silty clay.

The lower unit is correlated with the Valentine beds of Barbour and Cook (1917, p. 173), which constitute the basal formation of the Ogallala group of Condra and Reed (1943, p. 11). The correlation is based solely on lithologic similarity. About 55 feet of the unit is exposed in a gully in the SE cor. NW¼ sec. 1, T. 32 N., R. 4 W., Knox County. These strata are composed of partly calcareous, partly crossbedded grayish-orange sand, and some massive, highly calcareous, pale grayish green and pale-red silty clay. In addition, there are minor amounts of fine gravel and, locally, lenses of yellowish-green orthoquartzite. The grayish-green silty clay weathers to a vivid white characteristic of the formation.

The orthoquartzite consists of sand and fine gravel cemented by pale yellowish green opal or chalcedony that gives the rock its characteristic color. The sand is fine to coarse and constitutes a matrix for granules as much as a quarter of an inch in diameter. Individual particles are light colored, rounded, and of high sphericity. They consist predominantly of quartz, various unaltered feldspars, and a little mica, all from Rocky Mountain sources, together with fragments derived from subjacent formations, principally the Niobrara formation and Pierre shale. The rock is mostly massive, but some faint stratification is found, together with a few very small vugs, or cavities.

The orthoquartzite is represented only by residual irregular boulders, for the rock does not crop out in the Yankton area. The boulders lie at a maximum altitude of about 1,475 feet on the crests and flanks of three small knolls of Pierre shale in the SE¼SW¼ sec. 13, T. 33 N., R. 2 W., Knox County. The knolls evidently are remnants of a former butte that was capped by a lens of the orthoquartzite. The original thickness and extent of the lens is not known, but it was probably several feet thick and at least a quarter of a mile across. The absence of other residual sediments of the Ogallala formation at the locality suggests that the lens of orthoquartzite lay at or near the base of the formation. Comparable lenses of poorly sorted sand and granules in a similar stratigraphic position are found elsewhere in the Devils Nest, but they have no siliceous cement. The reason for the apparent selectivity of cementation by ground water is not known. Buttes still capped by similar rock include the Bijou and Iona Hills in Brule and Lyman Counties, S. Dak., the butte south of Butte, Boyd County, Nebr., and others in these states and Kansas.

The contact of the lower unit with the upper is sharp and conformable. It is placed arbitrarily at the

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top of the stratigraphically highest bed of grayish-orange sand. Owing to the similarity of pale greenish gray silty clay present in both units, the placement of the contact may depend locally on the extent of the outcrop and the thickness of the section exposed.

The upper unit is correlated with the Ash Hollow formation of Engelmann (1876, p. 260-262; see also Lugn, 1939, p. 1258-1261), which is considered by Condra and Reed (1943, p. 10-11) to overlie the basal formation of their Ogallala group. The correlation is based chiefly on lithologic similarity and partly on paleontology. About 15 feet of this unit is exposed in a gully in the SE cor. NW¼ sec. 1, T. 32 N., R. 4 W., Knox County. The strata consist chiefly of massive, highly calcareous, light-gray to greenish-gray silty clay, together with minor amounts of white volcanic ash and massive light-gray sand. The silty clay weathers a vivid white typical of the formation. In his unpublished thesis Schulte (written communication, 1952) states that a massive ledge-forming bed characteristically marks the base of the Ash Hollow formation of Englemann and of Lugn in Knox County; this bed was not observed in the Yankton area.

Expression and distribution.—The Ogallala formation is most commonly observed as bare spots on gentle slopes sparsely covered with grass, but locally it crops out in guillies and road cuts. The best single, accessible exposure is in a gully in the SE cor. NW¼ sec. 1, T. 32 N., R. 4 W., Knox County. Outcrops of the lower unit are found throughout the Devils Nest area, and the upper unit is exposed almost continuously west of Crofton along a section-line road 1 mile south of and parallel to Nebraska State Route 12. North of the Missouri River the formation is exposed only in the southern flank of Yankton Ridge near its western end. In this vicinity only the lower unit crops out, but the exposures are too small to be shown on the geologic map; the best section is in a landslide scarp in the NW¼NW¼ sec. 23, T. 93 N., R. 58 W., Bon Homme County.

Paleontology.—A few fossil vertebrate bones and numerous bone fragments were found in strata of the Ogallala formation in the NE cor. SE¼ sec. 34, T. 32 N., R. 1 W., Cedar County. C. B. Schultz of the University of Nebraska State Museum identified (written communication, May 20, 1949) them as follows:

Proximal end of metapodial of an antilocaprid (*Merycodus*-like form).

Proximal phalanx of an antilocaprid (*Merycodus*-like).

Fragment of left ramus of an antilocaprid (*Merycodus*-like).

Two upper molars of *Pliohippus*. Compares favorably with the Ash Hollow forms we have in the University of Nebraska collection.

Miscellaneous fragments of a mastodont, apparently of the longirostrine type. The specimens are too incomplete for definite determination but all evidence points to a Pliocene type.

Fragment of carapace of a giant turtle (*Testude*). Not diagnostic.

The above specimens probably are from Ash Hollow (Ogallala) deposits and would be considered to be middle Pliocene in age.

Fossils found in strata of the lower unit differ little from those observed in beds of the upper unit; the chief difference is a black staining or coating of iron and manganese oxides on some bones from the basal part of the lower unit. Fossil bones from the Ogallala formation are readily distinguished from fossils of later date by greater mineralization and, therefore, greater specific gravity.

Upper contact.—The Ogallala formation is separated from overlying deposits of Pleistocene age by a sharp unconformity. The altitude of this contact differs from one locality to another because of its erosional nature. Despite its sharpness the contact is not everywhere readily distinguished, owing to a general similarity between some of the silty clay and some silt of Pleistocene age. The position of the contact is readily ascertained on close examination, however.

Correlation and name.—Correlation of post-Cretaceous, pre-Pleistocene strata in the Yankton area with the Ogallala formation of western Nebraska is based on direct tracing from the type area, supported by paleontology and the similarity of lithologic characteristics lithologic sequence.

The name Ogallala was given by Darton (1899b, p. 734-735) to the "mortar beds," or "Tertiary grit," which composed the upper part of the Loup River beds of Meek and Hayden (1861, p. 433, 435). Hesse (1935, p. 79-80) later established a type locality for the formation 2 miles east and half a mile north of Ogallala, Keith county, Nebr.

ENGINEERING CHARACTERISTICS

Unconsolidated strata of the Ogallala formation can be excavated readily both by hand and by power equipment. Slopes cut in these beds are moderately stable, for a 70° slope as much as 15 feet high may recede only a few inches in 3 years' time. The strata are not subject to slumping internally, although locally they have failed owing to collapse of the underlying Pierre shale. Permeability may range from low to high, depending on the lithology of the particular bed: the permeability of sandy beds is high and that of silty clay beds low. Plasticity of the materials is low and trafficability will be good, with the possible exception of deep, loose sand found locally.

The orthoquartzite is hard and strong, and blasting and power equipment will be necessary for excavation if a lens is encountered. Slopes are nearly stable, although over a period of several years frost action may loosen some pieces. The rock will not slide unless too large a mass of the underlying Pierre shale should slump; the critical size of such a mass is not known owing to lack of quartzite exposures. Permeability of the rock is extremely low and principally limited to fine joints.

The Corps of Engineers Soils and Materials Laboratory at Omaha tested orthoquartzite of the Ogallala formation in order to ascertain its usefulness as a concrete aggregate. The tests were made of samples from a quarry near Burke, Gregory County, S. Dak. H. L. Weil (written communication, Feb. 21, 1950) states that expansion is considerably reduced when a low-alkali cement is used, for 8 out of 10 aggregate mixtures were then found to be nonreactive. The use of flyash with the high-alkalai cement reduced expansion about half, although it was still excessive. Weil concluded that flyash "had very little beneficial effect" toward inhibiting reactivity of extremely reactive aggregates, and the inhibiting effect on moderately reactive aggregates is much less and of about the same amount as obtained by the use of low-alkali cement alone. The tests also showed that the use of flyash with low-alkali cement caused more expansion than if no flyash were used.

A sample of pale greenish gray silty clay was channeled from a typical exposure of the Ogallala formation on the western part of Yankton Ridge, and submitted to the soils laboratory of the South Dakota State Highway Commission for soil analysis. The report (E. B. McDonald, written communication, June 27, 1952) is given below.

Soil analysis data of the Ogallala formation

Location: NE cor. SE¼SE¼ sec. 12, T. 93 N., R. 58 W., Bon Homme County

Depth: 8 to 18 feet below surface (entire thickness of deposit)

Textural classification [1]	Clay
Classification (Allen) HRB [2]	A–7–6(19)
Specific gravity [3]	2.72
Pounds per cubic foot, loose, dry	78.1
	Percent
Shrinkage ratio [3]	1.90
Shrinkage limit [3]	15.8
Volume change [3]	18.5
Passing ⅜ in. sieve [4]	100
Passing No. 4 sieve [4]	100
Passing No. 10 sieve [4]	100
Passing No. 40 sieve [4]	99.8
Passing No. 200 sieve [4]	97.2
Sand content [5] (2.0 to 0.05 mm diameter)	17.6
Silt content [5] (0.05 to 0.005 mm diameter)	37.6
Clay content [5] (less than 0.005 mm diameter)	44.8
Liquid limit [6]	53.8
Plasticity index [7]	29.6
Field moisture equivalent [8]	25.5
Centrifuge moisture equivalent [9]	63.8

1 The South Dakota State Highway Commission Soils Laboratory uses the textural chart developed by A. C. Rose of the U.S. Bureau of Public Roads (see Hogentogler, C. A., 1937, Engineering properties of soils, McGraw-Hill Book Co., New York, fig. 4, p. 36) modified slightly to coincide more closely with the Allan (see footnote 2) classification chart and the plasticity index of soils.

2 Allen, Harold, and others, 1945, Report of committee on classification of materials for subgrades and granular type roads, Highway Research Board Proceedings, v. 25, p. 375–392.

3 Idem; designation D 427–39, p. 66–69.

4 Procedures for testing soils, Am. Soc. Testing Materials, July, 1950; designation D 421–39, p. 43–44.

5 Idem; designation D. 422–39, p. 45–55.

6 Idem; designation D 423–39, p. 56–58.

7 Idem; designation D 424–39, p. 59–60.

8 Idem; designation D 426–39, p. 64–65.

9 Idem; designation D 425–39, p. 61–63.

PLEISTOCENE DEPOSITS

Deposits of Pleistocene age mantle bedrock formations throughout most of the Yankton area. These surficial materials represent different glacial segments of the Pleistocene epoch; interglacial time is denoted by now-buried soil profiles formed on the various deposits. As the epoch includes deposits of the Great Ice Age and contemporary strata, (Wilmarth, 1925, p. 47-49) it locally includes some postglaciation sediments. The standard Pleistocene stratigraphic sequence for north-central United States consists of stages and substages which have been identified and named for type regions and localities; the sequence is indicated below.

Wisconsin glacial stage
- Mankato substage
- Cary substage
- Tazewell substage
- Iowan substage

    Sangamon interglacial stage
Illinoian glacial stage
    Yarmouth interglacial stage
Kansan glacial stage
    Aftonian interglacial stage
Nebraskan glacial stage

The term "Bradyan interval" has been proposed by A. B. Leonard (1951, p. 325) and Ruhe (1952, p. 401) for the interstadial between the Tazewell and Cary substages, but it is not yet in general use.

Sediments of Pleistocene age in the Yankton area may also be referred to as glacial or nonglacial according to the manner of origin. In general sediments of glacial origin are composed of ice-laid (till) or ice-modified (ice-contact stratified deposits) material, and sediments of nonglacial origin consist of eolian (loess) and fluvial (outwash) deposits. North of the Missouri River trench the deposits are principally of glacial origin, but south of the trench Pleistocene sediments are dominantly nonglacial.

In many respects a deposit of one stage or substage is very similar to the comparable deposit of another. Because of this the descriptive stratigraphy of Pleistocene deposits is divided into two parts to avoid excessive repetition and to facilitate comparison of certain data. The first part is concerned principally with similarities of the physical geology of the several units, the second with the more variable aspects of their stratigraphy.

The physical geology of the several Pleistocene deposits includes their lithology, topographic expression, and engineering characteristics. The last includes information that is partly subjective field observations, and partly the results of laboratory testing by the writer, the South Dakota Highway Commission Soils Laboratory, and the Corps of Engineers Soils and Materials Laboratory, Omaha. Because it is economically impractical to make a detailed laboratory study of each deposit at all localities of occurrence, analytical data quoted are only indicative of the nature of the material sampled at the particular locality, and, to an even lesser extent, of the type of deposit. Thus the information constitutes only a guide to engineers and others and cannot replace detailed investigations necessary for large engineering projects.

GLACIAL DRIFT

Continental glaciers invaded the Yankton area from the north during the Kansan(?) and Illinoian stages, and the Iowan, Cary, and Mankato substages of the Wisconsin stage. It is not known whether the Nebraskan glacier entered the area or not. Each glacial advance resulted in the deposition of drift, which comprises, for this report, all deposits of glacially transported material whether made by the glacier itself, by melt water from it, or by both. Drift thus includes deposits that range from till (which is mostly unstratified and unsorted) through ice-contact stratified deposits (which are in part stratified and size-sorted) to outwash (which is wholly stratified and size-sorted). It does not include loess or other deposits of nonglacial origin, whether composed of material once transported glacially, or not. Each of the three principal types of drift possesses characteristic features of form and lithologic character which permit recognition.

The drift probably averages 50 feet in thickness. The greatest thickness reported (Todd, 1895, p. 76) is 215 feet in a municipal well at Tyndall, Bon Homme County, S. Dak. Drift is believed to be 50 to 100 feet thick under the crests of most larger end moraines, and more than 100 feet beneath the end moraine in the SE cor. T. 95 N., R. 55 W., Yankton County (pl. 1). Drift less than 25 feet thick is found at many localities; and the basal contact is exposed most commonly on the bedrock ridges, which suggests that drift is thinner in these areas. Well logs supply some information as to thickness, but such data are sparse and generally inaccurate.

Drift is chiefly responsible for the subdued relief north of the Missouri River, where it mantles and modifies pre-Pleistocene topography. High areas may have been eroded slightly by successive advances of the ice, but modification of relief by filling of low areas with drift was far more important. Because the slopes in the Yankton area are gentle and grass covered, and because they are commonly mantled by colluvium, exposures are poor and the study of Pleistocene deposits largely has been limited to road cuts, gullies, cut banks of streams, and gravel pits. Additional information has been obtained through extensive use of a hand auger.

TILL

Till (unstratified drift) is the principal component of drift in the vicinity of Yankton. It consists of a chaotic, calcareous mixture of mineral and rock fragments which range in size from colloidal particles to large boulders, and which were transported and deposited by glacial ice. Till deposits within the mapped area represent the Illinoian stage, and the Iowan, Cary, and Mankato substages; pre-Illinoian (Kansan?) till may be present but has not been identified by the writer.

Various size fractions of the several till sheets were studied in detail (Simpson, 1952, p. 111-137, app. VII, VIII) in a largely inconclusive attempt to find a means of correlating and differentiating individual till exposures. This use of lithologic characteristics is not new. Carman (1917, p. 416) differentiated Nebraskan from Kansan till by color, as did Condra, Reed, and Gordon (1950, p. 20). Both state only that unweathered Nebraskan till is slightly darker than unweathered Kansan till. Five features helpful in correlation of till sheets in the vicinity of Yankton were described by the writer in 1947, and Flint (1955, p. 31-33, 59-60) found similar characteristics useful elsewhere in eastern South Dakota for differentiating Wisconsin till from pre-Wisconsin till.

Till sheets exposed in the Yankton area are similar in lithologic characteristics and general appearance. Size-frequency analyses and comparison of other physical characteristics including joints, secondary mineralization, induration, presence of ventifacts, and color indicate they differ only slightly.

LITHOLOGY

The investigation included qualitative field observations, composition counts of boulders, cobbles, and pebbles, pebble orientation analyses, and mechanical analyses of the finer fractions. It was limited chiefly by the small number of outcrops where the till exposed was of known or of presumed age. Results of the investigation are summarized on the following pages, with conclusions and inferences.

Color and oxidation.—Till ranges from medium gray to medium light gray when unweathered, and weathers to pale grayish orange or pale yellowish to dark yellowish orange owing to oxidation of iron present. The color is homogeneous throughout an exposure, although in some, streaks of more intense color mark the location of joints (see pl. 7*D*). Field observations suggest that Kansan (?) till is somewhat darker than younger tills. As no exposures of unweathered till have been correlated strictly on the basis of stratigraphic position, this inference is based on outcrops of presumed age. The presumption is based on other internal evidence and proximity to outcrops where the age can be established.

Size distribution.—Sand, silt, and clay fractions compose the greater part of till; pebbles and larger stones, although conspicuous, constitute only a small percent by weight or volume. Boulders are generally small; an estimated 90 percent are less than 2 feet in diameter, and those over 5 feet are rare. The largest boulder observed had a maximum dimension greater than 14 feet.

Subjective observations made during the field investigation suggested that the median grain size of till increases with increasing youth of the till sheet represented. Samples trenched from exposures of known age representing five till sheets were submitted to the South Dakota Highway Commission Soils Laboratory for analysis. The results (written communications, E. B. McDonald, June 27, 1952, and June 21, 1955) are reproduced in table 4. The data support the inference regarding the median grain of till and imply that an increase in the amount of sand-sized material at the expense of clay-sized material may be responsible for the qualitative difference observed. These conclusions are inconclusive, however, owing to the small number of available samples that met geologic requirements for analysis.

A difference in size sorting may well be a major factor controlling other physical characteristics. For example, an increase in clay content would (1) decrease permeability and, this in turn, would (2) hinder oxidation, (3) cause a darker color owing to a greater amount of retained water and to a greater proportion of dark-colored material, and (4) result in greater firmness which would in turn cause a difference in jointing. The cause of a difference in grain-size distribution is not definitely known. It may be the amount of very fine grained material derived by successive glaciers from bedrock formations of the region. Theoretically these were more deeply weathered and better exposed to glacial erosion during early Pleistocene time than they were later, when any regolith had either been removed or was mantled by drift left by the earlier glaciers.

Composition.—The till is composed chiefly of material derived from shale, argillaceous limestone, and iron-manganese concretions within the Yankton area and nearby. In addition other material was derived from the Sioux quartzite which is exposed in an adjacent area to the north, from siltstone, sandstone, and lignite similar to those exposed in the Fort Union formation of Eocene age in North Dakota, from limestone and dolomite of early Paleozoic periods exposed in southern Manitoba, Canada, and from igneous and metamorphic rocks of the Canadian Shield. No material known to have had an original source in the region to the west was found.

Most of the boulders are composed of various igneous and metamorphic rocks, chiefly of granitic and gneissic types; the rest are derived from Sioux quartzite. In the cobble fraction the relation is the same, but limestone and dolomite are also present. No boulders or cobbles of shale, argillaceous limestone, or schist were found.

The detailed investigation of till composition was limited to the boulder, cobble, pebble, and sand fractions owing to the ease of examination. Observations of the boulder and cobble fraction were restricted, moreover, to the three till sheets of Wisconsin age because of the scarcity and small size of exposures of pre-Wisconsin till. Among the three, Iowan till is least well represented because it contains fewer large stones, and because it is mantled by a thicker more widespread loess mantle that effectively conceals features of the till surface.

A characteristic frequency relationship was sought among rock types in the separate Cary and Mankato till sheets by means of composition counts of boulders and cobbles from each sheet. Six analyses were made by counting 100 or more stones in each of six piles at the edge of various fields. The six piles lay along an east-west traverse that crossed the common boundary of the two tills. Three counts were made from piles collected from Cary till exposed on Turkey Ridge, and three from piles collected from Mankato till on the floor of the James Valley lowland. The localities are shown in plate 10, and the results in the table below.

Frequency distribution, in percent, of rock types in Mankato and Cary till

	Mankato till			*Cary till*		
	A	B	C	D	E	F
Sioux quartzite	<1	<1	12	75	68	60
Other rock types [1]	100	100	88	25	32	40

[1] All stones of Canadian Shield source.

Subjective examination of other piles within a mile of the traverse indicates the proportions above are valid. These data show that material from the Sioux quartzite is more common in Cary till than in Mankato till, and that the amount of quartzite in the Mankato till decreases toward the west.

Composition counts of the pebble fraction were made (Simpson, 1952, p. 116-121, app. VII) of 28 collections of 200 or more pebbles each, from 24 localities. At four localities where two till sheets were exposed, a count was made from each till. The distribution of collections with respect to the age of the till is as follows:

Known or presumed age of till	*Number of counts*
Mankato	2
Cary	10
Iowan	9
Pre-Wisconsin	7

In counting, pebbles were separated into 12 classes on the basis of lithologic character. These classes were grouped in four provenances, according to the general area where kinds of rocks yielding these classes underlie much of the surface. For convenience the four groups may be referred to geographically; the classification is shown below.

Classification used in pebble counts, showing kinds of rock and grouping by provenance areas

Kind of rock	*Provenance area*
Shale Iron-manganese concretion fragments Argillaceous limestone and marl Sioux quartzite	South Dakota
Siltstone Sandstone Lignite	North Dakota
Limestone Dolomite	Manitoba Basin
Metamorphic rocks Igneous rocks Quartz and quartzite	Canadian Shield

The pebble counts do not show a distinguishing pattern of pebble composition for any single drift sheet. In fact, differences in composition are as great between two adjacent counts from the same exposure and drift sheet as between counts from two tills of different age at one locality. The data do indicate, however, that in till of late Wisconsin age the pebbles derived from Sioux quartzite decrease in number with increasing distance west of Yankton, so that beyond the longitude of Niobrara pebbles of Sioux quartzite are rare.

Composition of the pebble fraction best indicates the source of the till material. Pebbles of South Dakota provenance, despite their softness and weakness, are most numerous in 61 percent of the total number of analyses; pebbles of Manitoba Basin provenance dominate 29 percent of the counts, pebbles of Canadian Shield origin 10 percent of the counts, and pebbles of North Dakota origin, none. The average of all counts shows the following frequency distribution on pebbles among the four provenance groups:

	Percent
South Dakota	45
North Dakota	1
Manitoba Basin	30
Canadian Shield	24

Particles in the sand fraction, because of their small size, commonly represent mineral constituents of the various rocks and are not representative fragments of the rocks themselves. The principal exceptions among small particles are those grains composed of groups of even finer sedimentary particles, such as siltstone. However, the sand fraction may indicate most accurately the mineral composition of the till. The grains consist chiefly of quartz, feldspars, ferromagnesian minerals, and micas, all derived from igneous and metamorphic rocks, and fragments of siltstone and sandstone. Minor components are a variety of accessory minerals from igneous and metamorphic rocks.

Sorting and stratification.—Sorting and stratification are completely absent. Locally, however, partings that roughly parallel the land surface produce a crude fissility. This fissility suggests that the till accumulated by "plastering" at the base of the ice. Most till in the Yankton area was probably deposited in this way, for morainal deposits resulting from ablation or slumping have not been identified. Very rarely lenses or layers of sand or gravel as much as a few feet thick, or contorted masses of crudely sorted and stratified sandy till or sand a few feet across, are found. All indicate minor reworking of the till by melt water during accumulation.

Roundness, sphericity, and form.—Most boulders and cobbles show a high degree of roundness and sphericity. The flatiron shape said by von Engeln (1930) to be a characteristic feature of stones transported by glaciers was not observed. Most pebbles are rounded, and the chief exceptions are irregular fragments of iron-manganese oxide concretions, and blocky pieces of lignite. Sphericity of pebbles appears to be highest for sedimentary rocks; the average sphericity of pebbles derived from igneous and metamorphic rocks is notably lower, although the coefficient of sphericity ranges from low to high. Apparently the size and form of a pebble are largely an expression of the relation of original size and form as controlled principally by planes of weakness within the source rock, hardness, and amount of attrition. In general the amount of attrition of a given stone varies directly with the distance transported. Sand-sized grains are generally more equidimensional, and may be angular to rounded, although subangular and subrounded grains are most common.

Cobbles of limestone and dolomite commonly are characterized by parallelism of two prominent surfaces which originally were probably joint or bedding planes. Similar parallelism of surfaces is more common in the pebble fraction. These surfaces are caused not only by joints and bedding planes, but more commonly by planes of weakness indicated by mineral orientation, micaceous layers, and relic fossil structures.

Fine-grained rock types generally have smooth surfaces, but on pebbles of medium- and fine-grained igneous and metamorphic rocks a pitted surface is common owing to weathering and erosion of the ferro-magnesian minerals. On the larger stones this pitting is present or most pronounced on the side once exposed at the till surface. Rocks of igneous and metamorphic origin containing biotite are generally weak and rotten. This is probably caused by alteration (baueritization) of the biotite (see Wager, 1944, and Eskola, 1949). The alteration probably occurred since deposition, else weak stones likely would have been destroyed during glacial transportation.

Surface markings.—Striations and chatter marks are rare and are most often found on cobbles and pebbles of limestone or dolomite. They are less common on igneous and metamorphic stones and are absent from soft rock types such as shale, argillaceous limestone and siltstone. Apparently limestone and dolomite are more readily striated than harder, coarse-grained rock, and resist polishing better than softer rocks. The polishing action of the finer till fractions is important because it tends to remove striae made by coarser particles which are less abundant. In the sand fraction, grain surfaces are commonly smooth, although several are frosted.

Joints.—Joints are present in all till deposits, but the number and physical characteristics of them differ in tills of different ages. Ideally the comparison of joints should be made in unweathered till, but this is impossible owing to the lack of completely unweathered material of Cary or Mankato (late Wisconsin) age in outcrops. In several exposures however, tills of late Wisconsin age are only slightly oxidized, and are considered useful for comparative purposes.

Joints in Kansan(?) till are subparallel, a few inches apart, a few inches to a few feet long, 2 to 4 inches wide, smooth walled, almost planar, and open as much as an eighth of an inch. The till separates along these joints into moderately large angular to columnar blocks which break with a somewhat conchoidal fracture. In Illinoian till and in Iowan till joints range from a few to several feet apart, are as much as 27 feet long, at least a few feet deep, smooth-walled, almost planar, and open as much as half an inch. These tills break into moderately large, irregular chunks with uneven surfaces. The joint pattern typical of these tills is illustrated in plate *7D*; it is commonly emphasized by secondary mineralization. Cary till and Mankato till are characterized by hairline joints which are extremely numerous, very closely spaced, planar, 3 to 6 inches long, and 1 to 3 inches deep. They cause a fissility that commonly parallels the upper surface of the till, and the till separates along them into chiplike fragments 1 to 2 inches across and as much as a quarter of an inch thick. Large, conspicuous joints similar to those in older tills were sought unsuccessfully.

Secondary mineralization.—A characteristic of weathered till is the presence of one or more secondary minerals. These are apparent as coloring matter, as small, soft concretions, and as coatings on surfaces of joints and pebbles. Oxidation of unweathered (gray) till yields a pale yellowish orange that is in itself invalid for correlation purposes. In a general way, however, there is a broad relation between the completeness of oxidation and the age of the till, with the younger tills more weathered than older tills. This relation is the reverse of the expectable and is chiefly the result of differences in permeability and jointing. The joints are loci of oxidation, and owing to the permeability and close spacing of small joints in tills of late Wisconsin age, a small amount of oxidation gives a weathered appearance to an entire exposure.

Small soft nodules of iron oxide and of calcium carbonate are found in most exposures. Many of these prove to be weathered, reworked fragments derived from bedrock, but a few may be native to the till, especially among those in Cary and Mankato tills. Locally soft, powdery calcium carbonate fills open joints in Iowan, Illinoian, and Kansan(?) till.

Pebble and joint surfaces are commonly coated by iron oxides, manganese oxides, or both. Where both kinds of oxides are present, those of iron accumulated first and were subsequently covered by those of manganese. These oxides have a distinct preference for pebbles of limestone and dolomite. The iron oxide coatings are soft, powdery, and generally cover an entire pebble; manganese oxide coatings are by comparison thinner, scaly, and patchy; the total thickness may be as great as an eighth of an inch. The material was largely derived from constituents of the till itself: iron is available in many of the mineral particles, and manganese probably was obtained from manganese-rich concretions of the Pierre shale reworked by the glacier.

Manganese oxides coat the surfaces of joints in Kansan(?) till and are present on both joint and pebble surfaces in Illinoian till and Iowan till. Iron oxides are commonly found on both pebble and joint surfaces of all till sheets except Kansan(?).

Induration.—Till strength ranges from weak to nearly firm, and the strength increases with the amount of clay-sized material, and is the result of compaction. No standardized tests of strength or toughness were made, but in a general way it was noted that the dry strength of till broken in the hands increases with the age of the till, and the depth of penetration of a pick point decreases with age. These comparisons apply only to newly exposed, moderately weathered material, for on prolonged exposure the older tills become case hardened by drying. No evidence of cementation by secondary mineralization was found in the field.

Fabric.—Pebble orientation analyses (Simpson, 1952, p. 126-135, app. VIII) verify locally the bearing of the ice advance, and also provide a possible means of differentiating and correlating till sheets and exposures. Sixteen analyses were made at 10 localities; at 3, where more than one till sheet is exposed, an analysis was made of each sheet. The resulting data are essentially in agreement with other field evidence as to the bearing of glacial advance, but usefulness in differentiation and correlation is yet indefinite.

Ventifacts.—Pebbles showing the results of wind abrasion are not, strictly speaking, an internal, physical characteristic of till. Commonly, however, ventifacts found are glacial erratics, either lying on the till surface, or projecting through from below. They have been found only at the surface of Iowan till beneath loess of post-Iowan age and are a result of abrasion during accumulation of the loess. Most of the pebbles found display only polishing, but a few, chiefly those of quartzite, are pitted and faceted.

Summary of lithologic differences.—Careful examination of till in the vicinity of Yankton indicates that six lithologic characteristics are helpful locally in correlating till outcrops, but that in many exposures these characteristics are absent or inconclusive (Simpson, 1947). Correlation based on them is tentative because their accuracy can be evaluated only at those few outcrops where the age of the deposits can be established by other means. By means of these characteristics an outcrop of till may be placed in one of three principal age groups. Pre-Illinoian (Kansan?) till constitutes one group, Illinoian and Iowan tills a second group, and Cary and Mankato tills a third. More precise correlation is questionable. The six characteristics in approximate order of importance are joints, secondary mineralization, induration, ventifacts, size sorting, and color; they are summarized in the following table.

TOPOGRAPHIC EXPRESSION

Accumulations of drift deposited chiefly by glacier ice and characterized by undulatory constructional topography is termed "moraine." It generally includes scattered lenses of water-laid, stratified material, and locally, in areas as large as several acres, may have a flat, constructional surface. Two kinds

Gross lithologic characteristics useful in correlation of till deposits near Yankton, S. Dak.

	Stage	Joints	Secondary mineralization	Induration	Ventifacts	Size sorting	Color (unweathered)
Wisconsin	Mankato substage.	Hairline joints extremely numerous; closely spaced, shallow, short, semiplanar approximately parallel to surface; produce chiplike fragments 1 to 2 in. across and as much as ¼ in. thick, with moderately smooth slightly curved surfaces.	Entire deposit commonly well oxidized. Iron oxide coatings on many joint and pebble surfaces, no manganese oxide coatings.	Low dry strength; crumbles readily to mealy fragments; matrix adheres to pebbles. Penetration by pick point greatest.	None.	Matrix sandy; stones numerous, larger.	Medium gray.
	Cary substage.					Gradational	
	Iowan substage.	Hairline joints numerous, open joints common; latter 1 to 12 ft. apart, deep, long, planar at various angles to surface; till breaks into irregular chunks with irregular surfaces.	Entire deposit may or may not be oxidized; oxidation to depth of 2 to 4 in. on both sides of joints. Iron oxide coatings on nearly all joint surfaces and pebbles, and coated in turn by manganese oxides; open parts filled with calcium carbonate.	Moderately high dry strength; breaks into discrete fragments with irregular surfaces; matrix does not adhere to pebbles. Penetration by pick point intermediate.	Locally, on till surface.		
	Illinoian.				None.		
	Pre-Illinoian.	Open joints numerous; generally a few inches apart, shallow, short to moderately long, planar approximately vertical; produce angular to columnar blocks that break with conchoidal to uneven fracture.	Entire deposit nearly unoxidized; oxidation to depth of as much as ¼ in. on both sides of joints. No iron oxide coatings on pebbles or joint surfaces, but manganese oxides coat many pebbles and joints.	Relatively high dry strength, considerable hand pressure required to break; breaks into discrete fragments with smooth surfaces, matrix does not adhere to pebbles. Penetration by pick point least.	None.	Matrix dominantly clay and silt; stones comparatively few and small.	Medium dark gray.

of moraine are present in the Yankton area: ground moraine and end moraine. Both are found in areas of Cary and Mankato drift, and south of the Yankton area a broad, low, well-dissected loess-mantled end moraine(?) marks part of the Iowan drift border. Most Iowan and all pre-Iowan drift lacks constructional topographic expression owing to extensive erosion and a blanket of younger deposits.

Ground moraine.—A blanketlike deposit composed chiefly of till and characterized by knolls and swales (undrained depressions) is termed ground moraine. The knolls and swales are commonly without apparent orderly arrangement, but locally, as southwest of Lesterville, the swales are somewhat concentrated in elongate groups 1 to 2 miles long and ½ mile or less wide. The axes of these groups differ somewhat in orientation, but generally are subparallel to an inner Mankato drift border. The knolls and swales are conspicuous both on the ground and in aerial photographs. Soil is eroded from the knolls, leaving light-colored areas, and accumulates in adjacent swales. As the material is fine grained and occupies depressions, it collects and retains moisture, and areas of relatively dark soil and vegetation result. Where the swales are elongate and interconnected, the dark and light earth produce an indistinct convolute pattern that covers areas of less than a quarter of a square mile.

End moraines.—Ridgelike deposits composed chiefly of till are end moraines. Like ground moraine, an end moraine may be marked by knolls, but swales, if present, are few. The principal basis for distinction therefore is whether the form of the deposit is blanketlike or ridgelike. In the vicinity of Yankton end moraines are discontinuous, but the segments are generally alined, and one chain can be traced for 20 miles or more within and beyond the borders of the Yankton area. The segments are commonly 2 to 3 miles long and about ½ mile wide, but they range from large knolls to ridges nearly 13 miles long. Between the parallel axes of the major ridges are shorter subparallel ridges that are less clearly alined.

Crests of the end moraines commonly stand 10 to 20 feet above the general level of the ground moraine surface, although some crests, such as those in the southeastern part of T. 95 N., R. 55 W., Yankton County, and in the NW¼ sec. 6, T. 94 N., R. 55 W., Yankton County, rise 100 feet or more above the adjacent ground moraine. Only ridges with a height of 10 feet or more above the ground moraine are mapped as end moraines.

Erratic boulders are more numerous on the surface of end moraines than on ground moraine. This is caused in part by absence from the end moraines of a thin mantle of loess that covers much of the ground moraine, and by the erosion of fine till particles from end moraine surfaces owing to somewhat steeper slopes. It was found that within the inner Mankato drift border, lines separating areas of abundant erratics from areas of few erratics are nearly coincident with the boundaries of end moraines. The abundance of exposed boulders apparently differs on the several drift sheets: they are most numerous on the surface of the younger Mankato end moraines, much less so on older Mankato end moraines, and still less on Cary end moraines. Few boulders are found in areas of Iowan till south of the Missouri River trench, and most of those are larger than all but a few boulders in younger till.

End moraines lie at or near the maximum position attained by the glacier front during the Iowan, Cary, and Mankato substages. In addition, end moraines of Mankato age, together with groups of swales in the ground moraine, mark the position of the ice front at several stages during the last glacial recession.

The Iowan end moraine(?) (see pl. 10), about 3 miles south of Coleridge, Cedar County, Nebr., is a prominent, broad, loess-covered ridge. The rolling topography is in part the result of postglacial erosion. Approximately 3 miles southwest of the community the loess-covered crest of the ridge attains an altitude of about 1,750 feet, some 50 to 100 feet above the adjacent surface. Toward the east and northwest the end moraine becomes less prominent and is finally lost in heavily dissected terrain.

End moraines of Cary age mantle Turkey Ridge northeast of Clay Creek, and form moderately distinct but discontinuous ridges on Yankton Ridge. End moraines are absent from the Cary drift border elsewhere in the Yankton area. The highest point of the Cary end moraines on Yankton Ridge is at an altitude of about 1,670 feet in the SW¼ sec. 34, T. 94 N., R. 57 W., Yankton County.

End moraines of Mankato age form two prominent chains; the outer of these marks much of the Mankato drift border, whereas the inner only indicates the position of the ice front at some unspecified time during recession. The longest end moraine in the vicinity of Yankton is a segment of the outer morainal chain; the segment is nearly 13 miles long, and lies on the northwest flank of Yankton Ridge. Along the southwest flank of Turkey Ridge prominent, moderately long segments represent both the outer and inner chains. West of James Ridge the inner moraine is not composed of individual ridges but rather is a broad belt characterized by end moraine topography. The crest of the outer Mankato end moraine in the NE¼ sec. 21, T. 94 N., R. 57 W., Yankton County, is at an altitude of 1,500 feet, and 6 miles farther north of the surface of the inner morainal belt is at an altitude of only 1,405 feet.

Todd (1899, p. 29-32, pl. 8) correlated most of the outer end moraines with the "Altamont moraine" of Chamberlin (1883, p. 388), and some segments of the inner chain with Chamberlin's "Gary moraine." Chamberlin's names are not used in this report because they have been consistently misapplied in adjacent States, and because the location of principal Mankato end moraines of this report differ in part from the positions indicated by Todd.

ENGINEERING CHARACTERISTICS

The physical characteristics of till differ somewhat with age and extent of weathering. Most till is soft, but till of Wisconsin age is commonly a little softer than pre-Wisconsin till; on prolonged exposure, moreover, the latter becomes casehardened. The dry strength of pre-Wisconsin, notably Kansan(?), till is distinctly greater, and that of Iowan till somewhat greater than the dry strength of late Wisconsin till. Late Wisconsin till breaks readily in the hands into crudely chiplike pieces and crumbles easily into a meal. Iowan and Illinoian till separate a little less readily into irregular chunks bounded by slightly curved surfaces, and Kansan(?) till, although it separates with moderate ease into columnar segments bounded by joint surfaces, is broken into smaller pieces with difficulty. Excavation of all till is possible by hand, but power equipment is particularly desirable for work in material of Kansan(?) age. Blasting is not necessary unless an unusually large boulder is encountered. Permeability is low in late Wisconsin till, and probably lacking in older deposits, although a very small amount of water may seep slowly through joints. Lenses of sand or gravel may occur within till; these lenses may contain water, and if of considerable extent may yield a continuous discharge, especially during spring. Plasticity ranges from moderately low in late Wisconsin till to moderately high in older tills; because of this plasticity, till may be difficult to traverse when wet. Surface drainage ranges from good to poor. End moraines are generally well drained, although locally there are swampy, closed depressions. Drainage of ground moraine is fair to poor owing to the knoll and swale topography, the near absence of integrated drainage, and the low permeability of underlying till. Slopes cut in till are of moderate to good stability: Illinoian(?) till in a nearly vertical face about 40 feet high is almost unmodified after 5 years of exposure. For till of late Wisconsin age a slope of 60° or less is desirable if the face is more than 15 feet high. Slumping under these conditions is not likely.

Channeled samples from five exposures of till were submitted to the soils laboratory, South Dakota State Highway Commission, for complete soil analysis. Each sample is known to represent one of the five till sheets, Kansan(?), Illinoian, Iowan, Cary, and Mankato. They were collected from exposures that are similar in extent of weathering and that are believed to be representative of all till in the vicinity of Yankton. The results of analysis (written communications, E. B. McDonald, June 27, 1952, and June 21, 1955) are given below.

TABLE 4.—*Soil analyses of five till samples*

Test	Kansan(?)	Illinoian	Iowan	Cary	Mankato
	A	B	C	D	E
Depth of sample below ground surface	8–11 ft	0–8 ft	3–10 ft	25 ft	30–10 ft
Textural classification [1]	Heavy clay	Clay	Clay	Clay	Clay loam
Classification (Allen) HRB [2]	A–7–6(14)	A–7–6(17)	A–7–6(13)	A–6(9)	A–6(8)
Specific gravity [3]	2.72	2.76	2.73	2.73	2.69
Pounds per cubic foot, dry, loose	72.0	80.6	82.6	79.3	79.6
	Percent	*Percent*	*Percent*	*Percent*	*Percent*
Shrinkage ratio [3]	1.95	1.96	1.94	1.84	1.82
Shrinkage limit [3]	14.6	14.7	14.7	17.6	17.7
Volume change [3]	12.9	12.4	17.5	7.47	6.41
Passing ⅜in. sieve [4]	100.0	99.3	100.0	100.0	100.0
Passing no. 4 sieve [4]	99.3	99.0	100.0	98.7	99.0
Passing no. 10 sieve [4]	98.1	98.3	98.7	96.7	96.8
Passing no. 40 sieve [4]	93.4	94.6	92.8	87.0	90.6
Passing no. 200 sieve [4]	79.3	82.2	76.6	63.8	65.6
Sand content [5]	18.8	28.7	33.2	40.2	42.2
Silt content [5]	20.6	34.6	33.2	24.8	30.6
Clay content [5]	58.7	35.0	32.3	31.7	24.0
Liquid limit [6]	41.6	46.0	41.1	35.8	34.3
Plasticity index [7]	24.9	28.2	22.4	16.8	15.0
Field moisture equivalent [8]	20.1	21.0	23.7	21.7	21.2
Centrifuge moisture equivalent [9]	36.0	34.3	31.8	18.9	21.6

[1-9] For references to test methods see p. 45.
A. NW cor. sec. 18, T. 32 N., R. 4 W., Knox County.
B. NE cor. NW¼NE¼ sec. 13, T. 93 N., R. 57 W., Yankton County.
C. NW cor. SW¼ sec. 26, T. 32 N., R. 1 W., Cedar County.
D. SW cor. NE¼ sec. 7, T. 93 N., R. 56 W., Yankton County.
E. NW cor. NE¼NE¼ sec. 29, T. 94 N., R. 55 W., Yankton County.

OUTWASH

Outwash consists of material transported by a glacier, but deposited beyond the glacier margin by melt water flowing therefrom. It is a minor component of the drift and is composed mostly of stratified and sorted material. In the Yankton area outwash represents the Illinoian stage and the Cary and Mankato substages. The deposits are similar in many respects and differ only a little in others. With one exception no characteristics were found that permit the differentiation or correlation of outwash, for variations within material of a given age are apparently as great as the range of differences between the several deposits.

Outwash was deposited both as valley fill and as an extensive mantle suggestive of an outwash plain or apron at the ice margin. The Illinoian stage, and the Cary and Mankato substages all include valley fills, but only Cary drift includes a deposit similar to an outwash plain.

Outwash of the Illinoian stage and the Cary substage include two facies each. The two facies of Illinoian outwash grade imperceptibly into one another. One is lithologically similar to other outwash in the area and consists largely of material of Canadian origin. The second is composed chiefly of gravel reworked from alluvium of western provenance by melt water from the Illinoian glacier. This facies contains scattered small boulders, cobbles, and pebbles of Canadian source, and for this reason is considered as outwash in this report. For convenience the first facies is referred to informally hereafter as the glacial facies, the second as the alluvial facies. The two facies of Cary age are well separated from one another geographically. One facies is a typical outwash gravel of northern provenance and is known only north of the Missouri River trench; the second, which forms an outwash plain(?), is composed chiefly of sand, silt, and clay, and is found only south of the trench. For convenience the first is referred to in this report as the northern facies, the second, as the southern facies.

LITHOLOGY

With one exception physical characteristics are of little value in correlation or differentiation. The exception is the lithologic composition of outwash belonging to the alluvial facies of Illinoian age. Because of the similarity few detailed lithologic studies were made; the general field observations are summarized below.

Color and oxidation.—The color of outwash deposits is commonly brownish gray to very pale orange, and is a result of staining by iron oxides. In deposits of Cary and of Mankato age alternating streaks of browns and black owning to iron oxides and manganese oxides are locally present; the streaks reflect differences in permeability. The most distinctive color observed was a grayish orange-pink characteristic of the alluvial facies of Illinoian outwash; it is caused by orthoclase, a major constituent of the predominant rock.

Size distribution.—Outwash is composed chiefly of sand and gravel. Lenses of silt as much as several feet across were observed in both facies of Illinoian outwash and in the northern facies of Cary outwash. The southern facies of Cary outwash consists chiefly of silt and fine sand, with moderate amounts of clay and medium sand; locally the deposit is difficult to distinguish from overlying loess. Cobbles are locally numerous in the glacial facies of Illinoian outwash, and the alluvial facies contains many cobble-sized bodies of greenish-gray and pale-red silty clay. These are lithologically typical of the Ogallala formation and were derived either directly from it or from the intermediate Grand Island formation. Cobble beds and cobble gravel are most common in Mankato outwash; the terrace deposit in the W½ sec. 29, T. 95 N., R. 55 W., Yankton County, is an example of the latter. Boulders are scattered throughout many outwash deposits including the alluvial facies of Illinoian outwash. Rarely "boulders" of till 1 to 3 feet in diameter were noted in Cary outwash along Beaver Creek (S. Dak.).

Composition.—The approximate lithologic composition of the gravels is indicated by results of pebble-composition analyses at localities considered typical of the several outwash deposits. In each count of 100 stones, rock types referred to are the same as those in pebble-composition counts of till (see page 48). The sources of the rocks are also the same with one exception: pebbles of grayish orange pink granite (a silicic igneous type) reworked from the Grand Island formation and originally derived from the Rocky Mountains constitute nearly half of the alluvial facies of Illinoian outwash. Most outwash stones were derived from the same debris that the glacier deposited as till, but the pebble fraction of outwash differs in composition from the pebble fraction of till in two respects. One is the presence in outwash of the pink granitic pebbles described above, and the second is the near absence of weak or soft rock types. The scarcity of soft, weak, stones probably expresses an inability to resist the abrasion characteristic of transportation by melt water streams. Typical pebble-composition counts of the several kinds of outwash follow.

Approximate composition of the glacial facies of Illinoian outwash from NE cor. NW¼ sec. 23, T. 93 N., R. 57 W., Yankton County

Rock type	*Percent*
Shale	1
Iron and manganese concretions (fragments)	2
Sandstone	2
Quartz and quartzite	26
Limestone	23
Dolomite	6
Metamorphic	2
Igneous	38
	100

Approximate composition of the alluvial facies of Illinoian outwash from NW cor. SW¼ sec. 11, T. 93 N., R. 57 W., Yankton County

Rock type	*Percent*
Sandstone	1
Quartz and quartzite	42
Dolomite	4
Metamorphic	5
Igneous	48
	100

Approximate composition of the southern facies of Cary outwash from NE cor. SE¼ sec. 26, T. 33 N., R. 1 E., Cedar County

Rock type	*Percent*
Iron and manganese concretions (fragments)	1
Argillaceous limestone	9
Quartz and quartzite	30
Limestone	30
Igneous	30
	100

Approximate composition of the northern facies of Cary outwash from NE cor. SE¼ sec. 12, T. 94 N., R. 56 W., Yankton County.

Rock type	*Percent*
Shale	3
Iron and manganese concretions (fragments)	2
Argillaceous limestone	4
Sioux quartzite	6
Quartz and quartzite	29
Limestone	24
Dolomite	7
Metamorphic	11
Igneous	14
	100

Approximate composition of Mankato outwash from NE cor. NW¼ sec. 5, T. 93 N., R. 59 W., Bon Homme County

Rock type	*Percent*
Shale	10
Iron and manganese concretions (fragments)	10
Argillaceous limestone	6
Sioux quartzite	1
Quartz and quartzite	5

Limestone	32
Dolomite	19
Metamorphic	10
Igneous	7
	100

A cursory examination of the sand fraction of four samples representing the glacial facies of Illinoian outwash, both facies of Cary outwash, and Mankato outwash showed that the composition of the sand fraction is similar to that of till. The grains consist chiefly of quartz, feldspars, ferromagnesian minerals, micas, various accessory minerals of igneous rocks, limestone, and dolomite. Most grains have a frosted surface.

Sorting and stratification.—Sorting ranges from good to poor. In general it tends to range from fair to poor in Illinoian outwash and from good to fair in outwash of the Cary and Mankato substages. Stratification is commonly absent, but if present it may be either horizontal or inclined. Where present, individual strata are rarely more than a few inches thick and the contacts are abrupt and moderately smooth. Current-type crossbedding is commonly found in better sorted, better stratified outwash.

Roundness and sphericity.—Pebbles, cobbles, and boulders in the outwash are generally well rounded. Some however, are subrounded, and a very few which were fractured shortly before deposition are angular to subangular. The pebbles are more or less inequidimensional, and the larger stones somewhat less so. The general form of a stone commonly reflects its form as it was being transported by the ice, and, indirectly, its original form. As a group the most nearly equidimensional stones are those in the alluvial facies of Illinoian outwash which were reworked from the Grand Island formation. The sand fraction is commonly subrounded to subangular, and individual particles are dominantly equidimensional. These characteristics reflect a homogeneity of a mineral particle that is generally lacking in a rock fragment.

Secondary mineralization.—None of the deposits are cemented. Hollow, unfractured calcium carbonate concretions as large as 1 inch in diameter are found locally in the southern facies of Cary outwash. The lack of concentric layering suggests the concretions were formed during just one period of precipitation.

Fossils.—The only fossil material found consisted of a few, scattered, badly water-worn, nonidentifiable fragments of petrified wood and vertebrate bones from the alluvial facies of Illinoian outwash in the NW¼SW¼ sec. 11, T. 93 N., R. 57 W., Yankton County. The nature of petrification indicates that the fragments were reworked, together with the enclosing gravel, from the Grand Island formation.

TOPOGRAPHIC EXPRESSION

Outwash was deposited partly as valley fill and chiefly as a moderately rolling mantle suggestive of an outwash plain. Both facies of Illinoian outwash and the northern facies of Cary outwash lack any apparent constructional topography, for these are exposed only in buried profile along valley walls. Of the three facies, only the Cary outwash causes any break in the valley crossprofile, and although it is mild, it can be traced for several miles along Beaver Creek (S. Dak.) and the James River. The distribution, continuity, and altitude of exposures of these several deposits indicate the sediments originally constituted valley fills with almost flat surfaces.

The southern facies of Cary outwash and the Mankato outwash both preserve much of the original topography. The southern facies lies at the ground surface in an area of moderately rolling constructional terrain that has been partly modified by erosion. The origin of the deposit and its position relative to the ice front suggest an outwash plain, but the large relief and rolling surface make the term somewhat misleading. Mankato outwash forms valley trains with nearly flat surfaces in several draws and valleys once occupied by melt water; including the James River trench and Beaver Creek (S. Dak.) valley. Slightly older outwash of Mankato age once formed a higher valley fill, segments of which now constitute fill terrace deposits along the same stream.

ENGINEERING CHARACTERISTICS

Outwash is loose and readily excavated by hand or power equipment unless there are very large boulders. Permeability is high, and drainage is good although puddles may form locally in the basal part of a deposit if it lies on an irregular surface of impermeable material. No difficulty in traversing outwash is expectable. Slope stability is poor unless faces are cut at angles of about 30° or less.

A sample of the glacial facies of Illinoian outwash from a ridge in the NE¼ sec. 23, T. 93 N., R. 57 W., Yankton County, was tested in the Corps of Engineers Soils and Materials Laboratory at Omaha to ascertain suitability of the material as a source of concrete aggregate. Results (H. L. Weil, written communications, November 23, 1948, November 8, 1949, and January 6, 1950) in the files of the Corps are abstracted below.

	Percent
Deleterious materials:	
Soft flaky particles	0.2
Shale	.1
Iron-manganese concretion fragments	Tr.
Finer than No. 200 sieve	3.2
Absorption, after 24 hours immersion	.5
Specific gravity	2.60

Unit weight: Loose: 99.5 pounds per cubic foot.
Rodded: 107.0 pounds per cubic foot.

Mortar strength after 7 days: 4,357 lbs. per square inch (by ASTM C 87–46)

Reactivity:
High-alkali cement: negligibly reactive.
Low-alkali cement: nonreactive.
Potentially reactive materials constitute less than 2 percent of the aggregate and are mostly cryptocrystalline to glassy igneous rocks; the remainder are chalcedonic chert.

Particles that are porous, friable, or argillacoeus make up 3 percent of the total. Carbonates and ferrous oxides coat less than 1 percent by volume of the particles and few of these are covered on more than half their surface.

Use of the alluvial facies of Illinoian outwash for heavy construction may prove undesirable owing to the presence of three cleavage directions in the orthoclase, a major mineral constituent of the facies. The numerous balls of silty clay and any fragments of petrified wood and bone are readily removed by screening. The degree of reactivity of this facies with alkalies in portland cement is not available, but it is inferred to be nonreactive to negligible with low-alkali cement, and negligible to doubtful with high-alkali cement. The inferrence is based primarily on reactivity of the Grand Island formation, from which the alluvial facies of Illinoian outwash chiefly was derived.

ICE-CONTACT STRATIFIED DEPOSITS

Ice-contact stratified deposits consists of material transported by a glacier and deposited, chiefly by melt water, at or behind the ice margin. It is a minor constituent of drift in the Yankton area, where deposits represent the Iowan(?), Cary, and Mankato substages. None of the lithologic characteristics observed are useful in differentiation or correlation of the several deposits.

Kinds of deposits.—The several deposits are of two kinds: those consisting wholly of sorted material (sand and gravel), and those consisting of both sorted and nonsorted (till) material. Those of sand and gravel constitute kames and kame-terrace deposits. For the purposes of this report kames are knolls or short ridges composed of sorted material that accumulated as cones or deltas against the ice margin, or as crevasse or moulin fillings behind it. Kame-terrace deposits are composed of sorted material that accumulated between a glacier and an adjacent valley wall, or ridge. Such terraces are commonly paired, but may be single. Owing to the proximity of the glacier at the time of deposition the sediments may enclose quantities of till. The deposits are then referred to as kamelike in order to distinguish them from those that apparently consist wholly of sorted material. As the till is typical of adjacent morainal material, only the sorted component is described below. In the Yankton area kames represent the Iowan(?) and Mankato substages, and kame-terraces and kamelike deposits the Cary substage.

LITHOLOGY

Ice-contact stratified drift is of minor significance in the solution of stratigraphic problems in the Yankton area owing to the small extent of the deposits. For this reason little work was done on physical characteristics of the sediments, and detailed observations were largely restricted to possible sources of concrete aggregate.

Iron oxides commonly stain the ice-contact deposits a moderate yellowish brown. Locally streaks of dark brown and black caused by iron and manganese oxides reflect differences in permeability. Deposits of Iowan (?) age are a pale yellowish gray that is somewhat distinctive.

The material is chiefly sand and gravel and includes scattered cobbles and small boulders; boulder beds with stones as large as 4 feet in diameter were observed in a Cary kame-terrace deposit in the SE cor. SW¼ sec. 35, T. 95 N., R. 56 W., Yankton County. Kamelike deposits of Cary age are about one-half sandy till.

Composition of the sediments is about like that of outwash, except for the till component locally present. A count of 100 pebbles collected from a pit in the SE cor. sec. 25, T. 32 N., R. 1 W., Cedar County showed the following composition.

Rock type	*Percent*
Iron and manganese concretions (fragments)	1
Argillaceous limestone	16
Quartz and quartzite	29
Limestone	19
Dolomite	1
Igneous	34
	100

Provenance of these pebbles is the same as for those of till (see p. 48).

H. L. Weil (written communication, August 30, 1949) furnished the following information from files of the Corps of Engineers Soils and Materials Laboratory on the petrographic analysis of the sand fraction of one Cary kame-terrace deposit. The sample was taken from a pit in the NW¼NE¼ sec. 34, T. 95 N., R. 56 W., Yankton County.

Constituents	*Percent*
Quartz	59
Feldspar	22
Phaneritic igneous and gneiss	6
Quartzite, sandstone, and graywacke	3
Limestone	3
Chert	3
Iron and manganese oxides	2
Shale	1
Miscellaneous	1
	100

Sorting is generally poor and only somewhat better in deposits of the Mankato substage. Stratification is commonly crude and inclined. Individual strata are not more than a few inches thick, and contacts are gradational and moderately smooth. The best stratification is found in Cary ice-contact deposits. In many stratified deposits, a lack of stratification or tilted strata (pl. 8A) in a part of the exposure suggests collapse on recession of the glacier margin.

The roundness, sphericity, and surface markings of stones are similar to those of outwash.

Cementation is lacking except in the kame-terrace deposits in secs. 34 and 35, T. 95 N., R. 56 W., Yankton County, where scattered beds of sand are lightly cemented and some beds of boulders are firmly cemented by oxides of manganese and iron.

Concretions are found only in Iowan(?) ice-contact deposits. They are of calcium carbonate, as much as 4 inches in diameter and their lack of layering suggests that they formed during a single period of accumulation.

TOPOGRAPHIC EXPRESSION

The original constructional topography of many ice-contact stratified deposits has been destroyed by erosion or hidden beneath a mantle of younger deposits. This is true of the Iowan(?) kames and Cary kame-terrace deposits. The Iowan (?) kames are exposed naturally only in profile along the sides of draws and cause no break in slope. Natural outcrops of the Cary kame-terrace deposits are similar, but owing to their greater area cause a drainage pattern characteristic of loose sand. Cary kamelike deposits and Mankato kames retain their constructional topography. The Cary kamelike deposits are characterized by rolling topography. Of the two, the northern deposit is the higher; its crest is marked by several knolls that stand as much as 75 feet above the surrounding surface. Two Mankato kames in sec. 25, T. 94 N., R. 56 W., Yankton County, are single knolls about 50 feet high. The Mankato kame mapped in the SW cor. sec. 31, T. 94 N., R. 54 W., Yankton County, was a single knoll about 15 feet high; it is since been excavated, graded, and obliterated.

ENGINEERING CHARACTERISTICS

Ice-contact stratified material is loose and readily excavated either by hand or power equipment except for rare beds of large boulders, which may or may not be cemented by oxides. Permeability is high and drainage excellent. Slope stability is good as slopes are cut at angles of about 30° or less in sandy material, or less than 60° in mixed deposits of till, and sorted sediment. Locally, faces exposing cemented layers appear stable at angles as high as 75°. Steeper slopes than these appear to gully or slump over a period of 2 or 3 years. Trafficability ranges from fair to good in all weather.

The Corps of Engineers collected samples from a pit on the west side of Beaver Creek, in the SE cor. NW¼NE¼ sec. 34, T. 95 N., R. 56 W., in Yankton County in order to ascertain suitability of the Cary kame-terrace deposit as a source of concrete aggregate. Laboratory reports (H. L. Weil, written communications, Nov. 8, 1949, and Jan. 3, 1954) include the following data.

	Percent
Deleterious materials:	
Clay lumps	0.09
Soft flaky particles	.2
Shale	.1
Iron-manganese concretions	1.1
Finer than No. 200 sieve	2.6
Absorption, after 24 hours immersion	1.0
Specific gravity	2.60

Unit weight:
Loose: 101.5 pounds per cubic foot.
Rodded: 106.5 pounds per cubic foot.

Mortar strength after 7 days: 4,342 pounds per square inch (by ASTM C 87–46)
(Type III portland cement, 2-inch cube).

Reactivity: (fine aggregate)
high alkali cement: negligibly reactive.
low alkali cement: nonreactive.
Potentially reactive materials constitute slightly more than 1 percent of this sand; chalcedonic chert accounts for 1 percent of this amount, and opaline sandstone and

A. Collapsed strata in a Cary(?) kame-terrace deposit exposed in the SW cor. SE¼ sec. 16, T. 95 N., R. 56 W., Yankton County. Dip of strata ranges from 60° to 85° NE.

B. Wind-stratified post-Iowan pre-Mankato loess exposed in the NW cor. SW¼NW¼ sec. 7, T. 32 N., R. 7 W., Knox County cryptocrystalline to glassy igneous rock account for traces. Total chert in this sample amounts to 3 percent.

Fineness modulus (average of five samples):

	As received	*Washed*
Range	2.59 to 3.34	2.56 to 3.39
Average	2.94	3.07

NONGLACIAL DEPOSITS

The term "nonglacial deposit" refers here to an eolian or fluvial deposit, not deposited by melt water, of Pleistocene age. The deposit may have accumulated during either a glacial stage or substage and may lie beyond or within the glaciated region. Nonglacial deposits are of great importance in correlating the several drift sheets in the vicinity of Yankton because nonglacial units are widespread, are readily identified either by distinctive lithologic characteristics or diagnostic fossils, and are interbedded with the drift sheets. The deposits consist of several sheets of loess and a coarse-grained alluvial deposit.

LOESS

For the purpose of this report loess is defined as an eolian sediment in which the silt fraction is larger than either the sand or clay fraction. The condition of eolian genesis separates loess from fluvial, lacustrine, or other silts, and throughout central United States this wind-blown origin can be demonstrated by detailed study; the conditions of size and relative quantity separate loess from dunes of sand or clay. Previous authors have included in definitions of loess reference to various physical features such as color, jointing, stratification, homogeneity, and calcium carbonate content. Because these features differ from one exposure to another and may differ even within a single outcrop, they are omitted from the definition adopted here.

Loess has been mapped only where it is about 5 feet or more thick. This figure has been chosen because it eliminates the need of mapping the many areas where loess is very thin and patchy. To map such areas in the detail accorded other formations would be impractical. One criterion for recognizing the presence of loess north of the Missouri River is the scarcity of erratics on the ground surface. Where till immediately underlies the surface, glacial stones are exposed, but where 2 feet or more of loess is present, the surface is stone-free.

NOMENCLATURE

Loess in the vicinity of Yankton has been divided stratigraphically into five sheets. Four of these are correlated with the Illinoian stage, the undifferentiated Iowan and Tazewell substages, the Cary substage, and the Mankato substage respectively. The fifth is correlated with the Farmdale loess of Leighton and Willman. Where recognized formational names are not available, these deposits are customarily designated by the name of the associated drift. For the purpose of this report the loess sheets are identified as follows (see also fig. 8).

Loveland loess: lies upon Illinoian till and is overlain by Farmdale loess; it is late Illinoian in age.

Farmdale loess of Leighton and Willman: lies upon Loveland loess and is overlain by Iowan till; it is considered to be early Iowan in age in this report, but may date from a separate, pre-Iowan, Wisconsin substage.

Iowan and Tazewell loess: lies upon Iowan till and is overlain by Cary till; it is not differentiated, and probably is from late Iowan or late Tazewell in age.

Cary loess: lies upon Cary till and is overlain by Mankato till; it is of late Cary age.

Mankato loess: lies upon Mankato till; it is of late Mankato age, but locally may include a little undifferentiated loess of Recent age.

The term *Wisconsin loess* refers to undifferentiated loess of Wisconsin age. The term *post-Iowan loess* refers to undifferentiated loess deposited in the Yankton area since the climax of Iowan glaciation. The phrase *post-Iowan pre-Mankato loess* refers to undifferentiated loess deposited in the Yankton area between the climax of Iowan glaciation and the beginning of Mankato glaciation. The name *Peorian loess*, common in literature of Great Plains stratigraphy since 1898, is not used here because of general confusion in present definition and usage of the term.

FACIES

Two loessial facies are readily recognized in the Yankton area. One is the upland phase of Condra, Reed, and Gordon (1950, p. 8–9) which consists of unmodified loess and is described below. The second is the colluvial slope phase of the same authors. It consists of the material immediately underlying natural slope surfaces and is loess modified and reworked chiefly by the interaction of gravity, vegetation, slope wash, and frost. The valley phase of Condra, Reed and Gordon which consists of a mixture of wind- and water-transported material was not recognized.

LITHOLOGY

The loess sheets were investigated to determine what physical characteristics, if any, are of value in correlation, and to learn the relation of particle size to areal distribution. The investigation con-

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sisted largely of detailed qualitative observations and mechanical analyses. It was limited by the moderate number of outcrops where the loess exposed was of known or presumed age. Loess of post-Iowan age mantles much of the area and is well exposed in many road cuts and some natural faces. Pre-Iowan loesses are exposed almost wholly in road cuts. There are five exposures of Loveland loess within the area, and two more close by, but only one outcrop of the Farmdale loess of Leighton and Willman was identified. Results of studies of color and oxidation, size distribution, composition, calcium carbonate, secondary mineralization, stratification and sorting, contacts, and structural features are summarized below.

Color and oxidation.—When fresh, loess is medium to medium light gray, but owing to its high permeability it is rapidly and deeply oxidized to other colors. Fresh loess is found only in the lowest part of the thickest sections. Where thick post-Iowan loess overlies relatively impermeable material such as till, oxidation of the basal part of the deposit proceeds slowly, and commonly is incomplete; the result is a distinctive mottling of the basal part. No unoxidized Farmdale loess or Mankato loess was observed in the area.

Loveland loess is generally oxidized a characteristic pale reddish brown. Parts of some exposures are somewhat lighter, however, and other parts are yellowish brown like oxidized post-Iowan pre-Mankato loess. The variations in color are normally found only in the lower part of thick deposits. The predominant reddish brown of the formation is so characteristic over large areas that it is a basis for tentative correlation. Correlation by color alone must be tentative, because the color is also typical of the somewhat younger Farmdale loess of Leighton and Willman and of older Pleistocene deposits which are not exposed in the map area but crop out elsewhere in the region.

Oxidized Iowan and Tazewell loess and Cary loess are yellowish brown, although at a few localities where Cary loess is thin its color is a little darker. Mottling is found in the lower part of thick sections of both these loesses, but it is more common in the Iowan and Tazewell loess. Mankato loess ranges from grayish black to medium light gray, depending on the amount of humus present. The dark color of this loess is a distinctive feature and is useful in correlation over much of the central Great Plains.

Size distribution.—Loess deposits in southeastern South Dakota and northeastern Nebraska consist chiefly of well-sorted silt. The deposits include a small amount of clay distributed throughout the material, and an even smaller amount of very fine sand. The sand generally is concentrated in thin laminae but is found also in thin lenses. In some exposures the loess encloses pebbles too large to have been transported by the wind. Generally these pebbles can be demonstrated to have been introduced by slope wash or soil creep, but in rare cases their relation to animal burrows indicates they were emplaced by rodents.

Samples of the several loess sheets were analyzed by pipette and sieve methods (Simpson, 1952, p. 177–182) to determine variations in grain-size distribution and the source of the silt. The samples were channeled from undisturbed loess; those from loess of pre-Iowan age each represent 1 foot of section, and those from post-Iowan loess each represent 5 feet of section. The samples fall into 2 groups. One group of 40 samples was collected from 8 localities along a traverse extending southward 85 miles from the south bluff of the Missouri River trench opposite Yankton to a point a few miles north of Columbus, Nebr., as shown in figure 4. The second group, consisting of 67 samples from 26 localities in the vicinity of Yankton represents nearly all outcrops of known or presumed age. Cumulative curves were drawn of each analysis, and typical curves are reproduced in figure 5.

Each curve represents the average of three samples from a single deposit of given age. Deposits represented by curves 1 through 3 overlie one another in that order in one exposure, and deposits represented by curves 4 and 5 are exposed in another outcrop. Except for position relative to the Missouri River, an important difference, the geomorphic settings were similar at the two localities; so the curves are considered essentially comparable. Median grain sizes for the several curves are similar to those obtained from curves representing loess deposits of the same ages elsewhere in the area.

Conclusions drawn from the complete set of cumulative curves are summarized as follows.

1. A striking similarity between cumulative curves of loess and certain samples of colluvium and till indicates that in some cases differentiation of these deposits is more reliable by field criteria than by mechanical analysis in the laboratory.

2. It is not possible to differentiate or correlate exposures of loess or loess sheets solely on the basis of the median grain size or other mathematical characteristics shown on cumulative curves. Local factors affecting deposition such as topography,

changes in wind direction, and position both horizontally and vertically relative to the source area,

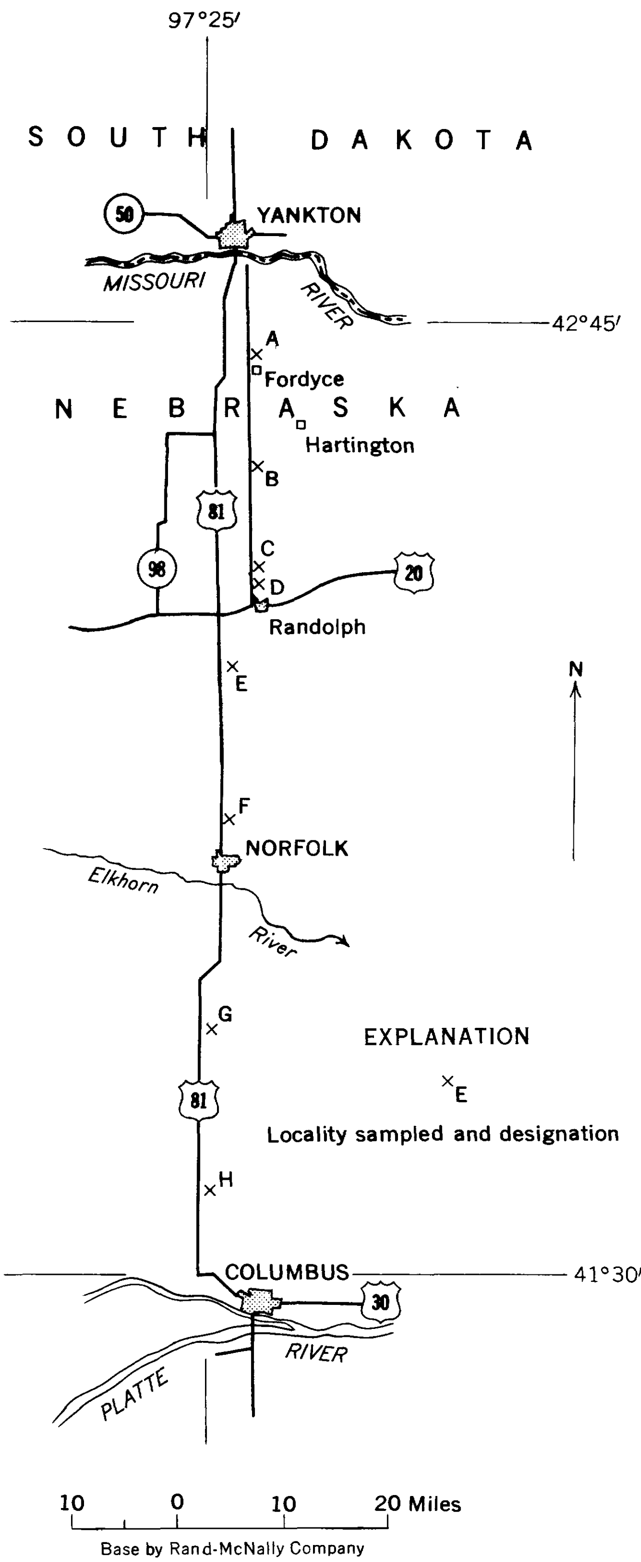


FIGURE 4.—Map showing localities at which loess of post-Iowan pre-Mankato age was sampled south of Yankton, S. Dak.

cause a large variation in grain-size frequency over a short distance.

3. The median grain size of Cary and Mankato loesses is somewhat greater than that of older loess. Moreover, there is some indication that the median grain size of all loess sheets increases slightly with upward progression in the geologic column, except for the Farmdale loess of Leighton and Willman which is marked by a decrease. Inferences concerning the Loveland and Farmdale loesses must be drawn very tentatively, however, for only two outcrops of the former and one of the latter are represented in the analyses. The slight increase upward in grain size may indicate either an increase in wind velocity, an increase in the amount of coarse material available, or possibly a winnowing action.

4. The average median grain size of post-Iowan pre-Mankato loess decreases with increasing distance south of the Missouri River, as shown in figure 6.

5. The coarse-silt fraction of post-Iowan pre-Mankato loess decreases in percent of weight and the medium-fine silt fraction increases with increasing distance south from the Missouri River. Apparently the finer fraction gains at the cost of the coarser fraction. This is shown in figure 7.

6. The median grain size of post-Iowan loess is larger on the south bank than it is on the north bank of a given melt water channel. It is inferred from this that the dominant winds depositing the loess had a northerly component.

Conclusions comparable to 4 and 5 above were reached by Smith (1942, p. 153-156) from traverses of similar length southeast of the Illinois and Mississippi Rivers in Illinois, and for 4 by Swineford and Frye (1951, p. 309 and fig. 1) from 7 short traverses south and east across Kansas from the Platte, Republican, and Arikaree Rivers. From this unanimity in three separate regions we may infer that the origin of loess is the same throughout the central United States.

Composition.—After the sand fractions had been processed for mechanical analyses, they were examined under a binocular microscope for general information as to the rocks and minerals present and their provenances. Several qualitative observations are:

1. Quartz and feldspar are the most common minerals. Although their provenance may be western, it is probably Canadian, for most of the feldspar grains are light-colored plagioclase characteristic of igneous and metamorphic rocks of Canadian

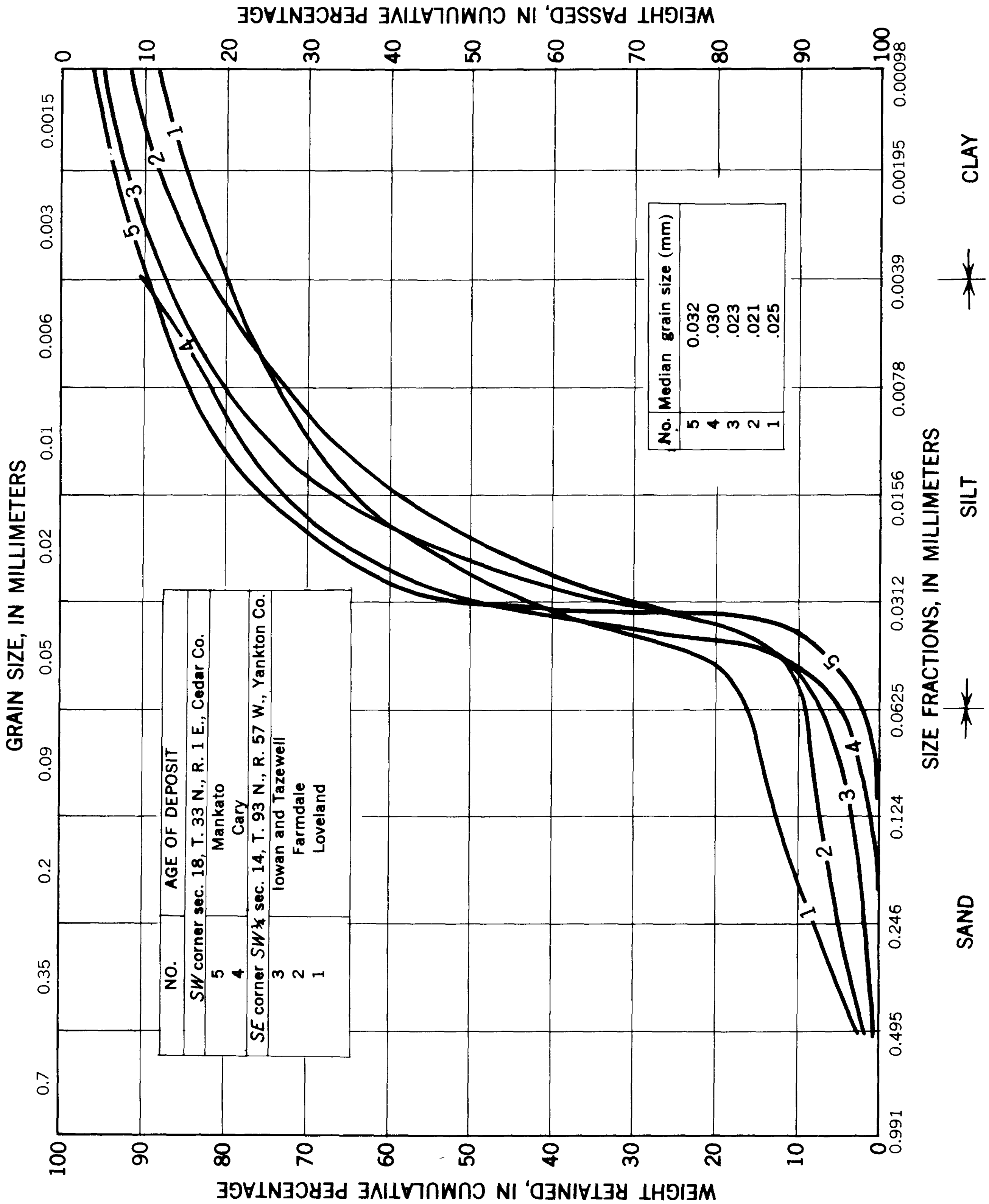


FIGURE 5.—Cumulative curves representing grain-size distribution characteristics of loesses in the vicinity of Yankton, S. Dak. Each curve represents the average of three samples from a single deposit of given age.

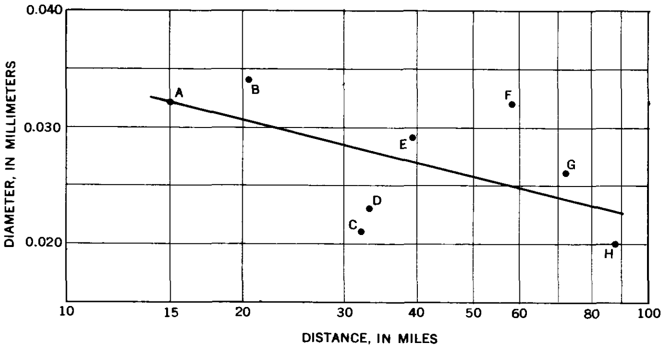


FIGURE 6.—Decrease in average of median grain sizes, post-Iowan pre-Mankato loess with increasing distance south from the Missouri River. Letters indicate sampling localities shown in figure 4.

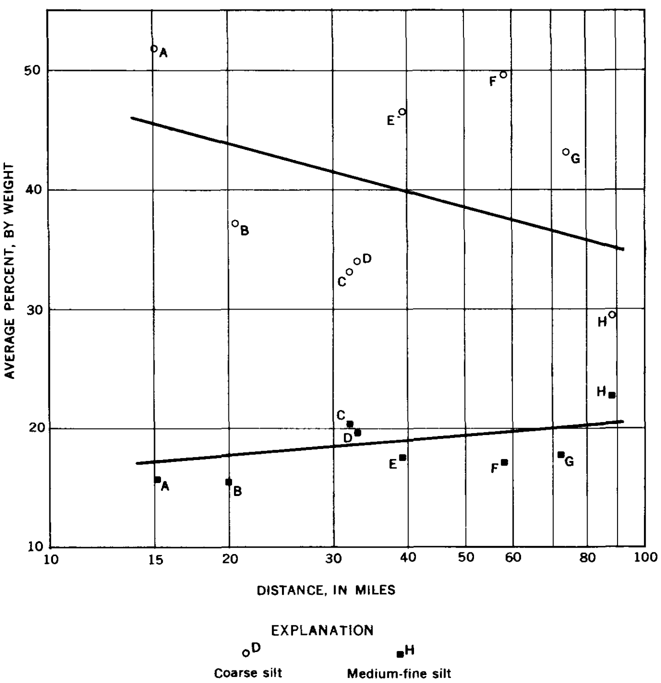


FIGURE 7.—Variation of average percent by weight of the coarse silt fraction and medium-fine silt fraction of post-Iowan pre-Mankato loess with increasing distance south from the Missouri River. Letters indicate sampling localities shown in figure 4.

origin, rather than pink orthoclase characteristic of the Grand Island formation.

2. Calcite and dolomite are fairly common. They are fragments of limestone and dolomite of Canadian origin.

3. Mica is very scarce in the coarser sand fractions but is fairly common in finer sand and silt. It was derived from the Canadian igneous and metamorphic rocks.

4. Siltstone similar in appearance to that exposed in North Dakota makes up as much as 35 percent of the finer sand fractions of some samples.

5. Ferromagnesian and other dark or heavy minerals are few. They are present most commonly in samples adjacent to the Missouri River and decrease sharply in number southward.

6. Sand-sized grains are generally of high sphericity, the surfaces are frosted to clear, and the edges are angular to rounded. No relation of frosting to distance from the Missouri River was observed.

These observations indicate that the composition of the sand fraction of the loess sheets is practically the same as the composition of the sand fraction of the several till sheets. From this one may conclude that the loess materials were derived from glacial drift.

The only significant nonglacial component of the loess consists of fragments of vegetation. Minute soft particles of carbon found throughout the loess are locally numerous, but these are destroyed during mechanical analysis. The form of some of the larger fragments shows they were once pieces of twigs or roots.

Calcium carbonate.—Calcium carbonate present in the loess is in part primary, in part secondary. The primary material consists of grains of limestone and dolomite of Canadian origin and fossil shells. The secondary deposits were made by ground water and comprise firm concretions, soft blebs, stringers, and dispersed particles. No quantitative tests were made to ascertain the amount of calcium carbonate present.

In Loveland loess and the Farmdale loess of Leighton and Willman all calcium carbonate is secondary. These deposits were completely leached before accumulation of overlying post-Iowan loess, but have been recharged with secondary calcium carbonate leached from the younger loesses above. All the types of secondary deposits listed above are present. Iowan and Tazewell loess contains both primary and secondary calcium carbonate. This is also true of many outcrops of Cary loess and Mankato loess, but several deposits of Cary loess and all deposits of Mankato loess are completely leached.

The depth of leaching in the vicinity of Yankton is as great as 4 feet, but it does not vary regularly with the age of the deposit. The depth of leaching, therefore, cannot be used as a basis for differentiation or correlation. The cause of the variation is in part the scarcity of moderately level areas where the depth of leaching is not affected by erosion and runoff. Generally, loess either has not been deposited in level areas that do exist or it is so thin that the calcium carbonate has been entirely leached.

Secondary mineralization.—Concretions in the loess are of three types. Two are composed of calcium carbonate, and one of calcium carbonate heavily stained by iron oxides. Both the carbonate and oxides were leached from overlying strata and redeposited during the process of soil formation. The most common type consists of somewhat irregular, solid, moderately firm, white nodules of calcium carbonate which are rarely more than half an inch in diameter and have rough surfaces. They are locally numerous in the upper part of the C horizon of the soil profile and lie on the ground in great numbers where erosion has exposed them. These concretions are not limited to loess but are found in all of the fine-grained surficial deposits including till and fluvial silt, and so cannot be used in differentiating loess from other silty deposits.

The second type of concretion consists of hard, white, irregular nodules with smooth surfaces that range in size from a millimeter or less to more than an inch in diameter. These nodules are also composed entirely of calcium carbonate and have an outer rind that suggests two stages of accumulation. Most of the nodules are hollow-centered and radially cracked owing to dehydration, but a few are solid and moderately soft. They are scattered throughout the C horizon and are found only in loess.

The third type of concretion is composed of silt cemented by calcium carbonate and iron oxides into vertically oriented cylindrical bodies as much as 1¼ inches in diameter, and 3 to 4 feet long; normally, however, these are broken into segments 2 to 4 inches in length. The concretions are characterized by a light to moderate brown color and concentric banding about a central longitudinal duct as much as 3 millimeters in diameter. The ducts were formerly occupied by rootlets and now serve as passageways for water moving downward through the loess. The water carries the cementing materials in solution and deposits them in the adjacent silt. This type of concretion occurs only locally in the Yankton area. It generally is found south of the Missouri River, commonly in the upper part of the C horizon.

Small, soft, irregular nodules of the first type are found in all loess sheets; the larger, hard nodules are found only in thick sections of post-Iowan pre-Mankato loess. Although locally present, concretions are rare in Mankato loess. None of the three types are helpful in differentiating the loess sheets, but a difference in concretion size may indicate an obscure contact.

Stratification and sorting.—In contemporary literature loess is generally described as nonstratified, and some authors (Russell, R. J., 1944, p. 4) make the absence of stratification a part of the definition of loess. However, most exposures of post-Iowan pre-Mankato loess in the vicinity of Yankton exhibit some degree of stratification, as do many other outcrops south and east along the Missouri River. Indeed, stratification is so common it constituted a major point for those who favored a fluvial depositional agent in early discussions on the origin of loess. The stratification is due to three major causes: variations in competency of the wind, temporary puddles on the loess surface during accumulation, and slope wash.

Stratification caused by the wind generally consists of cut-and-fill cross-lamination similar to that in sand dunes, or rarely, nearly horizontal layers in which the convergance angle of the cross-bedding is hardly apparent. The cross-laminae are commonly a few inches long and about 2 millimeters thick, whereas the more nearly horizontal layers are as much as several feet long and a few millimeters thick. An example of the latter is illustrated in plate 8*B*. The most obvious stratification is found near the southern edge of the Missouri River trench, and cross-laminae are found within a distance of 5 to 6 miles south of the trench wall. Stratification is less apparent farther southward, and beyond a distance of about 10 miles from the trench it is almost undetectable. This relation implies a greater variation in competency of the wind near the trench, a condition which one may expect, for along it the wind is particularly turbulent and gusty owing both to the trench itself and the adjacent dissected terrain.

Wind stratification is absent from deposits of Loveland loess and Farmdale loess of Leighton and Willman in the vicinity of Yankton, but is conspicuous in these formations elsewhere, as for example at the type locality of Loveland loess in western Iowa. Near Yankton, wind stratification is common and most apparent in loess of post-Iowan pre-Mankato age; in Mankato loess it is generally absent, but locally a very crude stratification is observed.

Stratification caused by slope wash (pl. 9*A*) and temporary puddles on the loess surface is of little quantitative importance. Such strata are geologically significant however, because they indicate the former presence of a moderate amount of moisture, and thus constitute an additional clue to the environment in which the loess collected. Stratification caused by slope wash or puddles is generally indistinct, chiefly because of insufficient variation in grain size, but partly because of the small scale of the features. Generally the beds are less than an inch thick and are several inches to a few feet long. They are of no value in correlation because they are found in all loess sheets.

The sorting of loess is excellent and is shown in figure 5.

Structural features.—Two structural features are generally mentioned in descriptions of loess; these are vertical joints and minute vertical holes. Neither are valid for correlation of loess deposits. Vertical joints are common in the thicker exposures of loess. The joints are somewhat prismatic and tend to produce irregular blocks (pl. 11*A*) which are commonly 12 to 18 inches long and bounded by plane surfaces 2 to 6 inches wide. Joints appear to be best developed in the thicker sections, and generally are not apparent in thin deposits of loess or in exposures frequently reworked by road-maintenance equipment. They are found in most outcrops of pre-Iowan loess and commonly are observed also in exposures of post-Iowan pre-Mankato loess. Only the thickest sections of Mankato loess display joints. The cause of the jointing is not known; no evidence observed tended to prove or disprove the theory of loading commonly proposed by various students of loess. Minute vertical holes caused by plant rootlets are characteristic of all loess, although they are less pronounced in Mankato loess. Most of them are less than a millimeter in diameter, but some are as much as 2 to 3 millimeters. Many can be traced vertically for several feet.

Summary of lithologic differences.—The foregoing description of the physical characteristics of loess in the vicinity of Yankton leads to the conclusion that among them only one, color, is of known value in the tentative correlation of loess sheets. The reddish brown of Loveland loess and Farmdale loess of Leighton and Willman, and the gray of Mankato loess, serve to distinguish those formations from yellowish-brown deposits of Iowan and Tazewell loess and Cary loess. Other conclusions are: that loess is an extremely well-sorted material composed chiefly of the silt-sized fraction of glacial detritus; that with the exception of Farmdale loess of Leighton and Willman, of which only one sample was available, the median grain size of the several loess sheets generally increases upward through the geologic section, that the median grain size is larger on the southern side of an outwash channel than on the northern side, and that the median grain size decreases with the increasing distance southward from the source area.

CONTACTS

Contacts of loess with consolidated formations are sharp, smooth, and readily located. Contacts with fine-grained, semiconsolidated or loose materials such as till and other loess deposits range from gradational to sharp. Gradational contacts, including the one illustrated in plate 9*A*, are a result of intermixing by colluvial movement, wind action, rain, and slope wash. Four features found helpful in locating obscure loessial contacts are buried soil profiles, horizons marked by scattered, small, lag pebbles, slight changes in the size of enclosed carbon particles, changes in sorting, and changes in grain-size range. The exact nature of these three changes differs locally.

FOSSILS

Fossils generally are uncommon in the loess and vertebrate material is particularly rare. Only four bone fragments, all nondiagnostic, have been found, and a few earth-filled rodent-burrows, or krotovinas similar to those dug by the ground squirrel *Citellus* cf. *C. elegans* (Kennicott) have been observed. Invertebrate specimens are more common, and a few pulmonate gastropod shells have been collected. Where present, shells are normally scattered throughout the outcrop, but in one exposure of Iowan and Tazewell loess they are concentrated in a zone 1 to 2 feet thick near the middle of the deposit.

The only fossils found in Loveland loess and the Farmdale loess of Leighton and Willman are filled rodent-burrows; the absence of shells is understandable, for both loess sheets were completely leached prior to deposition of the overlying material. Each loess sheet of post-Iowan age contains a characteristic assemblage of pulmonate gastropods which aid in the differentiation of Iowan and Tazewell loess from Cary loess. The shells are found only in the unleached parts of the loess, and many outcrops are barren although still calcareous.

The pulmonate gastropod shells are geologically significant in two respects: first, they commonly provide the only means of determining the geologic age of an isolated loess outcrop, and, together with buried soil profiles and detailed mapping, provide the only dependable methods for the correlation of loess sheets; second, the shells are indicative of the environment in which the loess accumulated.

Collections of the pulmonate fauna were made by washing about 1½ cubic feet of loess per sample through a fine screen. Each sample represented 2 feet of section from outcrops selected because of

A. Gradational contact between reddish-brown (darker) Loveland loess and Sangamon soil with yellowish-brown (lighter) post-Iowan pre-Mankato loess exposed in the SE cor. NW¼NW¼ sec. 13, T. 30 N., R. 6 W., Knox County. The humified (A) horizon of the Sangamon soil lies above the shovel handle; stratification caused by slope wash. Blocky jointing characteristic of both deposits scraped away to show contact.

B. Alluvium of western origin correlated with the Grand Island formation of late Kansan age. Exposed in the NW cor. SE¼ sec. 12, T. 93 N., R. 58 W., Bon Homme County. Both facies, overlain by a few inches of colluvium, are shown.

their apparent geologic significance. About 9 of 10 samples were barren or nearly so.

TOPOGRAPHIC EXPRESSION

Loess commonly reflects in a somewhat modified manner the topography of the surface it mantles. Thus the surface of loess overlying an undissected fill terrace may be almost level, while that of loess overlying dissected terrain may be strongly rolling. Much loess, however, is marked by a somewhat dunelike constructional topography characterized by a maturely rolling surface; the amount of relief of the surface varies with the thickness of the deposit. A striking feature of loess hills is the smoothness of their slopes, for minor details of drainage are inconspicuous. The profile of a knoll from crest to draw is similar to half of a sine curve of moderate wave length and low amplitude.

The smoothness of the profile is partly due to the original form, and partly to soil creep. Mass wasting continually is moving colluvium toward the draws. The crests of hills lack humified material, but downslope the layer of colluvium increases rapidly in thickness. It is commonly 4 to 6 feet thick beneath the lower parts of slopes and even thicker in the draws. Colluvium derived from loess can be distinguished by the lack of joints, slightly darker color, slightly greater homogeneity owing to the lack of slope wash laminae, and extremely low dry strength from the parent deposit. Colluvium crumbles readily and without resistance in the hand, whereas loess resists hand pressure until, at a critical point, it crumbles suddenly and completely. Among the few, small outcrops of Loveland loess and Leighton and Willman's Farmdale loess there is no evidence to indicate that prior to burial the surface profile of either deposit was significantly different from that of the later deposits.

ORIGIN

The preceding description contains reasonable proof that loess is eolian in origin, that it is composed of the finer fractions of outwash, chiefly silt, derived from melt water channels, that the dominant winds were northwesterly, and that the loess sheets accumulated in an environment similar to that existing today.

The eolian origin of the loess is supported primarily by the terrestrial snail shells found within it and by its uninterrupted topographic distribution which ranges from the lowest terraces to the crests of the highest ridges. None of the physical features observed in the loess controvert an eolian origin and many mutually support it. Among these are the following: (1) the rolling topography of loess at all elevations, (2) the grain size, (3) the high degree of sorting, (4) the relation of grain size to distance from source, (5) the decrease in thickness with distance from source, (6) the lithologic composition, (7) the lateral distribution in relation to source, and (8) the occurrence as a mantle on a variety of formations.

The lithologic composition of the loess clearly shows its derivation from glacial outwash; its thickness, grain size, and geograhic distribution in relation to melt water channels indicate the loess was derived from the channels by wind action. Because loess of pre-Mankato age is thicker and the median grain size larger on the southerly side of meltwater channels, and because deposits of Mankato loess commonly lie southeast of the nearest source area, the dominant winds are inferred to have blown consistently from the northwest quadrant during late Pleistocene time, as they do today.

Fossil pulmonate snails found in post-Iowan loess sheets in the Yankton area are of the same species as those found in loess of comparable age in Kansas. Because of this, one may infer that the environment in the Yankton area during the deposition of the several loess deposits was not unlike that which existed in Kansas. A. B. Leonard (1952) has shown that in that State the mollusks that characterize the post-Yarmouth pre-Cary faunal assemblages required a moist ground litter for existence, and he concluded that during the periods of less accumulation the Great Plains were covered with grasses, herbs, and shrubs. He found that the fossil gastropod fauna in Loveland loess indicates a climate similar to today, although somewhat more moist, and perhaps slightly cooler. The fauna from the Iowan and Tazewell loess indicates a moderate amount of moisture, a plant cover at least as dense as the present, and slightly lower temperatures. Since Cary time, with the exception of the Mankato glacial substage, the Great Plains have become warmer and dryer, and the fauna of the Cary and Mankato loesses are identical with the sparse fauna living today in Kansas.

The environment in which the loess sheets accumulated was similar to the present environment. This is inferred from: (1) the physical environment of those living species of pulmonate gastropods that are also found as fossil species in the loess, (2) the evidence of moisture as indicated by stratification caused by slope wash and puddles, (3) the occurrence of carbon particles indicating vegetation, (4) the evidence of northwesterly winds, and (5) the geologic and topographic similarity of the terrain.

TIME AND RATE OF DEPOSITION

The intervals in the recurring glacial cycles during which the several loess sheets were deposited can be established by inference. The loessial material was clearly derived from outwash that occupied melt water channels. Thus accumulation of a particular deposit could occur at any time after melt water started to deposit outwash within a given drainage basin, and it could continue until outwash was no longer available because of lack of supply following recession of the ice from the basin or because of plant growth. However, the regimen of a retreating glacier is much more favorable to production of quantities of melt water and outwash than is that of an advancing glacier. From these inferences one may conclude that most loess accumulated during the latter part of the glacial stages and substages.

This inference is supported by another drawn from buried soil profiles. In a few exposures in the vicinity of Yankton, loess rests on, and is overlain by, till. The till below is unaltered except by oxidation and secondary mineralization which followed deposition of the loess. A buried soil profile, unless removed by erosion, is present on the upper part of the loess sheet and is overlain by the younger till. Because soil scientists conclude that the climate of the interglacial intervals was more favorable to the formation of soil profiles than the glacial intervals, one may infer that the loess accumulated after the deposition of till and retreat of the glacier from the immediate locality and before the interglacial interval.

Little is known concerning the rate of loess accumulation. Pre-Iowan deposits are thin and completely leached, but whether the leaching kept pace with deposition or was completed after it ceased is not known. Deposition of post-Iowan pre-Mankato loess probably was moderately rapid. It was fast enough to surpass the rates of oxidation and leaching and may have been rapid enough to cause a dilution of fossil material. The deposition of Mankato loess was probably somewhat slower, for the humified nature of this loess sheet indicates that accumulation progressed slowly enough for vegetation to flourish on it uninterruptedly.

ENGINEERING CHARACTERISTICS

Mankato loess is loose; all other loesses are only slightly indurated, and so are soft and weak: pieces are broken readily in the hands by exerting a small amount of force. When saturated loess loses the little strength it possesses dry. If the loess is jointed it breaks out in roughly prismatic pieces; if not jointed it breaks out in irregular chunks. Excavation of all loess is readily possible both by hand and power equipment; no blasting is necessary. Because the material consists chiefly of silt, there is no trafficability problem when it is dry, although there may be when wet. Owing to its fine grain size, equipment can cut smooth faces close to a limit without overbreakage. Permeability is high vertically, but somewhat less horizontally. Nonsaturated loess is generally stable in steep slopes. The steepest slopes, both natural and artificial, in the vicinity of Yankton are at angles from 70° to 80°; many road cuts have slopes of 50° to 70°. The steeper slopes are more subject to spalling, which may cause a slow recession of the face, but the gentler slopes are readily gullied by surface runoff. During a period of 5 years none of the slopes were significantly modified by slumping.

The engineering properties of loess have been studied extensively, and for technical data the reader is referred to such published reports on loess in Iowa and Nebraska as Bollen (1944), Gwynne (1950), Holland and King (1949), Judd (1950), Mielenze, Holland, and King (1949), Watkins (1945), and unpublished reports for Iowa State College by P. K. Fung (written communications, 1945 and 1949). The soils laboratory of the South Dakota State Highway Commission at Pierre made analyses of 7 samples of loess. Of the 7, Leighton and Willman's Farmdale loess was represented by 1 sample, Iowan and Tazewell loess by 1, Cary loess by 3, and Mankato loess by 2. All were channeled from exposures of known age and are typical of their respective loess sheets in the area. Results of the analyses (written communication, E. B. McDonald, November 27, 1950) are shown in table 5.

ALLUVIUM

The only nonglacial Pleistocene deposit of fluvial origin in the Yankton area is a coarse-grained alluvium correlated with the Grand Island formation of late Kansan age. The alluvium consists almost entirely of material derived from granitic intrusions in the Rocky Mountains similar to the Sherman granite of Precambrian age in Wyoming. The gravel apparently was transported eastward by the Niobrara River and deposited as an alluvial fill, but most of it has been removed by erosion.

TABLE 5.—*Soil-analysis data of typical loess samples from Yankton County*

Test	Loveland and Farmdale undifferentiated	Iowan and Tazewell	Cary	Cary	Cary	Mankato	Mankato
	A	B	C	D	E	F	G
Depth of sample below surface	6–12 ft	0–6 ft	2–6 ft	4–8 ft	0–4 ft	0–4 ft	0–6 ft
Textural classification [1]	Silty clay	Silty loam	Clay loam	Silty clay loam	Silty clay loam	Clay loam	Silty loam
Classification (Allen) HRB [2]	A–6(9)	A–6(8)	A–6(10)	A–7–6–(13)	A–7–6(12)	A–6(10)	A–4(8)
Specific gravity [3]	2.60	2.67	2.63	2.61	2.40	2.56	2.68
Pounds per cubic foot, dry, loose	72.9	74.4	73.8	65.1	61.6	60.9	70.8
	Percent	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
Shrinkage ratio [3]	1.89	1.79	1.88	1.88	1.86	1.82	1.70
Shrinkage limit [3]	14.5	18.4	15.0	14.8	12.2	15.8	21.5
Volume change [3]	11.3	9.1	8.7	11.8	17.41	17.5	2.5
Passing ⅜ in. sieve [4]	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Passing No. 4 sieve [4]	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Passing No. 10 sieve [4]	99.7	100.0	99.0	100.0	99.3	100.0	100.0
Passing No. 40 sieve [4]	96.5	99.8	94.5	99.8	98.1	97.2	99.8
Passing No. 200 sieve [4]	90.1	96.4	84.6	99.0	96.7	93.4	92.8
Sand content [5]	24.4	26.8	32.0	14.2	14.3	28.2	30.2
Silt content [5]	53.8	58.0	43.6	56.2	59.6	54.0	54.2
Clay content [5]	21.5	15.2	23.4	29.6	25.4	17.8	15.6
Liquid limit [6]	31.7	33.3	36.0	44.9	41.5	39.1	27.9
Plasticity index [7]	12.5	11.0	15.7	22.2	18.6	16.1	4.3
Field moisture equivalent [8]	20.4	23.5	19.6	21.0	21.5	25.4	22.8
Centrifuge moisture [9]	18.9	15.0	18.5	25.6	22.2	18.8	11.9

[1–9] For references to test methods see soil analysis report for the Ogallala formation, p. 45.

A. Center SW¼ sec. 14, T. 93 N., R. 57 W.
B. SE cor. NE¼ sec. 7, T. 93 N., R. 56 W.
C. SE cor. NE¼ sec. 7, T. N., R. 56 W.
D. NE Sor. SE¼SE¼ sec. 1, T. 93 N., R. 56 W.
E. NE cor. sec. 33, T. 94 N., R. 56 W.
F. NE cor. SE¼SE¼ sec. 1, T. 93 N., R. 56 W.
G. SW cor. sec. 17, T. 93 N., R. 58 W.

FACIES

Two facies of the formation are recognized, and are illustrated in plate 9*B*. The most widespread facies is a crossbedded gravelly sand; it is also the most distinctive of the two and is economically the more significant. The second facies consists chiefly of horizontally bedded medium to coarse sand, which includes a little crossbedded gravelly sand like that of the first facies. This second facies locally constitutes the upper part of the formation.

LITHOLOGY

The gravelly sand facies is a distinctive grayish orange pink and locally is stained slightly by iron and manganese oxides. This color is due to pink orthoclase feldspar, a major constituent of a western granite from which the sediment was derived. About 5 percent of the facies consists of pebbles. Two pebble-composition counts were made, one of 227 pebbles from a pit in the NW cor. SW¼ sec. 7, T. 93 N., R. 57 W, Yankton County, and the other 215 pebbles from a pit in the NE cor. sec. 11, T. 93 N., R. 57 W., Yankton County. To permit comparison with pebble counts of other Pleistocene gravels the same classification of rock types was used; the count results are:

Rock type	*Percent of sample from—*	
	Sec. 7	*Sec. 11*
Quartz	46	38
Igneous (granitic)	54	62
	100	100

The lithologic composition of the various sand fractions differs slightly from that of the pebble fraction, but the chemical compositions are probably very similar. The sand fractions were derived from the same western source and are simply finer grained. Thus they consist chiefly of grains of quartz and grayish orange pink feldspar; several grains contain both minerals and may be typed as granite. A minor constituent, mica, is an accessory mineral in the granite.

Sorting of the reworked facies is only fair, but stratification is good. The strata are characterized by conspicuous, distinctive crossbedding, with individual beds ranging in thickness from a fraction of an inch to a few inches. The direction of crossbedding was determined successfully only on Yankton Ridge; it is northeastward in the western part of the ridge, and eastward in exposures near the middle. Sand grains and pebbles are subangular to subrounded and of high sphericity; the surface of many of the sand grains is frosted. Induration is lacking. Contacts are generally abrupt and smooth, although locally, where the gravel is overlain by loess, the two deposits are intermixed through a distance of several inches owing to frost action, and to rainwash, slope wash, and wind action.

Four distinctive features are found in the gravel; they are inclusions of clayey silt and very fine sand, concretions of calcium carbonate, silicified wood, and vertebrate fossils. The silt and fine sand comprise soft, weak spherodial masses as much as

2 feet in diameter and were observed in nearly all exposures. They are grayish yellow green or pale reddish brown and apparently have been derived from the underlying Ogallala formation. The silicified wood and the concretions occur locally and are generally found in association. The concretions are spheroidal, as much as 5 inches in diameter, and are composed of calcium carbonate. A rindlike deposit suggests two periods of deposition, the dates of which are not known. Dehydration has cracked the concretions radially, and the surfaces commonly bear intricate dendrites of manganese oxides.

The petrified wood is commonly fragmentary, but partly flattened logs 8 to 10 inches in diameter and several feet in length were observed. The petrifaction is siliceous, grayish yellow to dark yellowish orange, and peculiarly light in weight; growth rings have been destroyed, but the bark is generally well preserved on larger pieces. The formation also contains a few vertebrate fossils useful in correlation. These are also preserved siliceously, are white to very light gray, and are not water-worn. They are readily distinguished by lack of greenish color and lighter weight from vertebrate fossils in the Ogallala formation, and by lack of water-wear from those in the reworked facies of Illinoian outwash.

The sandy facies constitutes a small part of the Grand Island formation. It consists mostly of nearly white, medium to coarse sand composed largely of quartz, feldspar, and mica. The sand is well sorted and marked by excellent horizontal stratification; individual beds are only a few millimeters thick. The sand grains are of moderate to high sphericity and are subangular to subrounded. The material is unindurated and lacks any secondary mineralization. Contacts are abrupt and smooth, and features characteristic of the gravelly sand facies are lacking.

TOPOGRAPHIC EXPRESSION

The formation has no characteristic topographic expression. It crops out along the sides of small valleys tributary to the Missouri River trench, and its position is generally marked during summer and fall by dry grasses.

ENGINEERING CHARACTERISTICS

The Grand Island formation is loose and readily excavated by hand or power equipment. No trafficability problem will be encountered. Permeability is high and drainage good. Slopes are moderately stable only when cut at an angle of about 30° or less, although such faces may gully a little. Silt balls, concretions, and fossil material are readily removed by screening. Overburden generally consists of weak loess or weak to semifirm till that may be as thick as 20 feet.

The soils and materials laboratory, Corps of Engineers, Omaha, made a petrographic analysis of a sample of the gravelly facies taken from a pit in the NW cor. Sec. 13, T. 58 W., R. 93 N., Bon Homme County. The results (H. L. Weil, written communication, Jan. 6, 1950) follow.

U.S. sieve series No.	*Percent by weight retained*
4	4.7
8	16.2
16	42.8
30	27.5
50	4.9
100	1.6
200	0.4
Pan	1.9
	100.0

The lithologic composition of the fraction between 4.76 and 1.19 millimeters in diameter was found to be, in percent: quartz, 41; feldspar, 24; phaneritic igneous rock, 26; quartzite and chert, 6; limestone, 2; miscellaneous, 1. Soft, porous, friable, and argillaceous particles make up slightly more than 2 percent of the total, and calcareous and argillaceous material coats about 4 percent of the particles.

SUMMARY

Pleistocene deposits in the vicinity of Yankton consist of both glacial and nonglacial materials. Glacial drift is composed of till, outwash, and ice-contact stratified deposits, and ranges in age from Illinoian (or possibly Kansan) through Mankato. The drift is composed chiefly of fine material derived principally from pre-Pleistocene formations present in the area; other constituents were derived from strata that crop out in central-eastern South Dakota, North Dakota, and Canada. The several deposits of till resemble each other in gross appearance; the same is true of most deposits of outwash and also of deposits of ice-contact stratified material. Differentiation and correlation are based on stratigraphic position, soil profiles, nonglacial deposits, and detailed mapping.

Nonglacial deposits consist of five loess sheets and a gravelly alluvium and range in age from late Kansan through Mankato. Loess is composed chiefly of the silt-sized fraction of outwash derived from melt water channels by northwesterly winds. Loess sheets become thinner and finer grained with increasing distance southward from the Missouri River source area. Except for color, lithologic characteristics of the several loess sheets are similar. Loveland loess and Leighton and Willman's Farmdale loess can be differentiated by their reddish brown color from post-Iowan pre-Mankato loess, and Mankato loess can be distinguished by its gray color from older loesses. Correlation and local differentiation are based on fossils, buried soil profiles, and detailed mapping. The fossils are also significant because they indicate that the environment in which the loesses accumulated was similar to the present environment of the Great Plains.

AGE AND DISTRIBUTION

More variable aspects of the several Pleistocene deposits include the basis of correlation, their distribution, and the borders of the drift sheets.

Correlation of the several drift sheets with glacial intervals of the standard section of page 45 constitutes the major Pleistocene problem in the Yankton area. Despite the lack of conclusive internal evidence in the drift on which correlation can be based, correlation has been accomplished both locally and regionally by standard stratigraphic methods. Regional correlation is dependent chiefly on the stratigraphic relation of loess sheets and on the direct tracing of one till sheet into the Yankton area from its type locality. The age of the nonglacial deposits has been ascertained from stratigraphic position, lithologic characteristics, fossils, and the strength and sequence of buried soil profiles. In the following pages the bases of correlation of Pleistocene deposits are described briefly. Accompanying the discussion are a diagrammatic correlation chart (fig. 8), detailed descriptions of several stratigraphic sections, and a diagrammatic profile and cross section (fig. 9) illustrating the relation of many of the deposits to the Missouri River trench.

The term drift border is defined for this report as a line connecting and enclosing the outermost known deposits of till and ice-contact stratified drift left by a glacier of a given stage or substage. A drift border may not coincide with or even approximate the maximal position of a glacier margin, for the ice may not have laid down recognizable deposits of drift for some distance behind the margin. Moreover, the known border may lie within the true maximal position owing to concealment beneath younger deposits or to erosion. The regularity of a drift border as drawn varies indirectly with the amount of data available: fewer data require greater generalization. Data which determine the regularity and position of a drift border include the position and trend of end moraines, the pattern of melt water channels and outwash deposits, and the location of ice-contact stratified drift and exposures of till.

At least five drift borders, those of the Kansan(?) and Illinoian stages, and the Iowan, Cary, and Mankato substages, are known or inferred to be present in the vicinity of Yankton and are shown on plate 10[13]. The degree of coincidence of the drift border with the maximal position of the glacier margin is believed to be high, especially for the Cary and Mankato substages. The coincidence among Iowan and pre-Wisconsin glaciation is undoubtedly less, but it seems likely that the respective drift borders and ice margins were not more than a few miles apart.

PRE-WISCONSIN STAGES

Deposits of known pre-Wisconsin age include a fluvial deposit, the Grand Island formation of late Kansan age, and fluvial, glacial, and eolian deposits of Illinoian age. Pre-Illinoian (Kansan?) till is not known within the mapped area but is exposed nearby.

Scattered exposures of these pre-Wisconsin deposits are confined chiefly to dissected terrain adjoining the Missouri River and to a very few localities farther south. The Grand Island formation and Loveland loess crop out on both sides of the river, but Illinoian till and Illinoian outwash are found only north, and pre-Illinoian drift only south of the river. Of the pre-Wisconsin deposits only those of fluvial origin have a lateral extent of more than a few yards.

There are very few exposures in which the stratigraphic relations of pre-Wisconsin deposits are clearly demonstrable. This is due to the scarcity of remnants along the Missouri River trench and to the thick, widespread mantle of younger deposits on the uplands. Probably a major factor in the removal of pre-Wisconsin material was the creation

[13] Since this manuscript was prepared, subsurface evidence obtained by the Nebraska Geological Survey in the region thickly mantled with loess south of the Missouri River has added significant detail to the geologic relations of that area described in this report and illustrated in plate 10. Conclusions drawn by State Survey personnel from the evidence are: (1) the Nebraskan glacier covered the extreme southeast part of the Yankton area, and the drift border extends from the vicinity of St. Helena southwest past the village of McLean, Pierce County, (2) drift of Kansan age is present in most of the region south of the Missouri River and the drift border essentially coincides with that shown in plate 10, (3) the Illinoian glacier entered Nebraska, and the drift border extends from the vicinity of Niobrara southeast into the northeast corner of Pierce County, then bends north and reaches the present Missouri trench near Wynot, Cedar County, and (4) the Iowan drift border partly coincides with that shown in plate 10, but bends northward just west of Coleridge to coincide with the Illinoian drift border to the Missouri trench.

These conclusions are shown in Flint, R. F., and others, 1959, Glacial map of the United States east of the Rocky Mountains: Nat. Research Council, Washington, D.C., 1st ed., and modify or verify inferences in this report regarding positions of the drift borders; they do not alter the discussion of the geomorphic development or geologic history of the Yankton area.

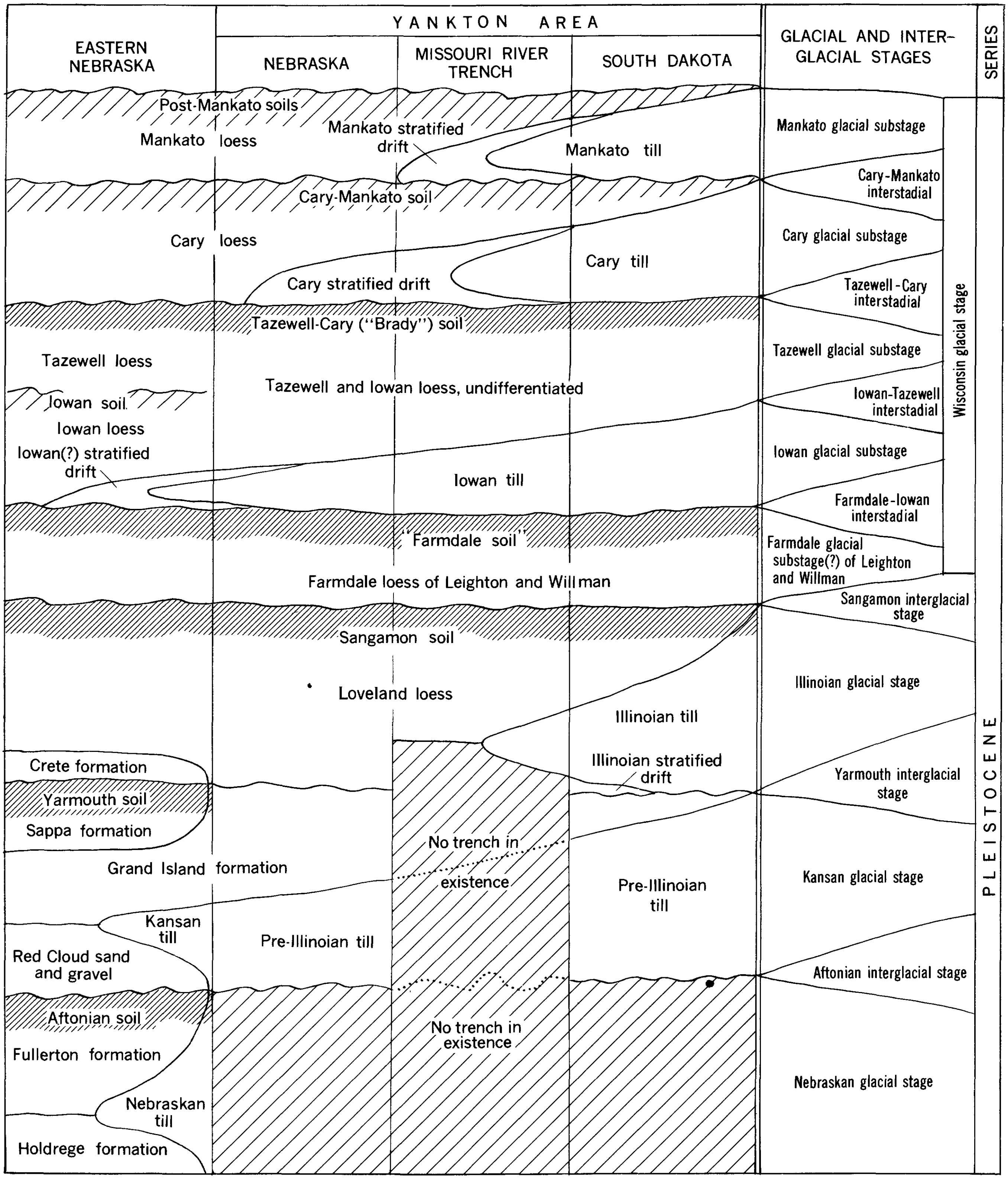


FIGURE 8.—Diagrammatic correlation chart of Pleistocene units in eastern Nebraska and the Yankton area. (In part after Condra, Reed, and Gordon, 1950, figure 6).

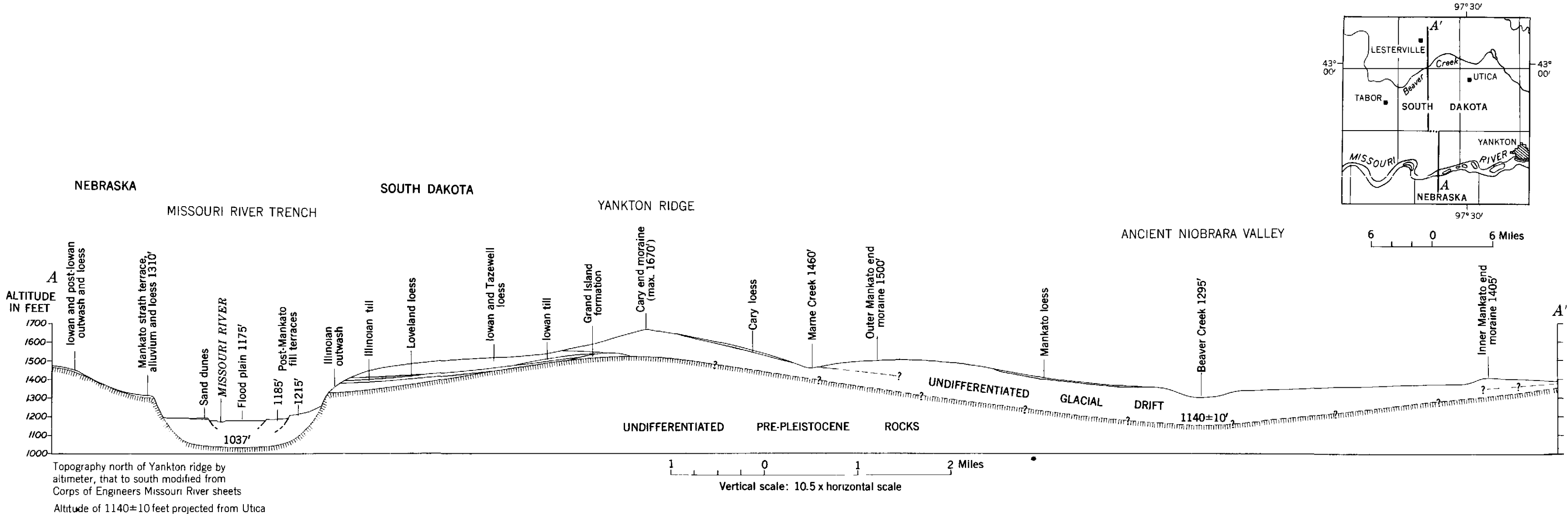


Figure 9.—Diagrammatic geologic section and profile from the NW cor. sec. 15, T. 95 N., R. 57 W., Yankton County, to the center sec. 21, T. 33 N., R. 2. W., Knox County.

of and deep dissection by the Missouri River. Another factor may have been an initial thinness of pre-Wisconsin deposits.

PRE-ILLINOIAN GLACIAL DEPOSITS

Pre-Illinoian drift is probable in the vicinity of Yankton, because Nebraskan and Kansan tills have been identified in eastern Nebraska on the basis of both field reconnaissance (Lugn, 1935) and subsurface investigations (Condra, Reed, and Gordon, 1950; R. D. Miller, oral communication, 1954), and because the Kansan drift border lies just south and west of the Yankton area. Till that is clearly different lithologically from most till of known or inferred Iowan or Illinoian age is exposed at several localities just beyond the boundaries of the mapped area and is reported at one locality within those limits. Pre-Illinoian age is inferred from a section 2½ miles north of Huntington described by Lugn (1935, p. 59) and reexamined by me in 1948 and 1954.

Measured section 1.—At Tiptop School, west side SW¼ sec. 13, T. 31 N., R 1 E., Cedar County

[Quoted from Lugn, 1935, p. 59]

	Feet
1. Loess, yellow silty clay under covered slope	4 to 10
2. Peorian yellow loess, exposed under soil in roadside bank	2
3. Kansan till, much disintegrated and weathered, for the most part much altered, but some small areas are typically boulder clay	0 to 2+
4. Inter-till sand and gravel, mostly brownish and gray sand, upper 6 to 8 feet oxidized to brownish color, normally contains no large cobbles or boulders here. Where the Kansan till has completely disintegrated over it a boulder and cobble concentrate has been let down on the inter-till sand	15 to 25
5. Nebraskan till, gray typical boulder clay with many quite small pebbles	10 to 12
6. Covered slope for about 30 feet. The Niobrara formation can not be far below the base of the slope and the lower or Nebraskan till may be as much as 30 to 40 feet thick here.	

In my opinion this section should be interpreted as follows:

1. Covered slope.
2. Post-Iowan, pre-Mankato loess.
3. Iowan till.
4. Outwash of undetermined age.
5. Pre-Illinoian till.
6. Covered slope.

Correlation of the third unit with Iowan till is based on physical characteristics, including several excellent ventifacts, and on its position below yellowish-brown loess of inferred post-Iowan pre-Mankato age. The lithology of the lower till (unit 5) differs distinctly from that of Iowan and Illinoian tills here or elsewhere in the area and is similar to till of known pre-Illinoian age exposed in east-central Nebraska.

Till with gross lithologic characteristics strikingly similar to those of inferred pre-Illinoian till described in section 1 is exposed at various other localities in the region. Two of the most accessible but previously undescribed exposures are:

1. Road cut on east side of road 0.1 mile south of the NW cor. sec. 18, T. 32 N., R. 4 W. Exposed 1954. As much as 8 feet of pre-Illinoian till underlain by as much as 3 feet of loose sand stained yellowish with iron oxides and overlain by a maximum of 8 feet of loose, relatively unstained sand.
2. Road cut in knoll crest on east side of road 100 yards north of SW cor. sec. 18, T. 32 N., R. 4 W. Exposed 1947. A maximum of 8 feet of pre-Illinoian till overlain by 8 feet of Iowan till and 7 feet of yellowish brown, post-Iowan pre-Mankato loess.

In addition Lugn (1935, p. 59–61) reported three exposures near Hartington in which, he concluded, pre-Illinoian till was exposed. Lugn's age assignments at each of these localities were verified by me in 1947.

No exposure of pre-Illinoian till within the mapped area is known to the writer. Lugn (1935, p. 69), however, reported pre-Illinoian till "6 to 7 miles west of Crofton, near the intersection of the Crofton-Niobrara road with the Bloomfield road" in a section described by him as follows:

	Feet
1. Peorian loess, yellowish silty clay	26
2. Kansan till, light gray fresh boulder clay, contains many limestone pebbles and some Niobrara boulders. The color of this material is in different contrast to the much more weathered and more brownish upper part of the lower till. The lower contact is quite uneven and is marked by a distinct ferruginous zone 3 to 4 inches thick, exposed for a few yards	60
3. Nebraskan till, typical boulder clay, brownish for the most part, contains fewer pebbles and boulders than the upper till, lower contact sharp	60–70
4. Niobrara chalk, a few feet exposed.	

The outcrop is thought to lie along a fairly deep road cut marking the corner of secs. 22, 23, 26, and 27, T. 32, R. 3 W., Knox County. Despite extensive hand augering the present writer was unable to recover the third and fourth units of Lugn's description, possibly owing to regrading of the road. The presence of the Ogallala formation rather than the Niobrara formation is more likely, however. Unit 2 is well exposed, and is mapped as Iowan till owing to its physical characteristics and stratigraphic position. It is inferred not to be Illinoian till owing to the complete absence of Loveland loess along the upper contact, the lack of a soil profile or erosion which could have removed it, and the presence of ventifacts. Unit one is undifferentiated post-Iowan pre-Mankato loess.

Lugn (1935, p. 59-69) inferred that his sections contain Nebraskan till, or both Nebraskan and Kansan tills, because he concluded (p. 151, 267) there is no post-Kansan drift in Nebraska. As shown below, however, Wisconsin till is present, and the upper till in the two sections quoted from Lugn is believed to be of that age. The lithologic similarity of exposures of pre-Illinoian till suggests that drift of only one pre-Illinoian glacial stage may be present. There is, however, little basis for choosing between the Nebraskan and Kansan glaciations. The Kansan drift border is known to lie a short distance southwest, however, and the position of the Nebraskan border where known is to the south and trends northeast (E. C. Reed, oral communication, 1950). (See also footnote 13, p. 71, and Flint, 1955, pl. 3). For this reason a Kansan age is thought to be more likely for pre-Illinoian till near Yankton.

Contacts of pre-Illinoian glacial deposits are abrupt and smooth.

That part of the Kansan(?) drift border shown as "known" in plate 10 is from an unpublished map by E. C. Reed, Nebraska Geological Survey, and is based on both surface and subsurface evidence (see also footnote, 13, p. 71). The position of the rest of the border has largely been interpolated by the author. It is supported, however, by the location of a major outwash channel, topography, and the distribution of outwash and a few erratics.

The name Kansan formation was originally given by T. C. Chamberlin in 1894 (*in* Geikie, p. 754–757) to the drift sheet now known to be of Nebraskan age; in 1896 (p. 872) he transferred the name to the younger drift that now bears it and that had previously been known as the East-Iowan, or Iowan formation (Chamberlin, *in* Geikie, 1894, p. 759–761; and 1895, p. 273–275). No type locality was specified. In 1909 Shimek (p. 408) named the older drift Nebraskan for exposures in the walls of the Missouri River trench in South Omaha and north of Florence (now North Omaha), Neb., and 4 miles north of Council Bluffs, Iowa. It should be noted, however, that recent work by geologists of the Nebraska Geological Survey and the United States Geological Survey (R. D. Miller, oral communication, 1954) indicates that till exposed at these localities is actually of Kansan age.

GRAND ISLAND FORMATION

Correlation of coarse alluvium of western provenance in the Yankton area, with the Grand Island formation is based on fossil content, stratigraphic relations, and lithology. The fossils, examined by C. Bertrand Schultz, University of Nebraska State Museum, consist of identifiable bones that have been reworked from the Ogallala formation, identifiable bones diagnostic of Kansan age, and bone fragments that are unidentifiable or undiagnostic. The reworked bones are readily distinguished from bones of Kansan age because the reworked bones are very much water-worn and are much heavier owing to more complete replacement.

Reworked bones and bones of Kansan age found at various localities in the Grand Island formation are listed below, together with stratigraphic notations by Schultz (written communication, Feb. 11, 1952).

1. *Adjacent gravel pits in the NE¼SE¼ sec. 12, T, 93 N., R. 58 W. Altitude about 1,575 to 1,590 feet.*
    a. Horse phalanx, small; compares favorably with examples of *Nannipus* from Late Pliocene deposits (upper Ogallala). Perhaps this specimen has been reworked from the Pliocene, or even from early Pleistocene sediments. *Nannipus* has been recorded from the Broadwater and its equivalents. [*Broadwater* is the name for the vertebrate faunal zone equivalent to the Red Cloud formation of early Kansan age: Schultz, oral communication, 1952.]
    b. Camel scapula, partial; compares favorably with examples of *Gigantocamelus fricki* from the Broadwater of northern and western Nebraska.
2. *Gravel pit near the SW cor. NW¼ sec. 13, T. 93 N., R. 58 W. Altitude about 1,580 feet.*
    a. Camel tooth, lower P4; very similar in size and form to holotype of *Titanotylopus nebraskensis* from the type locality of the Red Cloud formation (pro-Kansan) [sic; early Kansan].
3. *Surface of gravel exposure near SW cor. SE¼ sec. 12, T. 93 N., R. 58 W. Altitude about 1,580 to 1,590 feet.*
    a. Rhinoceros humerus, distal end; reworked from Pliocene deposits (Ogallala).
4. *Two adjacent gravel pits near the NW cor. sec. 13, T. 93 N., R. 58 W. Altitude about 1,580 feet.*
    a. Horse tibia, distal end; compares favorably with examples of *Equus excelsus* from the Grand Island and Sappa formations.
    b. Horse tooth, lower molar; compares favorably with examples of *Equus excelsus* from the Grand Island and Sappa formations.
    c. Cervid (deer) phalanx, proximal; compares favorably with examples of *Sangamona;* Grand Island, or later.

Specimen 3a is petrified more than other specimens and is badly waterworn; specimen 2a is slightly waterworn. From specimens 1a, b and 4a–

c, correlation of the alluvium with the Grand Island formation may be inferred. This inference is supported by the fact that material derived from the alluvium constitutes locally a large part of the reworked facies of Illinoian outwash, a fact which proves that the alluvium is not younger than early Illinoian.

Despite extensive search south of the Missouri River, no fossils were recovered from gravels mapped as Grand Island formation. The correlation of these deposits with those north of the river is inferred from their similar lithologic character, altitude, and stratigraphic position.

Most exposures are small and are marked by borrow pits. North of the Missouri River the gravel lies along the edge of the trench chiefly in T. 93 N., Rs. 56 and 57 W., Yankton County. South of the river exposures are more widely distributed and extend from T. 33 N., R. 4 W., to T. 32 N., R. 1 W., Knox County. From 5 to 15 feet of the Grand Island formation crop out in most exposures, and a maximum thickness of 55 feet in the NW cor. sec. 13, T. 93 N., R. 58 W., Bon Homme County. Both upper and lower contacts of the formation are generally abrupt and smooth, although where the formation is overlain by a little loess the upper few inches may be mixed with a small amount of silt. The basal contact ranges in altitude from 1,525 to 1,570 feet on Yankton Ridge.

In 1932 Lugn and Condra (see Lugn, p. 190) named the Grand Island formation for exposures in the Platte River valley near Grand Island, Hall County, Nebr. The formation is of late Kansan age.

ILLINOIAN STAGE

Deposits of Illinoian age near Yankton include outwash, till, and Loveland loess which is characterized by the Sangamon soil, a mature soil profile developed upon it during Sangamon time.

The Illinoian glacial stage was originally named the Illinois Till Sheet by Leverett (*in* Chamberlin, 1896, p. 874) for deposits in Illinois.

Illinoian outwash

Assignment of Illinoian age to this outwash is based on stratigraphic relations, lithology, fossil content, and topographic position.

Minimum age of the outwash is established at only one locality, which is described in measured section 2; at this locality the outwash is overlain by Illinoian till and Loveland loess. Maximum age is indicated by the composition of one facies of the outwash. It consists largely of quartz and orthoclase feldspar reworked from the Grand Island formation. Two bones found in this facies are petrified in a manner similar to that of fossils of Kansan age but are waterworn unlike such fossils. The fossils were examined by C. B. Schultz of the University of Nebraska State Museum, who made the following identifications and notations (written communication, March 7, 1952).

Gravel pit, outwash facies, in the SE cor. NE¼NW¼ sec. 23, T. 93 N. R. 57 W. Altitude about 1,350 feet.

Horse pelvis, fragment; compares favorably in size with examples of *Equus* from the Grand Island and Sappa formations. Not diagnostic.

Horse tooth, lower, incomplete; compares favorably with examples from the Grand Island and Sappa formations.

The altitude and profile of the basal contact of the outwash provide additional evidence of an age younger than that of the Grand Island formation. The outwash is at the same stratigraphic level as the Grand Island formation in a few places, but elsewhere it is lower. The profile of the basal contact and distribution of the outwash indicate that it was deposited in a valley that was not present when the Kansan gravel was laid down.

Because the outwash deposit postdates a late Kansan deposit and predates Illinoian till, an Illinoian age is assigned the outwash.

Illinoian outwash is exposed along the north wall of the Missouri River trench, on the south flank of Yankton Ridge, and along the sides of valleys tributary to the trench. The glacial facies crops out from sec. 18, T. 93 N., R. 56 W., Yankton County, to sec. 16, T. 93 N., R. 57 W., Yankton County. Along the southernmost part of the area of outcrop the deposit lies on the Niobrara formation; in the N½ sec. 23, T. 93 N., R. 57 W., Yankton County, the altitude of the contact is about 1,335 feet. From this locality northward toward the crest of Yankton Ridge the facies grades inperceptibly into the reworked facies. As the lithologic character changes, the altitude of the basal contact increases, so that the gravel lies on progressively higher members of the Pierre shale. Near the crest of the ridge the altitude of the basal contact is about 1,535 feet, just a few feet below the local base of the Grand Island formation. The reworked material was probably deposited by melt water flowing down the southern flank of the ridge toward some pre-Illinoian drainage course, whereas the glacial facies was laid down by melt water following that drainage course. From 2 to 10 feet of the glacial facies crops out in much of the exposure area, and thicknesses of 12 to 15 feet were observed in borrow pits in the reworked facies in the NW¼SW¼ sec. 11, T. 93 N., R. 57 W., Yankton County. Contacts are generally abrupt and smooth, but locally, where the formation is overlain by Loveland loess, the upper few inches may be mixed with silt owing to reworking by the wind.

Illinoian till

The age assignment of Illinoian till is based on its stratigraphic position. Only one section in the vicinity of Yankton yields stratigraphic proof that the till overlies Illinoian outwash and underlies Loveland loess; this measured section is described below.

Measured section 2.—NE cor. NW¼NE¼ sec. 13, T. 93 N., R. 57 W., Yankton County. Shallow exposure in draw; approximate altitude 1,400 feet. Exposed in 1941

	Maximum exposed thickness (feet)
Covered slope underlain by loess; moderate yellowish brown with medium light gray mottling, massive, calcareous. *(post-Iowan pre-Mankato loess)*	5
Contact distinct.	
Loess, light brown, massive, leached but recalcified. *(Loveland loess)*	5
Contact distinct.	
Till, light olive gray, weathers to moderate yellowish brown, massive, calcareous. *(Illinoian till)*	5
Contact sharp.	
Sand gravelly, yellowish-gray to grayish orange pink, contains pebbles, cobbles, silt balls, small silt lenses; pink feldspathic granules predominate in some beds. *(Illinoian outwash)*	5
Base concealed.	

Exposures of till believed to be of Illinoian age are rare. No Illinoian drift was found south of the Missouri River, and the very few outcrops observed are in the north wall of the Missouri River trench. Any remnants that may be present farther north are buried beneath post-Illinoian deposits. The most accessible outcrop of presumed Illinoian till is in a nearly vertical face marking the north wall of the trench from the Hutterite Colony westward for a distance of about 5 miles. The till in the face is from 40 to 45 feet thick and is overlain by several feet of Mankato loess. Contacts of Illinoian till are abrupt and smooth.

The Illinoian drift border is shown to be along the north side of the Missouri River because of a few widely separated outcrops of till known or inferred to be of Illinoian age found in the north wall of the trench (see also footnote, 13, p. 71). Between the western margin of the mapped area and the vicinity of Springfield the position of the Illinoian border is that mapped by Flint (1955, pl. 3). Along the southern side of Yankton Ridge the position of the border is inferred from outcrops of Illinoian till. East of Yankton there is a prominent reentrant in the border owing to postglacial erosion and alluviation by the James River. That part of the border lying along the southwestern edge of Turkey Ridge has been mapped on the basis of exposures of Illinoian(?) drift in the north wall of the Missouri River trench at Vermillion, Clay County, S. Dak., and at Sioux City, Iowa.

Loveland loess

Correlation of loess in the Yankton area with Loveland loess at its type locality is based on the stratigraphic position of the loess and the maturity and sequence of the soil profile.

The stratigraphic position of the loess is indicated both in measured section 2, in which the loess overlies till and outwash of post-Kansan age and underlies yellowish-brown loess of post-Iowan pre-Mankato age, and in measured section 3, below. In this section the maturity of the soil profile on Loveland loess can be compared with the maturity of the profile on the overlying Farmdale loess of Leighton and Willman. Comparable soil profiles are found in the same relative position on similar loesses in the type section of Loveland loess and in an exposure at Sioux City, Iowa. As originally described by Shimek (1909, p. 405), Loveland loess at the type locality[14] overlies gravel and till and is overlain by buff colored (post-Iowan pre-Mankato) loess. I believe, however, that the uppermost 5.6 feet of Loveland loess at the type locality is correlative with the Farmdale loess of Leighton and Willman. Reasons for this correlation will be given.

Measured section 3.—SE cor. SW¼ sec. 14, T. 93 N., R. 57 W., Yankton County. Cut on east side of road; approximate altitude 1,400 feet. Exposed in 1951

	Thickness (feet)
5. Loess, very pale yellowish brown with some light gray mottling in basal 1 foot, calcareous, massive, columnar structure moderate, contains scattered sand grains, granules, calcium carbonate concretions, and grains of charcoal. *(Cary loess, but may be Iowan and Tazewell loess)*	0–6
Contact(?) sharp, marked by a layer 0.1 inch thick of iron and manganese oxides as flaky particles and thin concretions, with strong staining in overlying 2 to 4 inches. Layer believed to mark an erosional contact. Contact has about 2 feet of relief.	
4. Loess, like above, but wholly mottled with light gray. Fossils, chiefly from basal 2 feet. *(Iowan and*	

[14] The original type section of Loveland loess described by Shimek has been destroyed by highway construction, but a new section that contains a similar stratigraphic sequence has been suggested as a new type (Daniels, R. B., and Handy, R. L., 1959, Suggested new type section for the Loveland loess in western Iowa: Jour. Geology, v. 67, p. 116–121).

Tazewell loess) 0–4.2

Contact transitional through basal 6 to 12 inches because of reworking by slope wash.

3. Loess, upper 15 inches A horizon, humified pale reddish brown, massive, leached but recalcified, firm, grades into lower 19 inches C horizon, pale reddish brown, prismatic jointing moderate, massive, leached but recalcified. *(Farmdale loess of Leighton and Willman)* 0–3.9

Contact distinct.

2. Loess, upper 9 inches A horizon, humified, pale reddish brown, massive, leached but recalcified, very firm, clay content estimated at 25 to 30 percent, grades into B horizon about 18 inches thick, clay content 40 to 45 percent, pale reddish brown; grades into C horizon about 3 feet thick, pale reddish brown to moderate yellowish orange. Moderate prismatic jointing; *Citellus*(?) burrows; basal 2 feet sandy. *(Loveland loess)* 0–5.2

Contact transitional; base of above unit drawn at base of dominantly silty material.

1. Alluvium, sandy silt and some clayey or silty sand, dark-gray to grayish-black, stratified, leached. (Correlated by direct tracing: *Illinoian outwash*) 2

Base of exposure.

The distinctive feature of the Loveland loess is the soil of Sangamon age developed upon it. The soil is characterized by pale reddish brown B and C horizons locally overlain by a dark gray humified (or A) horizon, and by its maturity, indicated by moderately strong clay enrichment in the B horizon. As the Sangamon soil is the only moderately strong profile exposed in the area, it is readily distinguished from all others. Although attention is usually attracted to the loess by its soil color, this in itself is not necessarily a valid means of identification. In the section above, the B horizon is about 18 inches thick and is not truncated. At this locality the loess mantles a fill terrace, is well drained, and has a nearly level surface; so the profile is probably normal and typical of the region. In several exposures the soil is so truncated that only the C horizon remains.

Small remnants of Loveland loess crop out, chiefly in road cuts, at localities along the walls of the Missouri River trench, and as far south as West Bow (Bow Valley) Creek. Seven exposures are known in the vicinity of Yankton. Of the seven only two are north of the Missouri River and only three are within the mapped area. From 2 to 5 feet of the loess are exposed at each locality. Where Loveland loess overlies a deposit of sand, silt intermixed with sand reworked from below by the wind forms the basal several inches of the loess. The upper contact is generally abupt, and although it is erosional, it is smooth. The contact profiles suggest the surface slopes were similar to, or a little steeper than, modern loess slopes.

Sections in which several loess sheets are superposed are very rare, but they are important because the several loesses can be compared at one locality. One such exposure near Yankton contains Loveland, Iowan and Tazewell, Cary, and Mankato loesses. A brief description follows.

Measured section 4.—NE¼NW¼ sec. 19, T. 33 N., R. 1 W., Cedar County. Road cuts on both sides of section line; approximate altitude 1,390 feet. Exposed in 1951

Thickness (feet)

6. Backfill and modern eolian silt 1

Contact distinct.

5. Loess, medium-gray, slightly humified, leached to depth of 2 feet, weak columnar structure, massive, unstratified, upper 10 inches medium dark gray (A horizon of surface soil). *(Mankato loess)* 0–3.9

Contact distinct.

4. Loess, dark yellowish orange, massive, calcareous, columnar structure weak. *(Cary loess)* 0–3.4

Contact distinct.

3b. Alluvium: sand, stratified, *(Cary outwash)* 0–7

(The lower part of the section is offset 50 feet north and 50 feet west.)

3a. Alluvium: same deposit as unit 3b 2.5

Contact distinct.

2. Loess, dark yellowish orange, massive, calcareous, columnar structure moderate. *(Iowan and Tazewell loess)* 0–2

Contact sharp.

1. Loess, pale reddish brown, leached but recalcified, massive, columnar structure moderate to good, *Citellus*(?) burrows. *(Loveland loess)* 0–5

Base of exposure.

The name Loveland was originally applied by Shimek (1909, p. 405) to a "joint clay" previously thought to be eolian, but which he believed to be fluvial in origin. The eolian origin of part of Shimek's unit was reestablished by Kay (1924, p. 73) and the name restricted to that part. The type section described by Shimek is an excellent exposure in the east bluff of the Missouri River trench about 75 miles south of Sioux City, Iowa, and 122 miles southeast of Yankton; it is named for the village of Loveland, Pottawattamie County, Iowa.

WISCONSIN STAGE

Various subdivisions of the Wisconsin stage have been proposed, and the classification in general use today (see page 45) consists of four glacial substages: Iowan, Tazewell, Cary, and Mankato. Other subdivisions have been proposed recently.[15]. The interglacial intervals, or interstadials, generally

[15] Since this report was written, the U.S. Geological Survey has adopted the terms "Farmdale substage" and "Farmdale loess."

are referred to by the hyphenated names of the substages between which each occurred.

In the Yankton area substages of the Wisconsin glacial stage have been differentiated and correlated by means of loess representing each of the substages, buried soil profiles that developed during each of the interstadials, areal extend of the individual drift sheets, and differences in the degree of erosional dissection of the drifts.

The Iowan, Cary, and Mankato drift sheets are represented by till and ice-contact stratified deposits, and the late Wisconsin substages by outwash, as well. All the Wisconsin substages include loess, although Tazewell loess has not been differentiated from Iowan. Post-Iowan pre-Mankato loess is all physically similar, and zonal soil profiles or other breaks in continuity are necessary for differentiation and correlation. In Nebraska and Kansas, Iowan, Tazewell, and Cary loesses are differentiated by weathering profiles. The Iowan-Tazewell interval is marked by a locally occurring, very weak soil, and the Tazewell-Cary interval by a more extensive, somewhat stronger soil (the Brady soil of Schultz and Stout, 1948, p. 570). Neither profile is exposed in the vicinity of Yankton, and owing to the lack of a basis for differentiation, most loess south of the Missouri must be mapped as undifferentiated.

Deposits of the Wisconsin glacial stage mantle almost the entire Yankton area. North of the Missouri River they consist chiefly of Cary and Mankato drift, with minor amounts of loess representing the Farmdale of Leighton and Willman, Iowan and Tazewell, Cary, and Mankato loess sheets. South of the river the major deposits are outwash, chiefly of Cary age, and loess representing sheets of post-Iowan age named above. Iowan till is moderately widespread, but it is mostly buried beneath the outwash and loess.

The term "Wisconsin" was first used by T. C. Chamberlin (*in* Geikie, 1894, p. 763–765) in naming the East Wisconsin formation, a drift sheet named for deposits in that state. The name was shortened to Wisconsin formation by Chamberlin in 1895 (p. 275–276), and additional changes led to the present usage.

FARMDALE SUBSTAGE (?) OF LEIGHTON AND WILLMAN

Leighton and Willman (1949, table 1, or see 1950, p. 602–603) have proposed an additional Wisconsin substage to rank with the four generally accepted. This substage which they called Farmdale is pre-Iowan and is named for loess exposed near Farmdale, Tazewell County, Ill. Their proposal of a pre-Iowan Wisconsin substage is based on the assumption that accumulation of loess in a given region is dependent on glaciation within the drainage basin of that region. On this basis they inferred that till of Farmdale age is present in northern Illinois. Such a drift has recently been inferred in that area by Shaffer (1954, 1956); but until the existence of Farmdale drift can be proven the possibility remains that Leighton and Willman's Farmdale loess accumulated during late Sangamon time and achieved its immature weathered profile under climatic conditions similar to but of shorter duration than those that produced the mature Sangamon soil.

Farmdale loess of Leighton and Willman

The Farmdale loess of Leighton and Willman (1950) is characterized by a reddish brown color and an immature soil profile. At the type locality it rests on Illinoian till (the top 3 feet of which is maturely weathered to a gumbotil) and is overlain by yellowish-brown loess of post-Iowan age.

Correlation of loess in the Yankton area with the Farmdale loess of Leighton and Willman is based on similar stratigraphic position, similar immaturity of the soil profile, and, indirectly, tracing by G. F. Kay.

The first two points of evidence are shown in measured section 3 (p. 77) in which loess (unit 3) which has an immature soil profile and is characterized by a reddish-brown color, overlies Loveland loess (unit 2), which has a mature soil profile and similar color, and underlies yellowish brown Iowan and Tazewell loess (unit 4).

Kay (1928) traced reddish brown loess from the type Loveland section eastward into southeastern Iowa, where he found reddish-brown loess overlying more than 3 feet of gumbotil (a mature soil profile) on Illinoian till, just as in the Farm Creek section in Illinois. From these sections he concluded that the reddish brown Loveland loess is much younger than Illinoian drift; later Kay and Graham (1943) concluded Loveland loess "is late Sangamon in age."

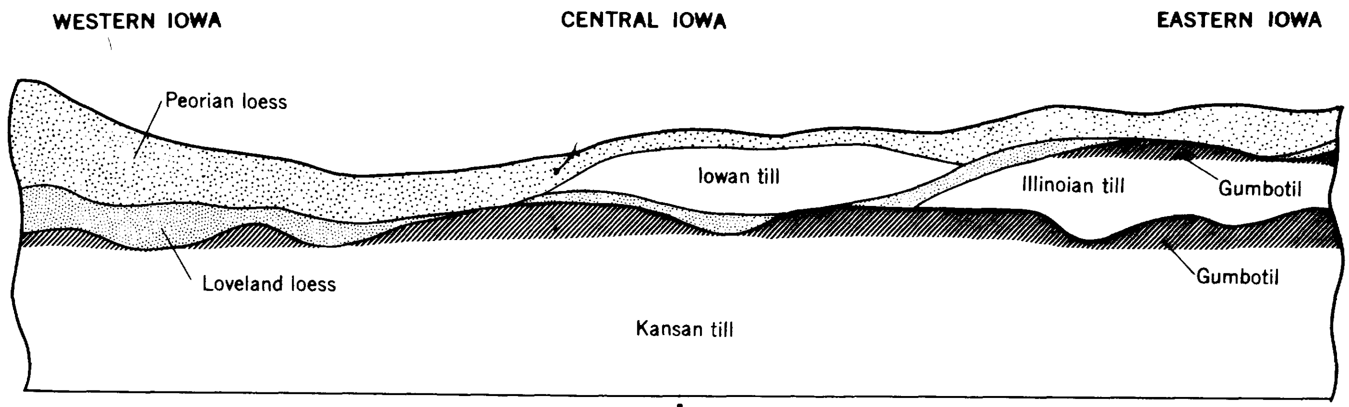
Apparently Kay, as well as others before him, did not realize that two loesses of identical reddish-brown color but having different soil profiles are exposed in the type section of the Loveland loess. The lower soil is mature, although the A horizon and part of the B are truncated; the upper soil is immature, and the A horizon is truncated. Thus the presence of the two loess sheets can be recognized only by very careful examination.

Kay, therefore, did not recognize that the Loveland loess, the lower of the two, actually pinches out east of the type section, and that it is the Farmdale loess of Leighton and Willman that extends eastward across Iowa. The relation inferred by Kay is illustrated diagrammatically in figure 10*A* and my inferrence is diagrammed for comparison in figure 10*B*. Thus it seems that Kay proved unknowingly the correlation of the upper reddish-brown loess in the Loveland loess type section with the Farmdale loess in its type section in Illinois.

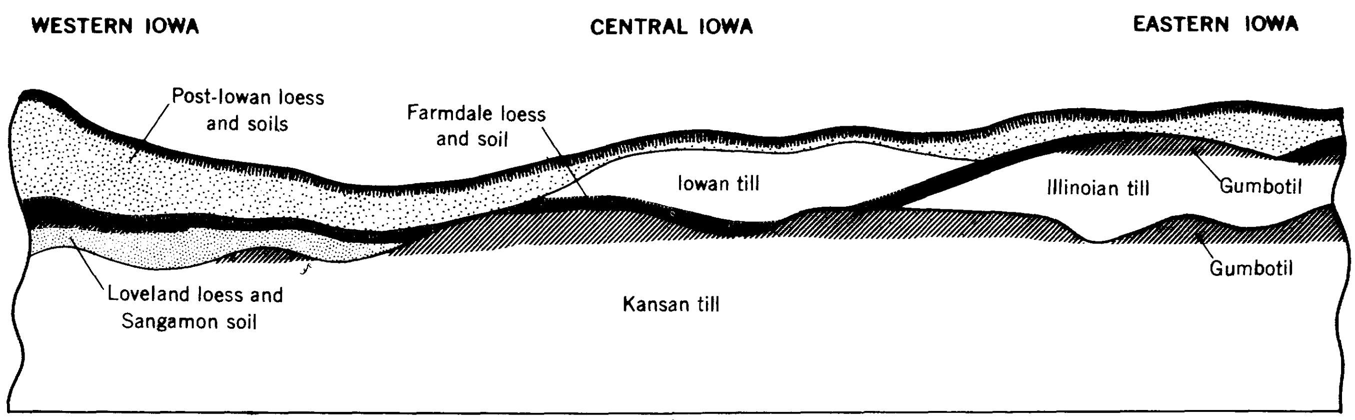
The maximum eastward extent of the Loveland loess in Iowa is apparently unknown. During 1955, however, I examined sections exposed in Union Pacific Railroad cuts in the vicinity of Atlantic, Cass County, Iowa, in the company of R. H. Ruhe and others. Ruhe demonstrated that along this west-to-east traverse the Loveland loess pinches out just west of Atlantic, or about 50 miles east of the Missouri River.

Correlation of loesses exposed in the Loveland loess type section with those exposed in the Yankton area is based on the same stratigraphic sequence and soil profiles previously described. The fact that the similarity of sequence and profiles is not chance is indicated by other comparable sections exposed at widespread localities, including the north bluff (Prospect Hill) of the Missouri River trench at the north end of the Sioux City—South Sioux City bridge, the Buzzards Roost section near North Platte, Nebr., and elsewhere in Nebraska (see Simpson, 1952, p. 219–221).

The sole exposure of Leighton and Willman's



A



B

FIGURE 10.—*A*, Diagram of the stratigraphic relations of Loveland loess eastward from the type locality in western Iowa (from Kay and Graham, 1943, fig. 13); *B*, Diagram of significant Pleistocene stratigraphic units and their relations in Iowa as inferred by Simpson. Note addition of the Farmdale loess of Leighton and Willman; maximum extent of Loveland loess eastward is unknown.

Farmdale loess in the Yankton area is described in measured section 3 (p. 77).

Like the Sangamon soil on the Loveland loess, the soil formed on the Farmdale loess of Leighton and Willman is pale reddish brown and locally is capped by a dark-gray A horizon. The Farmdale soil is readily distinguished by its immaturity from the older soil, however, for there is no apparent clay enrichment (B horizon) in the younger profile. It is readily distinguished from later soils by its reddish color. In measured section 3 no truncation of the soil is apparent. Since the Farmdale loess mantles a level blanket of Loveland loess and has a nearly level surface, the soil profile is probably typical of the region. If the A and B horizons of the Sangamon soil were truncated so that the two C horizons were superposed, the two soils could easily remain undifferentiated. Thus, it is necessary to examine carefully the lithologic details of each exposure of pale reddish brown silt to ascertain whether one or both loesses are present.

Farmdale loess was named by Leighton (*in* Wascher, Humbert, and Cady, 1948, p. 390) and described by Leighton and Willman (1950, p. 602–603) from silt exposed in the Farm Creek section near Farmdale, Tazewell County, Illinois. Earlier, Leighton (1926) had believed the silt to be Loveland loess of Sangamon age.

IOWAN AND TAZEWELL SUBSTAGES

Deposits in the vicinity of Yankton assigned to the Iowan substage include till inferred to be Iowan, loess which may be in part Iowan, in part Tazewell, or both, and ice-contact stratified deposits which may be either Iowan or Kansan in age, but which would more logically be Iowan. The loess which may be in part of Tazewell age is perhaps the only deposit representing that substage exposed in the area. As neither Tazewell till nor outwash has been recognized along the Missouri River trench, the Tazewell glacier probably did not reach it.

The term "Iowan" was first used for the drift to which it presently refers by T. C. Chamberlin in 1896 (p. 873–874) when he named the "Iowan Till sheet" for deposits in that state. Before that the names Iowan and East Iowan had been used by Chamberlin (*in* Geikie, 1894, p. 759–761; 1895, p. 273–275) for drift now known to be Kansan. In 1931 Leighton concluded that the then post-Iowan pre-Wisconsin interglacial stage (the Peorian, as originally defined by Leverett, 1898, p. 246) was not of interglacial magnitude but rather intraglacial, and he reduced the Iowan stage of glaciation to the rank of a Wisconsin substage. The Tazewell substage was named by Leighton in 1933 (p. 168) for deposits in Tazewell County, Illinois.

Iowan till

The assignment of Iowan age to till exposed in the Yankton area is based on circumstantial evidence. Along the west side of secs. 2, 11, 14, 23, 26, and 35, T. 32 N., R. 1 W., Cedar County, are several new road cuts 15 to 20 feet deep. Till exposed in several of these cuts contains irregular inclusions ranging in size from a few inches to a foot or more in diameter. Most are composed of pale reddish brown silt that I believe to be Loveland loess. If it is Loveland loess, the till is no older than Wisconsin age. If the silt is not Loveland loess however, the physical characteristics of the till indicate it is not older than Illinoian. The undissected till surface is overlain by yellowish brown, post-Iowan pre-Mankato loess, and thus must be pre-Mankato in age. As the physical characteristics of the till are unlike those of Cary till north of the river, the till south of the river is inferred to be older than Cary. Thus the till may be Illinoian, Iowan, or Tazewell in age.

The till is inferred to be Iowan. Illinoian age is improbable for two reasons. First, nowhere, either in the 6 miles of deep, new road cuts or elsewhere in that part of the area south of the river is there any evidence that Loveland loess lies upon the till, and the complete absence of that loess from the undissected till surface is unlikely unless the loess was never there. Second, the absence of any indication of a mature weathering profile in the upper part of the till, the presence of ventifacts at the contact between the till and the overlying loess and the lack of erosion all indicate that deposition of the yellowish brown loess on the till followed shortly after recession of the glacier. Thus the till is inferred to be Iowan rather than Illinoian.

To eliminate Tazewell age is more difficult. The positions of the Iowan and Tazewell drift borders in regions adjacent to the Yankton area are shown in Flint (1955, fig. 27). In easternmost South Dakota the James River lobe of the Tazewell glacier was less extensive than the same lobe of the Cary glacier. Therefore the southern extent of Tazewell drift north of the Missouri River is unknown, for it is hidden beneath younger deposits. The border of the early Wisconsin till south of the Missouri River is alined, both in position and trend, with the Iowan drift border mapped by Flint north and east from Sioux City, Iowa, and from the mouth of the Niobrara River northwest along the Missouri River trench. It seems probable, therefore, that early Wisconsin till south of the Missouri River is Iowan. If Tazewell age is eliminated the far more complex problem of explaining the absence of Iowan drift is raised.

The Iowan drift border from the vicinity of Bloomfield, Knox County, to the vicinity of Coleridge, Cedar County, is mapped on the bases of widely scattered exposures of till inferred from physical characteristics to be Iowan, a broad, low, completely loess-mantled, well-dissected ridge that trends east, and the drainage pattern in the vicinity of the drift border. The till exposures largely lie within the mapped area; those beyond are small and generally occur in road cuts in which the till is mantled by younger deposits. No outcrops of till having physical characteristics similar to those of Iowan till were observed southwest of the drift border. The loess-mantled ridge may reflect an end moraine, but no exposures of till beneath the loess mantle were observed in the ridge. The absence of Iowan end moraines elsewhere in central United States (Flint, 1955, p. 90) suggests that the ridge may not be caused by a buried end moraine, but this is not conclusive. The drainage pattern is shown in plate 10. The drift border approximately delineates a natural divide. Drainage on both sides of the divide consists chiefly of intermittent streams too small to have cut the valleys they occupy; the valleys are believed therefore to be former melt water channels. The orientation of the valleys suggests that those north of the divide may be marginal in origin, whereas those to the south apparently flowed away from the glacier margin. Post-Iowan headward extension of the streams has modified the pattern somewhat. The smoothness of the drift border reflects both the small quantity and subjective nature of supporting evidence. The drift border may extend eastward from Coleridge to the vicinity of Sioux City (see footnote 13, p. 71), and is interpolated (pl. 10) to extend from Bloomfield northwest toward the mouth of the Niobrara River. In each direction it joins with segments of the Iowan drift border mapped by Flint (1955, pl. 3).

All exposures of ground moraine within the mapped area south of the Missouri River trench probably are composed of Iowan till. The most conspicuous outcrops are in T. 32 N., R. 1 W., Cedar County, and along the face of the escarpment shown in the southwestern part of the map. Maximum thickness of the deposits is not known, but exposures 12 to 18 feet high are found along U.S. Highway 81 in the township referred to above, and 8 to 12 feet high along the escarpment. Contacts are generally smooth and abrupt.

Iowan(?) ice-contact stratified drift

A few small, scattered deposits of coarse gravelly sand exposed in borrow pits south of the Missouri River trench may be of Iowan age. The gravel is overlain by sand correlated with Cary outwash; as there is no evidence that the Cary glacier crossed the Missouri River trench, the gravel is assumed to be older than Cary. Because the oldest glacier believed to have entered the area was Kansan, the gravel is presumed to be Kansan, Illinoian, or Iowan in age. Illinoian age is unlikely, for there is no evidence that the Illinoian glacier advanced south of the present position of the Missouri River trench (see footnote 13, p. 71). The gravel tentatively is presumed to be Iowan rather than Kansan solely because older Kansan deposits are much more likely to have been destroyed by erosion than more recent Iowan deposits.

The gravel crops out in widely scattered borrow pits 10 to 15 feet deep and 25 to 50 yards across; generally the attitude of the contact with overlying Cary outwash suggests that the deposits are not much larger. The upper contact is distinct but a few inches of intermixed sand and silt indicate a little reworking of sand by the wind; the lower contact is not exposed.

Iowan and Tazewell loess

Assignment of Iowan and Tazewell age to the older of two sheets of yellowish-brown loess depends on stratigraphic position and on fossil pulmonate gastropods contained therein.

In measured sections 3–6 the stratigraphic position of the loess (units 4, 2, 3, and 1, respectively) is shown to overlie Farmdale loess of Leighton and Willman and Loveland loess, and to be separated from younger but similar Cary loess by Cary till or erosion surfaces.

An assemblage of fossil pulmonate gastropods was obtained from the basal 4 feet of the lower yellowish-brown loess (unit 4) of measured section 3. The shells were submitted to A. B. Leonard of the State Geological Survey of Kansas who made (written communication, March 19, 1952) the following identifications and notations:

Columella alticola (Ingersoll)
Discus cronkitei (Newcomb)
Discus shimeki (Pilsbry)
Hendersonia occulta (Say)

Pupilla muscorum (Linné)
Succinea avara Say
Vallonia gracilicosta Reinhardt
Vertigo modesta (Say)

In terms of the faunal assemblages we get in the zones of the Peoria [sic] loess in Southern Nebraska and in Kansas, this fauna would be transitional between Iowan and Tazewellian [sic].

Another collection of gastropods, made from unit 3 of the following section, was also submitted to Leonard.

Measured section 5.—Ctr. NW¼ sec. 23, T. 33 N., R. 1 W., Cedar County. Road cut, U. S. Highway 81. Exposed 1951

	Feet
4. Loess, pale yellowish brown. *(Cary loess)*	±18
Contact sharp, erosional; marked by a lag concentrate of scattered pebbles; relief greater than 6 feet.	
3. Loess, mottled pale yellowish brown and medium light gray. *(Iowan and Tazewell loess)*	0–6
Contact sharp.	
2. Alluvium, yellowish-brown, sandy silt. (Not correlated.)	0–12
Contact sharp.	
1. Argillaceous limestone. *(Niobrara formation)*	±90
Base concealed.	

He found that these gastropods are of the same species as those listed above, but with the addition of *Oreohelix strigosa cooperi* (Binney) and *Retinella* sp. (fragmentary), and he concluded that the faunal assemblage from this unit "is also what I would call a transition zone fauna, if it occurred in Kansas. That is, I would class it as early Tazwellian [sic] in age."

Because the loess sheet is post-Farmdale and pre-Cary in age, and because the faunal assemblage at both localities is transitional in nature between the faunas of the Iowan zone and the Tazewell zone in southern Nebraska and Kansas, the loess may be Iowan, or Tazewell, or both. As no physical break consisting of a weathered profile or erosional surface is found within the loess sheet, it is undifferentiated and tentatively inferred to be both Iowan and Tazewell in age.

Known exposures of Iowan and Tazewell loess are limited to those described in measured sections 4–6. A very few other exposures are inferred to contain Iowan and Tazewell loess, but proof of age is lacking, or dependent on direct tracing from the known exposures. All outcrops of known or inferred age are in or near the walls of the Missouri River trench and are only a few feet thick. Contacts are abrupt and smooth.

CARY SUBSTAGE

Deposits of Cary age near Yankton include till, outwash, ice-contact stratified material, and loess; in addition there are kame-terrace deposits of Cary(?) age.

The Cary substage was named by Leighton in 1933 (p. 168) for drift in the vicinity of Cary, McHenry County, Ill.

Cary till

Assignment of Cary age to a till sheet in the Yankton area is based on stratigraphic position and the areal distribution of deposits of the Mankato substage. In the section described below, Cary till overlies inferred Iowan and Tazewell loess and is overlain by loess inferred to be Cary owing to its physical characteristics and apparent continuity with adjacent deposits of known Cary age.

Measured section 6.—SW cor. NE¼ sec. 7, T. 93 N., R. 56 W., Yankton County. Gully and road cut on north side of road. Approximate altitude 1,400 feet. Exposed in 1949

	Feet
4. Loess, upper 18 inches humified, light to medium gray; lower 22 inches oxidized, light yellowish brown; leached to depth of 30 inches. *(Cary loess)*	0–3.3
Contact distinct.	
3. Stratified drift, gravelly sand. *(Cary outwash)*	0–2.5
Contact distinct.	
2. Till, upper 2 feet olive gray, clayey, firm; lower 23 feet oxidized, loose, sandy. *(Cary till)*	0–24
Contact abrupt.	
1. Loess, light yellowish brown, massive, cross-laminated, many grains of charcoal. *(Iowan and Tazewell loess)*	18
Base concealed.	

The possibility exists that the upper 2 feet of unit 2 is Mankato till, but there is no other field evidence to support it.

Exposures of till believed to be Cary in age are restricted to the area north of the Missouri River trench and south of the Mankato drift border, along the walls of Beaver Creek valley and James River trench north of the Mankato border, and on the crest of Turkey Ridge. These outcrops are from about 10 to a maximum of 24 feet thick. Contacts are distinct and smooth.

The Cary drift border lies along the north wall of the Missouri River trench and in effect coincides with the Illinoian border. Exposures on which the border is drawn are somewhat scattered. End moraines mark the border only along a reentrant tentatively inferred to have encircled the crest of the Yankton Ridge; both east and west of the ridge Cary drift has been removed by erosion or mantled by later deposits. Although no Cary till was recognized south of the trench, Cary outwash is exposed on the crest and southern flank of a low bedrock ridge that extends west of St. Helena along the southern edge of a large remnant of the St. Helena terrace channel. The outwash suggests that the Cary glacier may have reached as far as 1 to 2 miles south of the present Missouri River trench.

Cary outwash

Some deposits of sand and gravel in the Yankton area are believed to correlate with Cary outwash on the basis of stratigraphic position. The correlation of deposits north of the Missouri River is tentative, but reasonably certain for deposits south of the river.

South of the Missouri River, as in measured section 4, sand (units 3a and b) locally overlies yellowish-brown loess (unit 2), and is overlain by a similar loess (unit 4). In other exposures loess (unit 3) inferred to be Cary from other evidence overlies sand (unit 2) as in measured section 7. As the sand in measured section 4 rests on loess inferred to be Iowan, and in measured section 7 under loess inferred to be Cary, it must be either Tazewell or Cary in age. As the Tazewell glacier apparently did not reach the Missouri River trench, Tazewell age is unlikely, and the sand is inferred to be Cary outwash.

North of the Missouri River deposits of sand and gravel correlated with Cary outwash are enclosed between till sheets. The lower till is inferred to be of Cary age for it can be traced southward along the James River trench to an area underlain by Cary till south of, or outside, the Mankato drift border. The till is likely not Tazewell, for it is believed that the Tazewell glacier stopped short of the Yankton area. The till above the outwash is probably Mankato in age because the deposits are within, or north of, the outer Mankato drift border. The stratigraphic position of the sand and gravel indicates that they date from either the recession of the Cary glacier or the advance of the Mankato glacier. Because a receding glacier is more likely to leave large amounts of outwash than an advancing glacier, these deposits are tentatively correlated with Cary outwash.

Cary outwash immediately underlies the surface of about half the mapped area south of the Missouri River. The thickness of these deposits is generally from 2 to 15 feet and probably averages 4 to 8 feet. North of the river most exposures are found along the walls of Beaver Creek valley and the James River trench and are as much as 12 feet thick. Contacts in both areas are commonly distinct and smooth.

Cary(?) kame-terrace deposits

Kame-terrace deposits in the Yankton area are correlated with Cary outwash in the vicinity by direct tracing; in addition the stratigraphic position of the kame terraces is the same as that of the outwash.

Kame-terrace deposits have been exposed in the James River trench in T. 95 N., Rs. 55 and 56 W., Yankton County, and along the northeast flank of James Ridge from Beaver Creek valley northwest. In both townships exposures range from 10 to 100 or 120 feet high, but the thickness of the deposits is not known. Contacts with the overlying till are abrupt and smooth.

Cary ice-contact stratified drift

Correlation of ice-contact stratified deposits with the Cary substage is dependent chiefly on evidence that the Mankato glacier failed to reach the area of the deposits. The two kamelike deposits lie between ½ mile and 1½ miles south of the outer Mankato drift border in an area underlain by Cary ground moraine. The possibility that these deposits were formed at the margin of the Mankato glacier at a time when it lay south of the drift border is unlikely because on all sides of these deposits, Mankato loess lies on Cary loess with a level, uneroded, stone-free contact between. Moreover, a soil profile formed in the upper part of the lower loess does not appear to be truncated. Therefore the ice-contact stratified deposits are most likely of Cary age.

The drift constitutes two prominent, kamelike deposits in and immediately north of Yankton. The higher has a relief of about 75 feet, but the thickness of the deposit is not known. Numerous borrow pits in the deposit have a maximum depth of about 15 feet. No contacts are exposed.

Cary loess

Correlation of a light yellowish brown silt with Cary loess is based on its stratigraphic position.

North of the Missouri River loess assigned to this sheet rests upon Cary till in an area unoccupied by the Mankato glacier. In addition, this loess is physically similar to loess nearby on which a weak soil has formed and which is mantled by loess of Mankato age. South of the river the stratigraphic position of the loess is indicated by the following section, which is illustrated in plate 11*A*.

Measured section 7.—SW cor. sec. 18, T. 33 N., R. 1 E., Cedar County. Cut on east side of road; approximate altitude 1,275 feet. Exposed 1950

	Feet
5. Loess, pale yellowish brown to medium light gray;	

very recent in age 1.0–1.6
Contact sharp.
4. Loess, upper 15 to 28 inches A horizon of post-Mankato soil, dark-gray; rest of unit is of C horizon, medium light gray; calcareous, a few calcium carbonate concretions generally less than one-half inch diameter, prismatic structure poor. Firepit of early man 24 inches above base of unit. *(Mankato loess)* 5.6–10.2
Contact sharp.
3. Loess, upper 15 to 18 inches A horizon of Cary-Mankato soil profile, medium dark gray; next 25 inches is upper part of C horizon, oxidized a reddish color, calcareous, rest of unit is lower part of C horizon, grayish orange; both parts of C horizon have good prismatic structure, numerous secondary calcium carbonate concretions as large as half an inch in diameter. *(Cary loess)* 6.0–10.0
Contact sharp.
2. Outwash, sandy silt containing thin laminae of sand-sized particles of Niobrara formation, grayish-orange, contains erratic 3 feet in diameter. *(Cary outwash)* 4.0–11.0
Contact sharp.
1. Argillaceous limestone. *(Niobrara formation)* 17.0
Base concealed.

Other sections where loess inferred for various reasons to be of Cary age is known to crop out are described in measured sections 3–7.

An assemblage of fossil pulmonate gastropods was obtained from the upper 8 feet of Cary loess (unit 3) in measured section 7 and submitted to A. B. Leonard, State Geological Survey of Kansas, who made (written communication, March 19, 1952) the following identifications and notation.

Helicodiscus parallelus (Say)
Succinea avara Say
Vertigo modesta (Say)

This series of species is not very meaningful, and is too sparse to form the basis of good judgment. I should say, however, that the upper part of the loess [unit 4] is very young indeed, if not Recent, and the lower part [unit 3] late Wisconsinan [sic] in age.

The distribution and thickness of Cary loess north of the Missouri River is very different from that south of the river. To the north Cary loess forms a thin veneer of silt that mantles Yankton Ridge. Generally from 3 to 4 feet thick, it attains a maximum thickness of 4½ feet in the NE cor. SE¼ sec. 1, T. 93 N., R. 56 W., Yankton County. Because loess is not mapped where less than 5 feet thick, this deposit would not normally be shown on the geologic map. Owing to its significance in geologic history, however, it seemed desirable to indicate in a general way by a stippled pattern the approximate areal extent of the deposits, but no contacts have been drawn. South of the Missouri River Cary loess is much thicker. It is 15½ feet thick in the SW cor. sec. 18, T. 33 N., R. 1 E., Cedar County, and 18 feet thick 1½ miles west.

Cary loess may constitute much of the undifferentiated post-Iowan loess mapped south of the Missouri River. Road cuts 10 to 20 feet deep which do not expose the base of yellowish brown loess are numerous. Owing to the scarcity, small areal extent, and thinness of known remnants of Iowan and Tazewell loess and Mankato loess where they have been identified, much if not most loess immediately underlying the surface south of the river may be of Cary age. Because differentiation is possible only along the edge of the Missouri River trench where remnants of Iowan and Tazewell loess are expectably thinnest owing to more rapid erosion, loess south of the trench is mapped as undifferentiated post-Iowan loess.

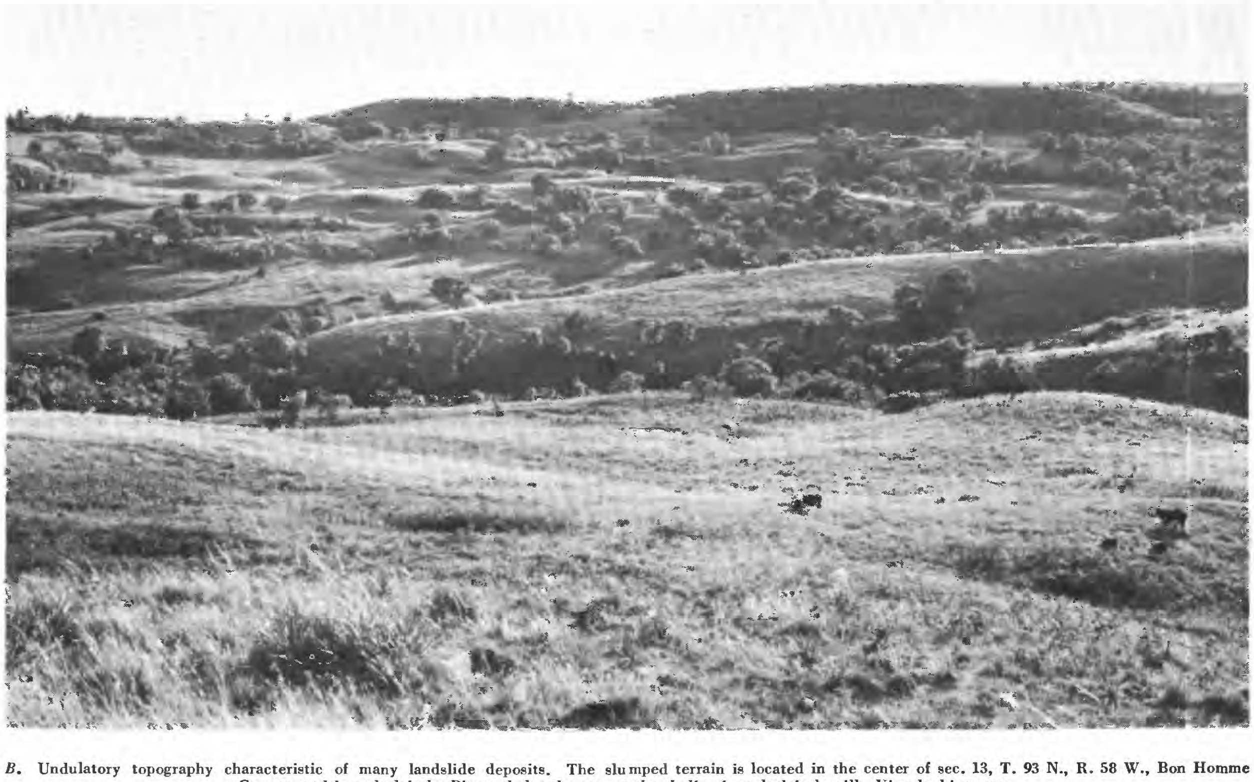
The thickest single section of undifferentiated post-Iowan loess is 43 feet, augered in the NE¼-SE¼ sec. 12, T. 32 N., R. 4 W., Knox County. North of the Missouri River the thickest known section is 34 feet, augered and measured in a road cut in the SE cor. SW¼ sec. 14, T. 93 N., R. 57 W., Yankton County. In neither section is there evidence that Mankato loess is present. Southward from the river undifferentiated post-Iowan loess thins, at first rapidly, until in the vicinity of Norfolk, Madison County, Nebr., about 60 miles from the trench, the loess is only 10 to 12 feet thick. Quantitative data on the rate of thinning were not ascertained, but it appears to be similar to that found by Krumbein (1937) and Smith (1942) in Illinois, and Simonson and Hutton (1954) in Iowa.

A weak soil formed on Cary loess has no particularly distinctive characteristics. It apparently consists of A and C horizons, for no B horizon was recognized. Normally the A horizon is 6 to 10 inches thick and dark gray to grayish black. The profile is exposed in the wall of a borrow pit in the SE cor. NE¼SE¼ sec. 1, T. 93 N., R. 56 W., Yankton County. A profile inferred to be unusually strong is described in measured section 7. At this locality the A horizon is considerably thicker than normal, and the C horizon has a faint reddish-yellow cast. These abnormalities are believed to be caused by greater downward percolation of surface water owing to the level ground surface and the permeability of underlying materials.

MANKATO SUBSTAGE

Till, ice-contact stratified drift, outwash, and loess constitute deposits of Mankato age in the

A. Cary loess with Cary-Mankato soil, overlain by Mankato loess with post-Mankato soil complex. Exposed in the SW cor. sec. 18, T. 33 N., R. 1 E., Cedar County. The man points to the base of the A horizon of the Cary-Mankato soil; note vertical jointing.



B. Undulatory topography characteristic of many landslide deposits. The slumped terrain is located in the center of sec. 13, T. 93 N., R. 58 W., Bon Homme County, and is underlain by Pierre shale; the area at the skyline is underlain by till. View looking west.

Yankton area. The substage was named by Leighton (1933, p. 168) for drift in the vicinity of Mankato, Blue Earth County, Minn.

Mankato till

The youngest till sheet in the vicinity of Yankton is correlated with the Mankato substage by direct tracing of the drift by Flint (1955, pl. 3) from the type locality of Mankato till to the southwest flank of Turkey Ridge, and by inference from circumstantial evidence in the vicinity of Yankton. A large inclusion of dark yellowish brown loess nearly 14 feet long is partly exposed in a road cut through an end moraine at the north side of NW¼ sec. 28, T. 94 N., R. 56 W., Yanktown County. As the dark color is characteristic of Cary loess north of the Missouri River but not of Iowan and Tazewell loess, drift in and north of the end moraine was tentatively inferred to be of Mankato age. Later Flint traced the Mankato drift border to the southwest flank of Turkey Ridge, whence the writer continued the tracing into the Yankton area and verified the inference made above. Mankato till has not been found resting on Cary loess although this relation was particularly sought. The till is found almost anywhere within the drift border and is exposed chiefly in ditches and shallow road cuts. Generally these outcrops are less than 8 feet high, but some are as much as 12 to 15 feet. The maximum thickness of Mankato till is probably 75 to 100 feet in the end moraine in the southeast part of T. 95 N., R. 55 W., Yankton County. Contacts of the till with adjacent deposits are abrupt and smooth.

Two drift borders of the Mankato substage are shown on the map, and are informally referred to as the outer Mankato and the inner Mankato drift borders; the position of each is known from detailed and reconnaissance mapping of Mankato drift. The outer Mankato border is believed to represent about the maximum extent of Mankato glaciation. Just east of Springfield, and to a lesser degree near the mouth of the James River, the form of the border indicates post-Mankato erosion by streams. The inner Mankato border represents the position of the ice margin at some time during the recession of the glacier, but whether it represents a minor re-advance of the ice front or a pause during its retreat is not known. The term "drift border" is used for the inner Mankato border only for convenience in reference. The inner border, however, does mark a change in topography, a change in grain-size distribution of the till, and may be the northern limit of Mankato loess.

Drift marking the outer Mankato border is thin and featureless along the lower course of Emanuel Creek and eastward to the western end of Yankton Ridge. Around the north flank of Yankton Ridge to a point north of Yankton, the border is clearly marked by prominent end moraines. The drift is also thin along the border from the vicinity of Yankton to the southwest flank of Turkey Ridge, where it is well marked by a distinct end moraine.

The inner Mankato brder is marked by prominent end moraines east of James Ridge; they are, however, fewer and less continuous than those marking the outer border. West of James Ridge, end moraines are absent from the inner border, and the topography north thereof is more strongly rolling than that to the south. In general the inner Mankato border is almost parallel to and well within the outer border except for the divergent loop of the inner border around James Ridge and except along the southwest flank of Turkey Ridge where the two borders are close together. The position of the ice margin at successive times during the recession of the Mankato glacier from the inner border is illustrated in plate 10. The several positions are approximate and are inferred from the drainage pattern and the orientation of minor end moraines and groups of swales in the adjacent ground moraine.

Mankato ice-contact stratified drift

The correlation of three small ice-contact stratified deposits north of Yankton with the Mankato substage is dependent chiefly on their position within (north of) the Mankato drift border, and partly on the intimate relation of two of the deposits to end moraines believed to be of Mankato age. The smallest deposit, now completely destroyed, was located in the SW. cor. sec. 31, T. 94 N., R. 55 W., Yankton County; the others are in sec. 24, T. 94 N., R. 56 W., Yankton County. Maximum thickness is probably about 50 feet. No contacts were observed.

Mankato outwash

Correlation of silt, sand, and gravel with Mankato outwash is dependent on stratigraphic position and relation to end moraines of Mankato age. Some of the outwash is overlain by thin, patchy, humified Mankato loess and lies on till that can be traced laterally into areas of known Mankato till. Moreover, fill-terrace remnants in Beaver Creek valley and the James River trench grade upstream into end moraines of the inner Mankato drift border. The terrace remnants may correlate with deposits of older terrace alluvium (terrace 2) along the Missouri River, but the only supporting evidence is the approximately similar height above water level. This evidence is inconclusive. Besides terrace remnants, the floors of James River trench and Beaver Creek valley are underlain by sand and cobble gravel outwash of the Mankato substage, mantled by several feet of younger deposits. Sandy Mankato outwash also may underlie younger deposits in the Missouri River trench but is yet undifferentiated from them. The outwash also forms a remnant of a low terrace in Tabor Creek near the western margin of the map but is absent from most small channels cut by melt water from the Mankato glacier. Whether outwash was never deposited in, or was eroded from, these small channels is not known. Mankato outwash at least 20 feet thick is exposed in a borrow pit in the NE¼SE¼ sec. 12, T. 94 N., R. 56 W., Yankton County. Approximately 80 feet of sand and gravel beneath the floor of James River trench were penetrated, but whether it is all of Mankato age is not known. Those contacts observed are distinct and smooth; locally, where overlain by Mankato loess the upper few inches of sand may be intermixed with a little loess, owing to reworking by the wind.

Mankato loess

Correlation of an eolian silt with Mankato loess is based on its stratigraphic position and areal distribution. A thin veneer of loess locally rests on Mankato till between the outer and inner drift borders, as in the area northwest of Utica and southeast of Beaver Creek. This proves the post-Mankato maximum age of the loess and appears to suggest that it accumulated only during the interval between formation of the two chains of end moraines. The suggestion well may be invalid, however, for there are very few likely sources of Mankato loess north of the inner drift border and within the Yankton area, and those few sources probably supplied some silt during Recent time as well. Because there is no soil profile or physical break in continuity, post-Mankato loess is undifferentiated.

Mankato loess is also found on Cary loess bearing the Cary-Mankato soil profile, as in a borrow pit in the NE¼SE¼ sec. 1, T. 93 N., R. 56 W., Yankton County, and in measured section 7. An assemblage of fossil pulmonate gastropods from the Mankato loess (unit 4) in that section was submitted to A. B. Leonard, State Geological Survey of Kansas, who made (written communication, March 19, 1952) the following identifications:

Discus sp. (fragment only)
Hawaiia minuscula (Binney)
Helicodiscus parallelus (Say)
Helicodiscus singleyanus (Pilsbry)

His comment regarding the age correlation of both this fauna and that of the underlying Cary loess (unit 3) is quoted on page 85.

Mankato loess is generally a thin patchy veneer found on the southeast side of the larger channels that carried melt water and outwash from the Mankato glacier. Within 6 miles north of the Missouri River trench the loess, where present, forms a thin veneer about 2 to 2½ feet thick. It attains a maximum thickness of about 18 feet along the low northern wall of the trench west of the Hutterite Colony. This exceptional thickness seems large even when the vertical and horizontal proximity to a major source of silt is considered, and it is possible that the section measured actually includes an undifferentiated deposit of Cary loess at the base. In the area of this thick accumulation the surface of the loess is nearly level and is marked only by two small shallow depressions that may be deflation hollows. South of the Missouri River where the thickness is expectably the greatest, the maximum known is 10 feet in the section described in measured section 7. The absence of Mankato loess from the higher parts of the area south of the trench but within the mapped area suggests it never accumulated there owing to lack of a local source material and the distance both vertically and horizontally from flood plains of the Missouri River.

The weak soil formed on deposits of Mankato age is an undifferentiated complex that may consist of any or all of several superposed profiles of post-Mankato date. This complex profile probably is the most widespread of the surface soils. Where undisturbed the A horizon is generally 8 to 12 inches thick on relatively permeable material like loess, but may be as much as 18 inches as in measured section 7; on till it may be as little as 4 to 6 inches. The A horizon rests directly on parent material; where the parent material is loess it is somewhat darkened by slight humification during accumulation.

Two hearth sites, neither associated with pottery, were found in Mankato loess. One hearth which was 24 inches above the base of the loess (unit 4) in measured section 7 contained a few grains of charcoal and numerous charred bone fragments. The second, near the center, SW¼ sec. 13, T. 93 N., R. 59 W., Bon Homme County, was in what was formerly a shallow draw tributary to the Missouri River trench. This hearth contained in addition to fragments of charcoal and bone a single discoid stone about 6 inches in diameter and 5 spheroidal stones 2 to 3 inches in diameter that may have been used either as hammers to crush marrow bones or simply as a fire ring.

SUMMARY

Pre-Wisconsin glacial deposits are present in the Yankton area, but exposures are very scarce owing in part to erosion and in part to the ubiquitous mantle of Wisconsin and Recent deposits. The presence of Illinoian till is proven stratigraphically in one section, and till believed to be of Kansan age has been observed in exposures south of the Missouri River. The age of Illinoian outwash is proven in part by its stratigraphic position and in part by its lithologic character and topographic position. Pre-Wisconsin nonglacial deposits include the Grand Island formation of late Kansan age, correlated chiefly on the basis of vertebrate fossils, and Loveland loess of late Illinoian age, correlated on the basis of stratigraphic position and maturity of its soil profile.

Wisconsin glacial deposits in the vicinity of Yankton consist of Iowan till and Iowan(?) ice-contact stratified drift, Cary till, outwash, and ice-contact stratified drift, and Mankato till, outwash, and ice-contact stratified drift. Nonglacial deposits are all loess, constituting at least three separate sheets: Iowan and Tazewell, Cary, and Mankato; the Farmdale loess of Leighton and Willman may well be a fourth Wisconsin loess sheet, but absolute proof of Wisconsin age rather than Illinoian is yet lacking.

Correlation of these deposits with the proper substage is based on one or more of the following criteria: stratigraphic position, location in relation to drift borders, fossil pulmonate gastropods, sequence and strength of buried soil profiles, and lithologic characteristics. The glacial deposits are correlated primarily on the basis of their stratigraphic relation to loess sheets, which are in turn correlated chiefly on the basis of stratigraphic succession, physical characteristics, fossils, and buried soil profiles. The principal exception is the correlation of Mankato till which is dependent in part on tracing by Flint from the type locality in Minnesota.

RECENT DEPOSITS

The present usage of Recent by the U.S. Geological Survey (Wilmarth, 1925, p. 49) is interpreted here as referring to time since the Pleistocene epoch; for the Yankton area this implies the time following the local retreat of the Mankato glacier. This usage presents a stratigraphic problem, however, because it is not practical to draw a sharp time boundary between glacial and postglacial deposits in this area. For example, postglacial deposits began to accumulate on Cary drift following the retreat of the Cary glacier and have continued to do so where deposition was not subsequently interrupted by Mankato ice. In this report, therefore, the term "Recent deposits" will refer to those which have accumulated chiefly since the Mankato glaciation but which may be partly of post-Cary age in that part of the Yankton area south of the outer Mankato drift border.

In the vicinity of Yankton, Recent deposits include landslide deposits, undifferentiated alluvium and colluvium, and swale deposits. Landslide deposits are restricted to dissected terrain on either side of the Missouri River trench, and undifferentiated alluvium and colluvium are found in nearly all tributaries and draws. Swale deposits are the most restricted in occurrence; they are found only north of the trench, and few are known in areas of Cary drift. Deposits that entirely postdate the Mankato maximum include terrace alluvium and tributary equivalents, alluvial fan deposits, flood plain alluvium, and eolian sand. Except for the eolian sand, each of these is found on both sides of, and adjacent to, the Missouri River.

Alluvial, colluvial, and eolian deposits are wholly of Recent age for they lie on Mankato drift or are younger than Recent deposits that do.

The passage of Recent time in the Great Plains and the Rocky Mountains has been characterized by the development of two distinct, now-buried, soil profiles. The first, soil, or early Recent, formed on Mankato deposits including late Mankato loess. The second, or late Recent, soil, formed on Recent deposits during the thermal maximum approximately 4,000 to 6,000 years ago. Neither has been identified in the vicinity of Yankton, but both probably are present in a composite soil at or close to the present ground surface.

The term "recent" was introduced by Lyell in 1833 (p. 52–53, 61) for that part of geologic time "which has elapsed since the earth was tenanted by man." It included what is now the Pleistocene epoch until Forbes separated the Pleistocene from the Recent in 1846 (p. 402–403).

LANDSLIDE DEPOSITS

Landslide deposits are defined for this report as earth materials that have moved perceptibly downward by sliding or falling as a relatively dry mass.

The landslides are divisible into three principal types. One is the soil fall, in which a block of unconsolidated material breaks away from the face of a stream-cut bank. It may settle rapidly as a unit, but most commonly shatters on impact with the channel floor. Of the three types this is the least significant in terms of size and number of individual slides. The second type of landslide is the earth slump, in which the transported material moves much less rapidly but as a unit mass, and it retains internal coherence. The third type is the combined earth slump and earth flow. In it the material moves at a speed comparable to that of the second type, with earth slump dominant near the head of the slide, and earth flow near the toe. In the earth flow facies of the landslide the material transported loses internal coherence and moves chiefly by flow. The earth slump and earth flow type of failure is probably the most significant in number of individual slides and area affected.

In the vicinity of Yankton landslide deposits consist chiefly of strata from all but the Sharon Springs member of the Pierre shale. Locally the deposit may include minor amounts of Pleistocene and Recent material that lay on the shale at the time of sliding. The slide deposits range in thickness from a minimum of 3 to 5 feet for soil falls to a maximum which may be as great as 100 feet for earth slump and earth flows; thicknesses of 10 to 50 feet are probably the most common, however. Vertical displacement of a single slide ranges from a few inches to about 25 feet, but the total displacement in a concentric series may be as great as 165 feet.

Slides are most common in eroded terrain bordering the Missouri River trench and are most numerous in areas of deep dissection and steep ravine walls. A few slides are found in the low sides of small draws cutting the upland. Despite the susceptibility to sliding, many slopes which are underlain by shale are stable. The slide areas are topographically distinctive. They are characterized either by low irregular knolls that form an undulatory surface like that in plate 11*B* or by arcuate subconcentric ridges. In blocks forming ridges the bedding and upper surfaces commonly dip back toward the surface of movement which is generally somewhat spoon shaped or occasionally semicylindrical. Landslide-deposit contacts are generally obscured by the deposit itself. The position and trend of the contact with underlying, undisturbed bedrock commonly is indicated accurately by a break in the microtopography of the slope or by a series of small, offset tension cracks. Locally a slide-deposit contact, or surface of rupture, is exposed in cross section in a stream course. These exposures show that the surface is smooth or finely striated and commonly marked by fault gouge from a few millimeters to half an inch thick. The scarp at the head of the landslide may be covered with colluvium and vegetation.

The primary cause of sliding has been the loss of support from the toe of a potential slide area; secondary causes have been an increase in pore-water pressure which decreases the shearing resistance of the material by reducing the effective intergranular pressure and the added weight of water. The loss of support is chiefly due to gullying, but in one case it was due to excavation in the bottom of a draw for construction of a small eastern dam. Mass-wasting normally does not become appreciable until a gully is 10 to 15 feet deep. The sides of the gully then begin to recede by the slumping of many blocks a few inches wide and a few feet long, producing an arcuate area of small ledgelike features commonly called cat-steps of terracettes. Where such arcuate areas form, a chain of sliding starts and spreads over an ever-widening area, affecting progressively larger blocks. Locally, initial movement of 5 to 10 feet vertically has affected a large block but there has been little or no apparent subsequent movement, either of the block or adjacent terrain. The larger slide areas commonly develop where surface runoff is concentrated along incipient draws extending downslope to a gully.

In the vicinity of Yankton the recognition of potential landslide areas is of little economic importance. Slides have, however, caused the destruction of some pasture dams built by farmers. These slides could be averted if material for the dam were obtained largely from the sides of the draws, thereby reducing the weight of potential slide areas, rather than from the bottom of the draws, thus reducing the toe support.

ALLUVIUM AND COLLUVIUM

A mixture of alluvium and colluvium underlies the floor and sideslopes of nearly every valley and draw in the Yankton area. For the purposes of this report alluvium includes not only stream-deposited material but also sediments transported by slopewash; colluvium includes those materials transported downslope primarily by the force of gravity. The alluvial part of each deposit is concentrated along the stream channel, whereas the colluvium underlies the side slopes. Generally the alluvium and colluvium consist of silt, clay, fine sand, and minor amounts of coarser sand and fine gravel. The color of the deposits ranges from black to grayish orange and is dependent on such factors as the color of the parent material and amount of humification. Its lithologic character reflects the local bedrock and Pleistocene deposits in the given valley or draw. The deposits are uncemented and locally contain small soft, irregular, calcareous concretions similar to one type found in loess. Stratification of any kind is generally not apparent in the colluvium, but in the alluvial facies cut-and-fill stratification is commonly good. Sorting, which is essentially lacking in colluvium, ranges from good to fair in the alluvium. The colluvial material is also structureless, but the alluvium locally displays poor to excellent prismatic jointing like that in loess. Thickness of the deposits is locally as great as 40 feet, but in most places is less than 15 feet; thickness is greatest in the bottoms of valleys and least on interfluves, especially in areas of Wisconsin loess.

The alluvial part of each deposit is concentrated along former and present stream channels, whereas the colluvium underlies the sideslopes.

Most slopes in the area are thinly mantled with colluvial material moving downslope. The mantle is most apparent on knolls of loess, for the crest is commonly bare of soil and the slightly humified colluvial veneer on the flanks thickens rapidly toward adjacent draws. Movement of the veneer is by creep, commonly accompanied by the formation of cat-steps. The alluvial and colluvial deposits have not been mapped where they are less than 2 feet thick or are in areas underlain by mappable landslide deposits.

The contact of the deposit with underlying materials is generally distinct and smooth. Fossils recovered include bones of modern buffalo, horse, and cow, and shells of clams.

SWALE DEPOSITS

Swale deposits consist of clay and some silt, and range in color from black near the surface through a mottled horizon to grayish green below. The material is characterized by high plasticity, very low permeability, and the absence of cementation and concretionary matter. Sorting is excellent, but recognizable stratification and structural features are poor. Deposits are commonly more than 2 feet thick, and some are known to be more than 5 feet thick. They are found in constructional depressions in the surface of the ground moraine, principally in the area underlain by Mankato till; a few are present in areas of Cary till, but none in pre-Cary till. Surfaces of deposits are level, and many of the swales contain shallow, intermittent ponds. No fossils were found, and the contact with the underlying till is distinct and smooth. The sediments accumulated in the depressions by slope wash, rill wash, soil creep, and wind deposition. Swale deposits have not been mapped where less than 2 feet in thickness or smaller than about 1 acre in area.

TERRACE ALLUVIUM

Within the Missouri River trench and its principal southern tributaries are two depositional terraces composed of alluvium. The surface of the older, higher, terrace deposit (terrace 2) ranges from 40 to 55 feet above the level of the Missouri River at low-water stage. The surface of the younger and lower, or "bottom land" terrace deposit (terrace 1) is from 15 to 25 feet above the river. The terrace deposits are separate and composed of different materials, and an exposed cross section of the contact between the two deposits shows the lower terrace is not a strath cut into the older material.

The age of the higher terrace deposit (terrace 2) is based on the absence of Mankato loess. This implies a date at least as young as deposition of the inner Mankato drift and end moraines, neither of which are mantled by this loess. As the lack may be the result of nondeposition or erosion, the implied age may be too great. It is also possible that the lowest, oldest, part of the deposit at Yankton is very late Mankato or early post-Mankato, and that the highest part is much younger. No evidence of a minimum date was found. The terrace has been correlated by Schultz, Leuninghoener, and Frankforter (1951, p. 36) with their terrace 1, which they consider of post-Mankato age. If their correlation is valid the terrace may be Recent, for they report (p. 37) a radiocarbon age of 2,147±150 years for charcoal collected from the middle of a terrace 1 deposit in northwestern Nebraska. The terrace 2 surface is approximately the same height above the Missouri River as the surface of an outwash terrace remnant in the W½ sec. 29, T. 95 N., R. 55 W., Yankton County is above the James River. This outwash terrace can be traced northward into end moraines within the inner Mankato drift border. Correlation is not necessarily valid, but if the two remnants are correlative, then the higher, or terrace 2 deposit is clearly late Mankato in age.

The terrace 2 deposit consists of three parts separated by distinct erosional contacts marked by weakly humified horizons of infantile soil profiles. The three fills are composed of grayish-orange silt and sand enclosing lenses of gravelly sand. The sorting is fair to good in some of the beds of silt but is poor in the gravelly lenses; stratification is chiefly horizontal but in part cut-and-fill. Some loesslike silt layers show prismatic jointing. The thickness of this compound deposit is more than 40 feet. The largest remaining segment of the terrace 2 deposit lies along the north wall of the trench in T. 93 N., Rs. 56 and 57 W., Yankton County. Most of the terrace has been cut away by migrating meanders of the Missouri River, but this remnant was protected by Gavins Point (White Bear Cliff), a spur composed of argillaceous limestone of the Niobrara formation. The terrace surface is nearly level and slightly uneven. Small remnants are found in various southern tributaries. Buried hearths unassociated with pottery were found in one of the two older parts of the deposit, but which part actually contained them could not be determined; no fossils were found. The contact with the younger terrace deposit is abrupt and smooth; the contact with the trench wall is not exposed.

The lower terrace deposit (terrace 1), like the higher, lacks a mantle of Mankato loess and therefore is as young as or younger than inner Mankato drift. Clearly the lower deposit is younger than the higher, against which it was laid down. A minimum date is suggested by sand dunes which rest on the bottom land terrace and which may date from the thermal maximum 4,000 to 6,000 years ago. If the above correlation of the higher, terrace 2 deposit by Schultz, Leuninghoener, and Frankforter (1951) is valid, a logical extrapolation may be the correlation of this lower terrace deposit with their terrace 0, the lower part of which they (p. 37) tentatively date as 900 to 1,000 years old.

The terrace 1 deposit consists chiefly of interbedded silt, clay, and fine to medium sand. The material ranges from grayish black to yellowish gray, and is unconsolidated. Sorting is fair, and horizontal stratification is good; some layers of silt and clay display prismatic jointing. Thickness of the fill is greater than 20 feet, and the contact with the flood plain generally is marked by a low scarp. The level terrace surface is scarred by old flood channels and ridged by former sand bars. As mapped, the deposit includes minor amounts of eolian sand.

TRIBUTARY ALLUVIUM

Tributary alluvium is correlated with terrace alluvium in the Missouri River trench. The chief differences between the two are lithologic and the lack by tributary alluvium of terrace form owing to dissection. The symbol subscripts on the geologic map indicate tentative correlations. Correlation is based largely on physical continuity and the absence of post-Mankato loess. These features imply that the tributary alluvium is of late Mankato age or younger. The tributary deposits consist of gravel, sand, silt, and clay. Their color ranges from grayish black through grayish orange to yellowish gray, and they are uncemented, without concretions, and at least 35 feet thick. Sorting is poor to fair, and the stratification, which is of various types, ranges from poor to good. Tributary alluvium underlies the nearly flat floors of the principal valleys tributary to the Missouri River and James River trenches. No fossils or contacts were observed in these deposits, for exposures are few and poor. The deposits probably accumulated during aggradation in the trench and may in part comprise backfills—sediments spilled into the lower courses of tributaries from an aggrading main stream.

ALLUVIAL FAN DEPOSITS

Alluvial fan deposits are believed to be Recent for they overlie late Mankato and Recent deposits. The deposits are composed of silt, sand, and clay, and locally contain pebbles and small cobbles. The color of the material depends largely on the color of the parent material and ranges from grayish black to yellowish gray. The deposits are uncemented, free of concretions, poorly sorted, and poorly crossbedded. No structural features, contacts, or fossils were found. The alluvial fans are found at the mouths of several small valleys tributary to the Missouri River trench and include three small, partly deltaic deposits in the James River. The deposits are slightly conical, as much as 25 feet thick, and are closely related both in material and time to alluvium and colluvium, into which they grade within the valleys.

EOLIAN SAND

Eolian sand is fine to medium grained, very pale orange, and composed chiefly of quartz and feldspar. The grains are of medium to high sphericity and are subangular to subrounded. The sand is loose, with concretionary matter, poorly crossbedded, and excellently sorted. No fossils or structural features were found, and no contacts are exposed. The maximum thickness is about 18 feet. The sand is drifted into now-inactive dunes that locally rest on the riverward edge of the bottom land terrace or in the Missouri River trench mark channel scars. A humified horizon beneath the surface of the dunes is believed to indicate a pause between periods of constructional activity. The dunes have not been mapped where the thickness is less than 2 feet.

Because the dunes rest on the bottom land terrace they are of Recent age, but the actual date of formation is not known. A soil profile buried 12 inches or more beneath the surface of the dunes consists of a brownish-black A horizon about 8 inches thick overlying loose sand that is slightly oxidized in the upper few feet. Although this soil may date from the warm, dry thermal maximum 4,000 to 6,000 years ago, it is quite possible that the dunes may have accumulated during that time, and that the soil is younger. If the possible correlation of the bottom land terrace with terrace 0 of Schultz, Leuninghoener, and Frankforter (1951) is correct, and if their tentative age of 900 to 1,000 years for terrace 0 is valid, then the dunes are very recent and the soil is modern.

FLOOD PLAIN ALLUVIUM

Flood plain alluvium is composed of fine sand and silt with a little clay and medium sand. Its color ranges from grayish black to yellowish gray. The material is uncemented and free of concretions. Crossbedding is good to poor, and sorting is generally good. Some prismatic jointing was observed, but no contacts or fossils. The thickness of the deposit is at least 10 feet, but the position of the base, below which the alluvium is of Pleistocene age, is not known. Flood plain alluvium is present along the Missouri River throughout the mapped area and borders the James River north of about sec. 5, T. 94 N., R. 55 W., Yankton County. The surface of the deposit is characterized by many low scarps and rill marks; exposures are largely restricted to the river channels. For mapping purposes the area subject to inundation during normal spring flood was considered to be part of the flood plain. It is delimited by a low scarp and the prevalence of willow brush and timber from the cleared bottom land.

ENGINEERING CHARACTERISTICS

Recent deposits have engineering characteristics that permit their division into two groups: landslides and alluvial and colluvial deposits.

Landslide deposits have almost the same characteristics as do the formations or deposits from which they were derived. Characteristics acquired through sliding are chiefly low slope-stability, landslide topography, increased permeability, and reduced drainage integration. Problems that result from sliding can be prevented, reduced, or eliminated by (1) locating construction in areas not underlain by the Pierre shale, (2) locating construction in areas away from existing landslides, (3) cutting slopes as low as possible, for the gentler the slope the more stable the cut; in general, slopes of 45° or greater are subject to sliding, but slopes of 30° are moderately stable, and slopes of 15° are probably stable, (4) preventing penetration of surface water into the ground in the vicinity of a cut or slide, (5) reducing water content of the soil by horizontal and vertical drains, and (6) reducing downcutting by streams in small valleys and draws. Astonishingly enough, a common error is the attempt to fill in the top of a slide. Because this adds weight to an already unstable mass, additional sliding generally occurs. Another common mistake is the clearing away of the displaced material at the toe of a slide; this removes support and further sliding commonly results.

Alluvial and colluvial deposits present no special problems. The materials are easily excavated either by hand or power equipment. Owing to the sand content most deposits should have good trafficability, although fine-grained parts of the alluvium in the bottom land terrace may cause some difficulty when wet. Slope stability in the finer grained materials is good; terrace deposits in the Missouri River trench stand well in nearly vertical faces, as do most tributary alluvium and undifferentiated alluvium and colluvium. The sandier materials are less stable at steeper angles, and loose dune sand is stable only at the angle of repose, about 30°. The deposits have smooth to moderately smooth surfaces. All the deposits are readily eroded, and frost action to a depth of 6 to 8 feet generally ranges from moderate to high.

Typical samples of four Recent deposits were collected by trenching and submitted to the soils laboratory of the South Dakota State Highway Commission for analysis. The report by E. B. McDonald (written communication, Nov. 27, 1950) is quoted below.

Soil analysis data of certain Recent deposits, Yankton County

Test	Swale deposit	Alluvium and colluvium	Terrace alluvium	
			Qta2	Qta1
Location (see notes)	A	B	C	D
Depth of sample below ground surface	0–2½ft	0–6 ft	15–35 ft	1–10 ft
Textural classification [1]	Clay loam	Sandy loam	Clay loam	Clay
Classification (Allen) HRB [2]	A–6(11)	A–6(3)	A–7–6(12)	A–7–6(20)
Specific gravity [3]	2.61	2.69	2.65	2.67
Pounds per cubic foot, dry loose	64.8	67.5	70.5	67.8
	Percent	*Percent*	*Percent*	*Percent*
Shrinkage limit [3]	16.0	19.3	15.3	12.5
Shrinkage ratio [3]	1.84	1.77	1.88	2.0
Volume change [3]	5.1	6.6	11.5	22.8
Passing ⅜ in. sieve [4]	100.0	99.3	100.0	100.0
Passing no. 4 sieve [4]	100.0	98.7	100.0	100.0
Passing no. 10 sieve [4]	99.3	93.7	99.7	100.0
Passing no. 40 sieve [4]	95.7	75.1	98.9	96.6
Passing no. 200 sieve [4]	81.2	46.1	94.9	91.4
Sand content [5]	36.6	62.2	22.1	18.2
Silt content [5]	41.7	20.6	47.9	30.0
Clay content [5]	21.4	10.9	29.7	51.8
Liquid limit [6]	39.9	33.4	41.5	66.2
Plasticity index [7]	17.0	12.3	19.9	39.6
Field moisture equivalent [8]	18.7	23.0	21.4	23.9
Centrifuge moisture equivalent [9]	21.7	14.6	22.7	36.6

[1–9] For references to test methods see soil analysis report from this laboratory for the Ogallala formation, p. 45.
A. SE cor. SW¼ sec. 14, T. 94 N., R. 57 W.
B. Center, SE¼NW¼ sec. 5, T. 94 N., R. 55 W.
C. Center SW¼SW¼ sec. 18, T. 93 N., R. 56 W.
D. SE cor. SW¼ sec. 18, T. 93 N., R. 56 W.

STRUCTURAL GEOLOGY

The principal structural features of the bedrock strata include joints, faults of small displacement, and minor warps, but the most distinctive characteristic is the nearly horizontal attitude of the Cretaceous rocks. A distinct but small westerly component of dip is apparent in the Niobrara formation in that wall of the Missouri River trench which forms the southern flank of Yankton Ridge. Altitudes of the several bedrock contacts indicate the dip is a little north of west at a rate of about 4 feet per mile. Data of the contact between the Niobrara formation and Pierre shale and observations within the spillway excavation for the Gavins Point Dam suggest that the dip is locally interrupted by reversals that may have as much as 35 feet relief.

The cause of the structural features is not clear. Because the fault displacements are small, it is doubtful that either local or regional forces of great magnitude, were exerted. Local forces seem the less likely. Darton (1909, pl. 10) concluded that the pre-Dakota surface slopes southeast in this vicinity, but the orientation of faults and joints does not indicate a direct relation to the buried surface. Regional forces offer more possibility, for Schulte (see page 31) plotted axes of minor folds that trend about N. 25° E. across Knox County, and it is possible that the faults and joints resulted from forces which caused these folds. This is suggested by the fact that the principal set of joints and most normal faults are roughly perpendicular to Schulte's reported trend, and the secondary joint set and the single thrust fault are almost parallel to it. As yet, however, available information on faults and joints is of too local a nature to be conclusive.

JOINTS

Joints are characteristics of all pre-Pleistocene rocks. Shaly strata at or near the surface are commonly broken to a depth of 30 to 40 feet by joints that range from a hairline to a quarter of an inch in width. The larger may have been caused chiefly by structural stresses and are filled with powdery calcium carbonate or gypsum rosettes as much as 10 inches across. The hairline joints probably are a result of weathering, for in long-exposed outcrops they are so numerous as to cause the shale to appear shattered. In marly strata the joints are somewhat less numerous and lack secondary mineralization. Below the surface some open joints at places contain coarse, yellowish, crystalline calcite.

Joints in the exposed part of the Smoky Hill chalk member of the Niobrara formation are commonly about half an inch wide and are filled with gypsum like that marking the bedding planes. Locally these joints are so numerous and complex that they resemble, together with the bedding-plane gypsum layers, a coarse "boxwork" illustrated in plate 5*B*. Cause of this jointing is not known; it may be structural stresses, weathering, or both.

The initial excavation for the Gavins Point Dam intake channel and powerhouse exposed about 25 feet of the lower part of the Smoky Hill chalk member through a horizontal distance of 870 feet. Joints observed in this excavation range from a hairline to as much as 8 inches in width; this width is in part a result of spalling. On both sides of open joints the argillaceous limestone is weathered to a depth as great as 12 inches, and the rock is commonly coated with as much as an eighth of an inch of calcium carbonate apparently deposited by ground water flowing through the passage. The joints cut one to three beds of limestone, rarely more, and generally begin and end at bedding planes marked by gypsum layers. Most joints are straight, but several are curved and a few are angular. Typical joints are illustrated in plate 12.

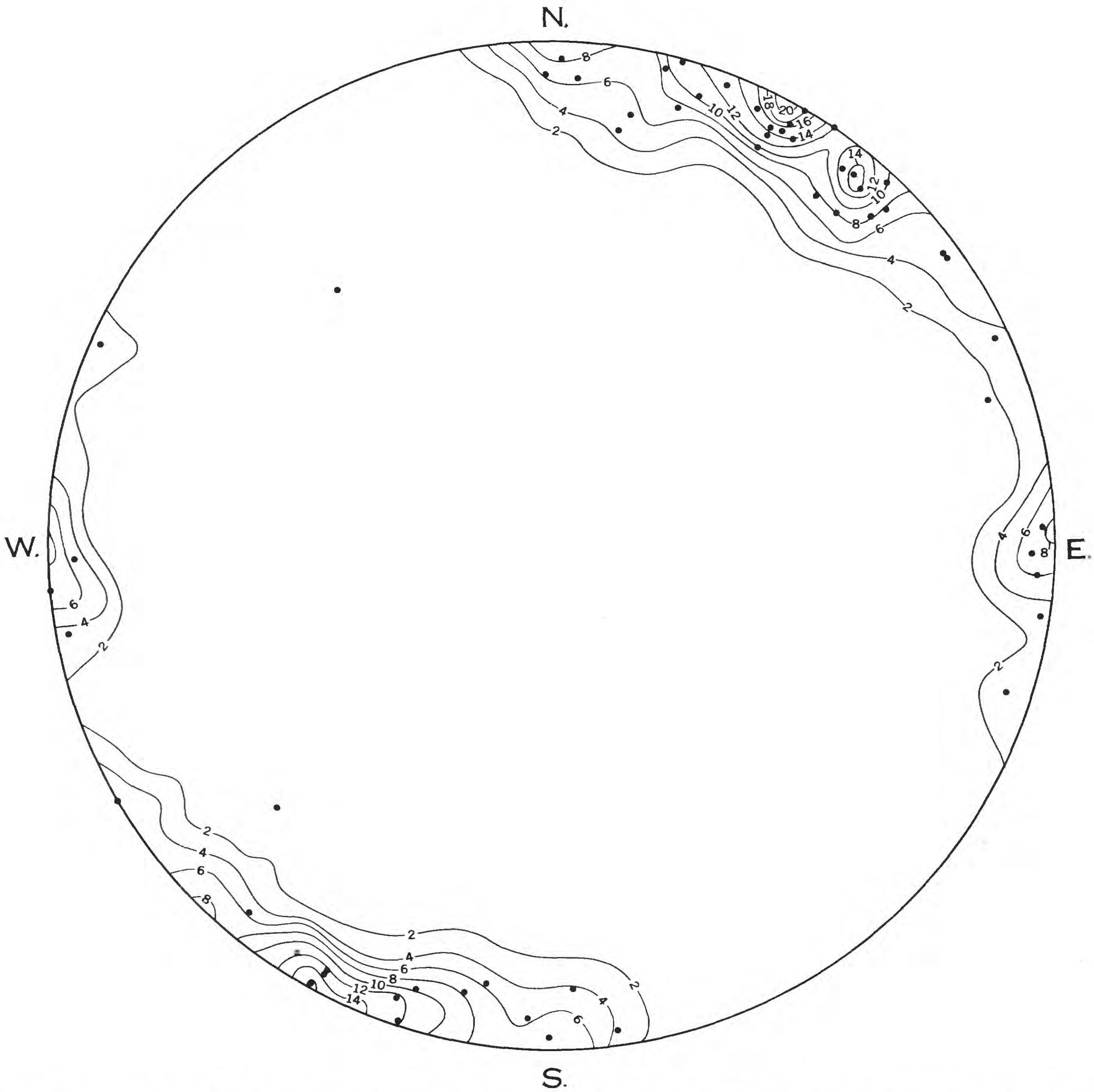


FIGURE 11.—Contoured polar diagram of 57 joints exposed in the northwest wall of the intake channel and powerhouse excavation, Gavins Point Dam. Poles plotted on upper hemisphere; contour interval in percent. Data by H. A. Jack, project geologist, Corps of Engineers.

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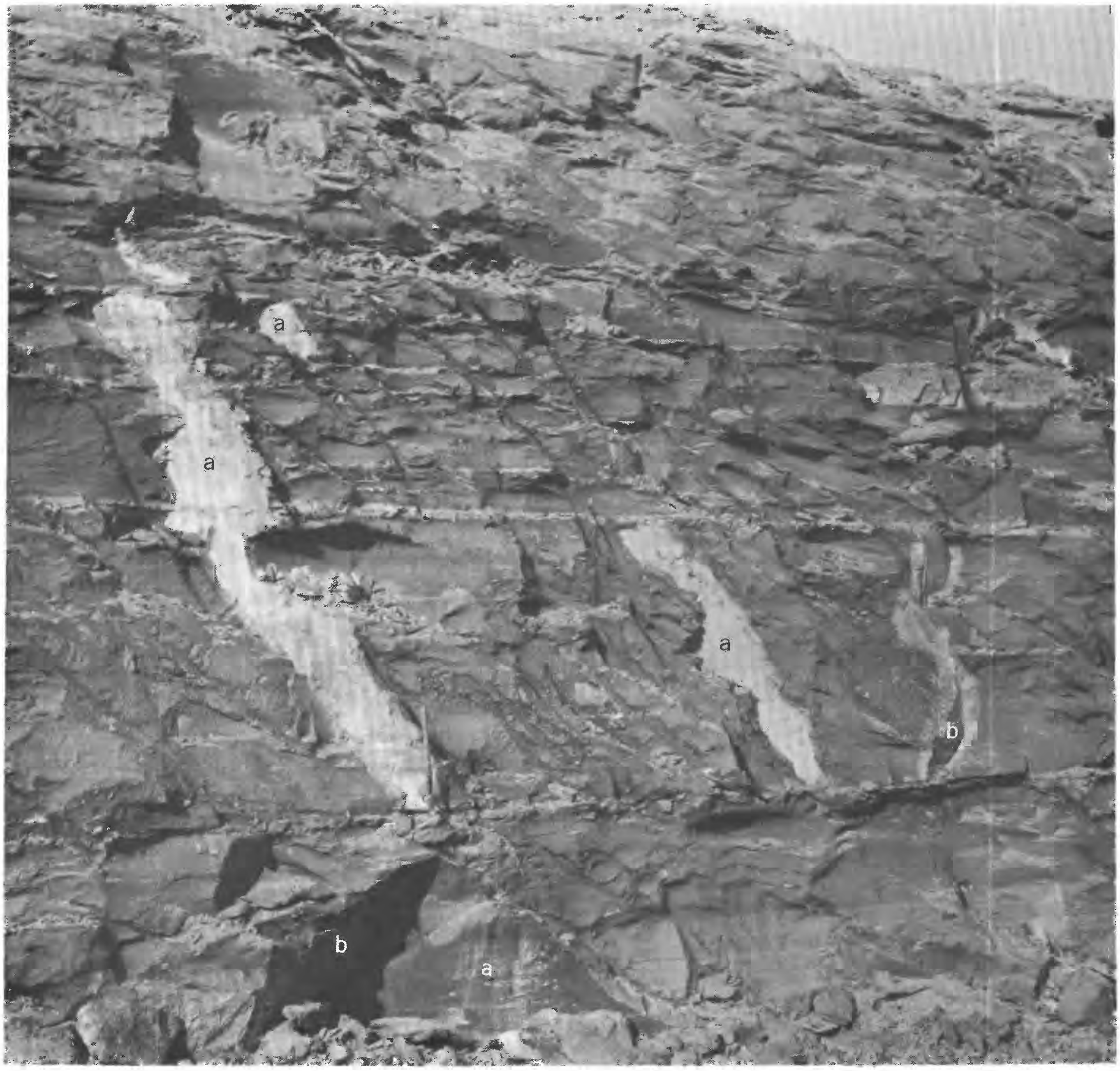

Typical joints representing two sets in the Smoky Hill chalk member, Niobrara formation, exposed in the initial intake channel and powerhouse excavation, Gavins Point Dam. Joints of the principal set are marked a, those of the secondary set b.

Harold A. Jack, project geologist, Corps of Engineers, recorded the dip and strike of 57 joints. I plotted these data in figure 11, which shows the distribution of poles perpendicular to each joint plane. The diagram indicates that the joints constitute two sets, a principal set that strikes N. 62° W., and a secondary set that strikes north. Of these joints 79 percent have dips steeper than 80°, with little uniformity in direction of dip. The joints clearly postdate the bedding-plane gypsum layers, for the layers continue uninterrupted across the top of open joints and are thought to have formed concurrently with most faults because the strikes are similar.

FAULTS

Little evidence of faulting was found, and most of it was observed in the initial intake channel and powerhouse excavation for the Gavins Point Dam. Nine distinct faults are exposed in the northwest wall of this cut; others, if present, are of insignificant displacement. Of the nine, seven are normal faults, one is a thrust fault, and one is a strike-slip fault. Displacement along the normal and thrust faults ranges from about 4 to 22 inches vertically, and from 9 to 43 inches horizontally; the amount of displacement along the strike-slip fault cannot be determined. The surfaces of movement are plane or slightly curved and are commonly marked by oxidized, structureless, argillaceous limestone (gouge) from a few inches to as much as 3 feet across. Little or no drag is present. The strike-slip fault is very similar in both bearing and dip to the joints and is distinguished from them by horizontally slickensided rock surfaces. Seven of the nine faults including the thrust and the strike-slip ruptures have surfaces of movement that permit determination of dip and strike. Of the five normal faults, four have an average strike of N. 40° W., and dip 51° to 60°; there is no preference for direction of dip; the fifth normal fault strikes almost west, and dips 81° S. The single thrust fault strikes N. 5° E., and dips 29° NW., and the strike-slip fault strikes N. 70° W., and dips 86° SW. These faults, like the joints, postdate the bedding-plane gypsum layers, and owing to a suggested similarity of strike and dip of the strike-slip fault, may have formed concurrently with the joints.

A feature believed to be a normal fault in the Smoky Hill chalk member of the Niobrara formation is exposed in a road cut in the SW cor. sec. 9, T. 33 N., R. 1 E., Cedar County. The fault strikes N. 25° W., dips 42° SW., and is marked by a curved surface of movement which feathers out at the upper end. Vertical displacement is about 8 inches, and horizontal displacement about 7 inches; drag has deformed the strata on both sides of the fault. The trace is covered by alluvium and loess. It is possible that the surface of movement may be that of a landslide, but owing to the apparent structural strength of the Niobrara formation, landsliding as a cause of this feature seems unlikely.

Faults in the Pierre shale were exposed at only one locality, a cut bank in the NE¼NE¼ sec. 11, T. 93 N., R. 57 W., Yankton County. The exposure consists of the shaly unit of the Gregory member which is cut by four indistinct, normal faults within a horizontal distance of 100 feet. Two of the faults have horizontal displacements of 7.6 and 2.8 feet and vertical displacements of 6.8 and 0.6 feet, respectively. The fault with the greater displacements strikes N. 50° E., and dips 65°NW.; the surface of movement is marked by a quarter of an inch of pulverized shale. All traces are mantled by colluvium. The slip surfaces are inferred to indicate faults because the direction of dip is away from the Missouri River, approximately 2 miles south.

WARPS

The altitude of the contact between the Niobrara formation and Pierre shale along the Missouri River trench differs locally by as much as 35 feet. These differences may be structural in origin, owing to gentle warping or folding, or they may have been caused by local variations in the accumulation or erosion of sediment. A structural origin is favored by Schulte's (written communication, 1952) conclusion that folds bearing about N. 25° E., are present in Knox County. It is also favored by a shallow structural downwarp, having an amplitude of at least 3 feet, which is exposed in the Smoky Hill chalk member of the Niobrara formation in the Gavins Point Dam excavation for the intake channel and powerhouse.

ENGINEERING ASPECTS

Joints and faults in the bedrock strata are significant to the engineer in a variety of ways, but because the rocks are soft and weak, it may be difficult to ascertain their presence or size, even in drill cores. Open joints are readily recognized by water loss during drilling, but because the rocks are soft, closed joints or faults commonly are indicated only as breaks in core continuity. A break may be bordered by oxidized rock, but as this material is readily ground away by interface abrasion within a drillstem, the amount of oxidized material recovered is no indication of the amount present.

Open joints constitute a potential cause of leakage below a dam or from a reservoir. As the joints dip steeply, and are irregularly spaced, holes for grouting purposes must be drilled at an angle, and the lower the angle the more joints a given hole may intersect. Owing to the small vertical extent of the joints, a drilling pattern with holes spaced 10 feet apart along lines 300 feet apart would probably be necessary for intersection of all joints.

The surfaces of open joints may be extensively weathered. Weathered rock bounding joints may be saturated, and according to E. M. Swift, Corps of Engineers (oral communication, 1952), moisture content is as high as 56 percent. Owing to the clay content, weathered, saturated material in jointed strata caused traffic difficulties for heavy wheeled equipment excavating for the Gavins Point Dam powerhouse and spillway.

During excavation, projecting corners of rock may be found to be separated from the main mass by joints or faults. These loose corners constitute a danger to personnel and equipment and can be removed or pinned. As the joints and faults are loci of weathering, and owing to the structureless nature, higher water content, and great plasticity of the weathered material, areas characterized by numerous joints and faults may cause a trafficability problem during excavation. Joints and faults are also a problem because they constitute planes of weakness and may cause slumping if the pit is unfavorably oriented in relation to them. The thoroughly fractured nature of weathered shale to depths of 30 feet or more speeds the rate of excavation, but it may increase the amount of support necessary to prevent collapse.

GEOMORPHIC DEVELOPMENT

Modern landforms in the vicinity of Yankton are the result chiefly of geologic processes which have been active in post-Pliocene time. In general, Pleistocene and Recent time has been characterized by deposition during glacial stages and erosion during nonglacial intervals. Evidence pertaining to development before the Cary substage has largely been destroyed by erosion or mantled by drift and loess of late Wisconsin age. In contrast, changes during late Wisconsin and Recent time are well recorded by the same deposits that cover the record of older events.

Geomorphic development of the area is primarily a series of drainage changes and began with establishment of an initial regional drainage pattern. Each of several glaciers that invaded the Yankton area wrought profound changes in the existing drainage by temporarily blocking valleys with ice and filling them with drift. Rivers were thus forced to abandon their old courses and to cut new channels beyond the ice margin. The old drift-filled courses were not always reoccupied by the former streams on recession of the ice and are now represented by broad, shallow valleys.

In addition to the large ancient valleys there are several smaller valleys, most of which contain quantities of sand and gravel. These smaller valleys were melt water channels, and although most simply led away from the ice margin, a few bisect interfluves and originated as temporary diversion routes. The preglacial channels and drainage diversion routes are shown in plate 10.

The most significant event in the history of the contemporary landforms probably was the origin of the Missouri River owing to glacial diversion during the Illinoian glacial stage. Another diversion is believed to have taken place during the Kansan glacial stage and others are known to have occurred during the Iowan and Cary substages. Thus the geomorphic development of the region may be divided into four principal periods which involve preglacial, pre-Illinoian, Illinoian, and post-Illinoian time.

PREGLACIAL TIME

Formation of the modern landscape began with dissection of the Ogallala formation, which took place during a long period of erosion that extended from late Pliocene time into the Pleistocene epoch. Downcutting probably was concentrated along an ancient, preglacial Niobrara River which became established at the time deposition of the Ogallala formation ceased. The ancient Niobrara was then master stream of the area about Yankton, and together with its tributaries composed a preglacial drainage pattern.

Because of Pleistocene erosion and a thick mantle of late Pleistocene sediments, very little is known about either the drainage pattern or principal landforms of preglacial time. The chief feature was undoubtedly the valley of the preglacial Niobrara River, but the nature of tributaries and interfluves is unknown. The nature of the Coteau du Missouri is not known either, but the preglacial Niobrara River probably crossed the escarpment through a gap in the vicinity of Springfield. Neither is the course of the river eastward known: it may have been northeast through Tabor and Utica, or roughly coincident with the present course of the Missouri River, or followed the foot of what is now the Coteau escarpment in Nebraska. At that time Yankton Ridge probably did not exist; very likely it was at or below the level of the preglacial Niobrara River. The maximum altitude in the area was at least 1,625 feet, approximately the highest altitude of the Ogallala formation now exposed in the vicinity of the gap. The minimum altitude is not known but may have been 1,400 to 1,500 feet. It could not have been less than 1,140 feet, the altitude of the bedrock floor of a pre-Illinoian valley at Utica.

PRE-ILLINOIAN TIME

The presence of Nebraskan and Kansan tills in eastern Nebraska has been recognized, and the positions of the drift borders have been established in central-eastern Nebraska (E. C. Reed, oral communication, 1950). The position and trend of the Nebraskan drift border (see Flint, 1955, pl. 3) suggests that the Nebraskan glacier failed to enter the Yankton area (see also footnote, page 71). Although the glacier must have disrupted the preglacial drainage pattern, no evidence of a diversion channel of Nebraskan age has been recognized in the vicinity of Yankton. Neither is there any evidence as to the course of the Niobrara River during the Aftonian interglacial age.

The position of the Kansan drift border indicates that the Kansan glacier did cover the Yankton area, but reconnaissance yielded no evidence of a diversion channel of unmistakable Kansan age. A diversion route of early Wisconsin age marks the approximate position of the Kansan drift border, and it well may have been cut initially by melt water and diverted western streams during the Kansan maximum.

Deposits of gravelly sand correlated with the Grand Island formation of late Kansan age rest on the Mobridge member of the Pierre shale along the crest of Yankton Ridge. Altitudes of the contact range from approximately 1,475 feet in the NW¼ sec. 23, T. 93 N., R. 58 W., Bon Homme County, to about 1,560 feet a mile north. This gravelly sand probably represents alluvium deposited by the ancient Niobrara River and indicates that in late Kansan time the course of the river at least temporarily nearly coincided with the present course of the Missouri River. Exposures of a lithologically similar gravel are found south of the Missouri River at about the same altitude, but although they are tentatively correlated with the Grand Island formation for mapping purposes, their age is unknown and they may or may not represent the southern margin of the late Kansan course of the Niobrara River.

An alternate, less likely possibility is that the gravel of the Grand Island formation was deposited by the ancient Niobrara River during late Kansan time in a diversion channel roughly marginal to the Kansan glacier. However, the necessary proximity of the glacier implies that the Grand Island formation should contain outwash. This it does not, unless gravel inferred to be Illinoian outwash should prove to be Kansan.

During Yarmouth time, the ancient Niobrara River occupied a course which extended north and east from Springfield through Tabor and Utica, thence southeast to a course coincident with the present course of the Missouri River. The river may have achieved this position by either of two means. First, if the Grand Island formation was deposited as an alluvial fill in a late Kansan valley of the ancient Niobrara River, the channel may have occupied such a position on the river flood plain at the beginning of Yarmouth time and become entrenched in that position. Second, if the gravel of the Grand Island was deposited in a diversion channel rather than a river valley, recession of the ice may have permitted the diverted water to return to an earlier, lower course, now represented by the valley through Tabor and Utica. In either case, by the close of Yarmouth time the ancient Niobrara River had cut a strath to an altitude of 1,140 feet, and relief in the Yankton area must have been as great or greater than at any time since.

The deposits south of the Missouri River tentatively correlated with the Grand Island formation may be gravel to which Todd (1912, p. 464–466, and 1899, p. 60–61) referred. He described a diversion route that he believed was adopted during either the Kansan or Iowan glaciation, probably the former, when the glacier had receded to approximately the position of the Missouri River trench. Todd called it the Coleridge Channel and traced it by scattered gravel remnants from the vicinity of Niobrara east and south past Crofton, Fordyce, and Hartington, thence southeast past Coleridge into Logan Creek and the Elkhorn River. Although distribution of the exposures of remnants suggests a channel as far east as Crofton, I have been unsuccessful in verifying the existence of Todd's supposed channel beyond that locality.

EVIDENCE OF A PRE-ILLINOIAN DRAINAGE PATTERN

The drainage pattern which existed in the vicinity of Yankton at the close of Yarmouth time differed somewhat from the present pattern. These differences are indicated by four geomorphic anomalies summarized below.

1. From Yankton upstream the Missouri River trench is 1½ to 2 miles wide from wall to wall; from Yankton downstream the floor widens to about 10 miles. The wide part below Yankton represents the former course of the combined ancient Niobrara and ancient James Rivers.

2. Parts of the upland surface slope toward the Missouri River trench, but at three localities the surface slopes away. Because there is no known lithologic or structural control that would cause such reverse slopes, they are thought to be related to an earlier drainage pattern. The three localities are: the north rim of the trench opposite the town of Niobrara, the northern flank of Yankton Ridge, and the south flank of the low, narrow bedrock ridge along the southern edge of St. Helena terrace and Crofton channel. Drainage in these localities reaches the Missouri River indirectly through secondary streams that empty into the Missouri in the Yankton area or nearby. This suggests that the former drainage pattern was not radically different from the present pattern in the vicinity of Yankton.

3. Three large valleys, now largely filled with Pleistocene deposits (chiefly drift), lie north of the Missouri River; two of the three lack through-flowing streams. The three filled valleys are the ancient Niobrara River valley, the ancient Ponca River valley, and the ancient James River valley; they are named for streams that formerly occupied them or now do. These valleys are described below and are indicated in plate 10.

THE ANCIENT NIOBRARA RIVER VALLEY

A former course of the Niobrara River through the central part of the Yankton area is now marked by a broad, conspicuous lowland flanked by Yankton Ridge on the south and by James Ridge and deposits of Mankato drift on the north. The upstream end is marked by the wall of the Missouri River trench just west of the Hutterite Colony. From the upstream end the lowland extends north and east through Tabor and Utica, then southeastward to a junction with the Missouri River trench at the mouth of the James River trench. The length of the lowland is about 24 miles, and the altitude of the surface is about 1,370 feet.

A cross section exposed in the wall of the Missouri River trench at the western end of the ancient valley segment shows both the profile of the valley sides and the nature of the fill. The valley sides are smooth and gently sloping and are represented by the contact of the Niobrara formation and the overlying drift. This contact dips below the bottom land terrace just east of the Hutterite Colony and reappears in the E½ sec. 16, T. 93 N., R. 59 W., Bon Homme County. Thus the width of the ancient valley at the present level of the Missouri River is about 5 miles, or more than twice the average width of the Missouri River trench between the mouth of the Niobrara River and the mouth of the James River. Well logs indicate that the ancient valley is filled with as much as 200 to 225 feet of glacial drift, and that the bedrock floor at Utica is at an altitude of about 1,140 feet. Along much of the lowland's length the ground surface is underlain by till, but the well logs indicate that sand and gravel are common and may form the basal part of the fill. Illinoian(?) till and Mankato loess are the chief components of the fill at the western end of the ancient valley and are well exposed in the north wall of the Missouri River trench from sec. 18, T. 93 N., R. 58 W. to sec. 14, T. 95 N., R. 59 W., Bon Homme County.

The ancient Niobrara valley segment is a former continuation of the Niobrara River valley in Nebraska. The two are colinear and are separeted by an intervening segment which extends from the mouth of the Niobrara River to the exposed ancient-channel profile in the north wall of the Missouri River trench. This intervening segment is about 14 miles long and is now occupied by the Missouri River. Downstream from the mouth of the James River trench the present trench of the Missouri River apparently coincides with the preglacial continuation of the ancient Niobrara valley segment. This reconstruction is the same as that of Todd (1912, p. 466–467) and Flint (1949b, p. 64, or see 1955, pl. 7, p. 151–152).

THE ANCIENT PONCA CREEK VALLEY

Unlike the ancient Niobrara valley, the ancient valley of Ponca Creek is represented on the ground surface by a lowland that is relatively indistinct because it is so broad and shallow. The lowland is about 14 miles long and extends in an arc from the northeast wall of the Missouri River trench in sec. 31, T. 93 N., R. 61 W., Bon Homme County, northeast to sec. 23, T. 93 N., R. 61 W., Bon Homme County, then east to Emanuel Creek, and southeast along Emanuel Creek to the Missouri River trench. The altitude of the highest part of this lowland is 1,450 feet, about 100 feet lower than terrain along the north edge of the Missouri River trench. The segment is now filled with sand and gravel of western origin and is mantled by till.

The ancient Ponca valley is a continuation of the present Ponca Creek valley in Knox County. The two are almost continuous and are interrupted only by the width of the Missouri River trench. This reconstruction is the same as that of Todd (1912, p. 467–468) and of Flint (1949b, p. 64).

THE ANCIENT JAMES RIVER VALLEY

The old valley of the James River is represented by a broad, distinct topographic depression between James Ridge and Turkey Ridge. Between those ridges the surface is at an altitude of about 1,300 feet. The southern end of the ancient valley lies between Turkey Ridge and Yankton Ridge, and the valley extends north-northwest beyond the limits of the Yankton area. The altitude of the bedrock floor is not known, but bedrock was not found in water wells drilled as deep as 80 feet (approximately 1,090 feet altitude) below the trench floor (Richard Machacek, well driller, 1950, oral communication) near the mouth of Beaver Creek. Probably the altitude of the bedrock floor of the ancient James valley is about the same as that of the ancient Niobrara valley, for the ancient James River was a tributary of the ancient Niobrara. This reconstruction is the same as that of Flint, (1949b, p. 64 or see 1955, p. 154–155). It should be noted that Flint's reconstruction indicated that only the lower course of the present James River follows the ancient James valley; the middle and upper courses of the river follow other ancient valleys. Glacial drift filling the ancient James valley is well exposed in the walls of the present James River trench. The material consists of till and minor amounts of sand and gravel, apparently all of late Wisconsin date.

Turkey Ridge and James Ridge, which rise well above the general level of the James River lowland, originated as interfluves between rivers of the ancient drainage system.

ILLINOIAN TIME

During the Illinoian glacial stage the drainage system was disrupted again. This disruption resulted in formation of the Missouri River and its establishment as the master stream of a new drainage pattern. The origin and history of this river are necessary to the understanding of the development of other geomorphic features in the Yankton area.

THE MISSOURI RIVER

The Missouri River has been a subject of interest to geologists for more than 80 years, chiefly because of three anomalous features: (1) the tributary pattern is asymmetric: almost all major tributaries enter from the west; (2) the cross profile of the steep-walled Missouri River trench is more youthful than the cross profiles of the major tributaries entering from the west; and (3) in contrast to the western tributaries which flow down the dip of the regional slope, the Missouri River follows the strike of this slope.

These anomalies, together with the distribution of glacial drift in North and South Dakota, led G. K. Warren (1869, p. 311) to conclude that the present course of the Missouri River was due to the glacial rearrangement of an earlier drainage pattern. Since Warren's statement, no one but A. G. Leonard (1916) has seriously questioned the glacial origin of the trench. Subsequent work by Todd, Flint, C. R. Warren, Crandell, and Simpson has substantiated the earlier conclusion of G. K. Warren.

In the vicinity of Yankton two of the three anomalies are present:

1. The drainage pattern of the Missouri River is asymmetrical. The nearest large tributaries entering the Missouri River from the south are the Niobrara River and Ponca Creek which join the Missouri well upstream from the Yankton area. The courses of these rivers form acute angles with the course of the master stream. On the north, the James River is the largest tributary, and is almost perpendicular to the Missouri.

2. The cross profile of the Missouri River trench is more youthful than the cross profile of the Niobrara River valley, and, to a lesser degree, than that of the Ponca Creek valley. The Missouri River trench profile is similar to the trench profile of the James River.

In the Yankton area the Missouri River does not anomalously follow the strike of the regional surface as it does upstream. Between Springfield and Santee the river passes through a gap in the

Coteau du Missouri and flows eastward in the direction of the regional slope.

PROCESS OF DIVERSION

A process by which the diversion and the resulting formation of the Missouri River may well have occurred has been described by Flint (1949b, p. 69). Although it is based chiefly on evidence found upstream from the Yankton area, it applies equally well in the vicinity of Yankton. The process is summarized below.

A lobe of a Pleistocene glacier advanced into eastern South Dakota, blocking the valleys of eastward-flowing streams as far west as the site of the present Missouri River. Drainage from the west and glacial melt water were ponded in front of the ice, and the level of each pond rose until it reached the altitude of the lowest point along the interfluve between that pond and an adjacent drainage system. The pond then began to drain through that outlet, rapidly cutting a channel into the weak bedrock. In some places the lowest escape route was along the ice margin, in others it was beyond the ice margin. The steepest component of slope between the land surface and the ice front was southeastward, and therefore the streams flowed in that direction. By the time the glacier retreated to expose the ancient valleys, now partly filled with drift, the diversion routes had become so entrenched that the rivers could not reoccupy their former valleys. Thus the Missouri River beheaded the lower courses of these streams and occupied connecting segments cut during the diversion.

DATE OF DIVERSION

The diversion of the ancient Niobrara River from its course between Springfield and Yankton which resulted in the origin of a comparable segment of the Missouri River is inferred to have taken place at about the maximum of Illinoian glaciation. The basis of inference is outlined below.

1. During Yarmouth time the master stream of the area was the ancient Niobrara River which flowed in a valley that extended north and east through Tabor and Utica. The age of this valley is inferred as follows: (a) The valley is post-late Kansan in age, for its bedrock floor is lower than the lowest part of the Grand Island formation and the deposits which fill it are not known to contain remnants of that formation. (b) The valley also is pre-Illinoian in age, for the upstream end contains till inferred from its lithologic character to be of Illinoian age, but stratigraphic proof that the till is not of Wisconsin age is lacking.

2. Drainage is inferred to have occupied a position coincident with the present Missouri River by the time the Illinoian glacier attained its maximum because: (a) Illinoian till is exposed within the same valley profile that contains the Grand Island formation; this implies that the Illinoian glacier crossed and therefore blocked the ancient Niobrara River valley segment which extended through Tabor and Utica. (b) The Illinoian glacier surmounted what is now Yankton Ridge (with a bedrock crest at about 1,525 feet altitude) and entered the diversion channel of late Kansan age which coincided with the present Missouri River. (c) No surface evidence was found which indicates that the glacier was able to advance more than a short distance onto the primary interfluve (the upland which now lies south of the Missouri River trench) south of that valley or to reach the foot of the Coteau du Missouri escarpment (see footnote 13, page 71.) (d) Southwest of the escarpment the lowest altitude of the interfluve was the floor of a cross-interfluve diversion channel at an altitude of more than 1,600 feet; this channel is believed to have been occupied temporarily during the Kansan glacial stage. No evidence was found to indicate that this channel was occupied during the Illinoian glacial stage. (e) Regional drainage from the north and west is therefore believed to have escaped across the coteau through the partly ice-blocked gap of the ancient Niobrara River, then to have flowed marginally to the Illinoian glacier eastward until it was able to re-enter the ancient valley in the vicinity of Yankton. (f) No evidence was found to indicate that the temporarily ice-blocked, till-plugged segment of the ancient valley between Springfield and Yankton ever served again as a principal drainage course.

In central South Dakota C. R. Warren (1952) and Crandell (1953, p. 588) independently discovered evidence near Chamberlain and Pierre, respectively, which indicated diversion and origin of the Missouri River took place during the Illinoian glacial stage. W. E. Benson (written communication, 1952) found similar evidence in southern North Dakota and concluded that the Missouri River was formed there at about the same time; he did not, however, consider the evidence in North Dakota so conclusive as that of Warren and Crandell.

ENTRENCHMENT

When the Illinoian glacier forced drainage from the north and west into a position marginal to the ice front, much of the load carried by the water would have settled out in the quiet of ice-dammed lakes occupying the blocked valleys. Water spilling over from the lakes would not be fully loaded and would thus have ability to cut. In this way a stream of water escaping past the toe of the Illinoian glacier from a lake in the glacially unoccupied part of the ancient Niobrara River valley would have been able to entrench itself.

The time at which the Missouri River cut its present bedrock floor is not known. Because interglacial intervals are characterized by dissection, it is possible that much if not all of the entrenchment took place during Sangamon time; but there is no evidence: dissection to the minimum altitude may have occurred in Wisconsin time.

By the time the Illinoian glacier retreated from the blocked segment of the ancient Niobrara River valley leaving it filled with drift, entrenchment of the Missouri River had progressed sufficiently so that the diverted drainage was unable to return to its former course. The actual amount of this entrenchment is not known, but an analogy with historic records is interesting. The flood of 1881, caused by an ice jam, raised the river stage to about 26 feet above the normal low-water stage. Despite the height of this rise, the river did not spill over the wall of its trench into the till-plugged segment of the ancient Niobrara River valley, the lowest point in the valley wall between the mouth of the modern Niobrara River and Yankton. This suggests that the new Missouri River may have entrenched itself several feet below the surface of the ancient segment preventing a return to the earlier course during some late Illinoian spring flood.

Lowering of the bedrock floor of the Missouri River trench to its present altitude may have been completed before the maximum of Cary glaciation. The drill hole at the New England Distillery Company in Yankton penetrated 69 feet of nonweathered till which overlies Carlile shale and is overlain by alluvium. About 300 yards south, drilling logs from the Yankton Bridge record several feet of "blue clay" having similar stratigraphic relations; "blue clay" is standard well drillers' terminology in the area for nonweathered till. The till at the two localities is presumed to be of the same age. The age is not known but is tentatively inferred to be Cary, for neither the Mankato nor the Tazewell glacier is inferred to have reached this locality. The till may be Iowan, but if it is either Iowan or Tazewell in age, completion of the trench at an earlier date than suggested above is indicated.

There is little evidence of significant change in the longitudinal profile of the trench since the maximum of Cary(?) glaciation. Beneath Yankton Bridge drill logs indicate that the river has cut no deeper into Cary(?) till than to 1,132 feet altitude, or approximately 30 feet below the present low-water stage. Upstream from the bridge remnants of alluvial fills indicate a sequence of four periods of filling, each followed by an interval of dissection. The last of these lowered the river to its present profile.

At the Gavins Point Dam, drill-hole data indicate the Missouri River trench, as illustrated in plate 13, is about one-third filled with alluvium. It forms a thin lens about 130 feet thick, which lies between steep bluffs cut in the Niobrara formation. The bedrock floor is somewhat saucer-shaped in transverse profile, has a minimum altitude of 1,037 feet, and is cut in Carlile shale.

POST-ILLINOIAN TIME

Diversion of an ancient drainage system in the vicinity of Yankton by the Illinoian glacier was not the last, although it may be the most significant. The Missouri River itself was diverted from its course during the Wisconsin stage by both the Iowan and Cary glaciers; in addition the Mankato glacier caused a third drainage disruption of less importance. Channels cut during the two diversions were occupied only briefly, and following the retreat of each ice sheet the Missouri River returned to its previous course.

IOWAN DIVERSION CHANNEL

Todd (1912, p. 464, 1899, p. 60–61) described a shallow valley connecting "the upper portion of the Verdigre and Bazile Creeks with the upper portion of the north branch of the Elkhorn [River]". Todd named this valley the Creighton-Plainview Channel and concluded that it was a diversion route marginal to either the Kansan or the Iowan glacier, probably the Kansan.

The channel is a shallow, elongate depression about 1½ to 2 miles wide, and 35 to 50 feet deep. It extends southeastward from sec. 22, T. 30 N., R. 6 W., through the towns of Winnetoon and Creighton, Knox County, to the Elkhorn River.

The topographic floor of the channel is nearly flat and is underlain by fine alluvium as much as 10 feet thick, which rests on outwash. Locally the alluvium is crossbedded with the inclined beds dipping to the southeast. In a gravel pit 1 mile east of Creighton, the outwash consists of gravelly sand at least 30 feet thick (Jake Yundt, pit owner, oral communication, 1955). The fill is mantled by yellowish-brown silty loess except where the loess has been removed by later erosion. The loess is inferred to be of post-Iowan pre-Mankato age. In the vicinity of Winnetoon the channel is shallowest, and the somewhat uneven floor attains its maximum altitude of 1,655 feet.

The northern end of this diversion channel has been dissected by an unnamed tributary of Verdigre Creek, and southeast of Creighton the channel is occupied by the headwaters of Bazile Creek. These streams are very small and could not have cut the broad Creighton-Plainview Channel.

The channel apparently carried melt water and the diverted discharge of the Niobrara, Ponca, and Missouri Rivers southeasterly while the Iowan glacier occupied the Missouri River trench from Niobrara downstream to the vicinity of Sioux City. This conclusion is based on the inferred post-Iowan pre-Mankate age of the loess mantle overlying the alluvium in the diversion channel, the inferred position of the Iowan drift border, and the altitude of the channel compared with the altitude of the Iowan drift border near Coleridge. The apparent lack of Cary till south of the Missouri River trench indicates that the Cary glacier was not thick enough to divert the rivers through this route and at this altitude, but the channel does lie approximately along the Kansan drift border, and it is possible the route was first used during the Kansan glaciation.

There is no record of geomorphic development from Iowan to Cary time. It is inferred that the Tazewell glacier did not reach the Yankton area, and any deposits within the Missouri River trench have been destroyed. Accumulation of loess on the uplands probably continued from late Iowan time through late Tazewell time, but the deposit is undifferentiated.

CARY DIVERSION CHANNELS

During the Cary substage the glacier dammed the Missouri River and forced it from its trench into a diversion channel that in part marks the foot of the Coteau du Missouri escarpment in Nebraska. Minor changes in the thickness of the ice or the position of the glacier margin during its early waning stages permitted the diverted discharge to adopt a series of successively lower channels. These were not wholly separate, but together compose a network of escape routes, each of which differs only in part from the preceding course. Three channels are apparent and are called Crofton channel, West Bow Creek channel, and St. Helena terrace channel.

CROFTON CHANNEL

This channel is represented by a shallow arcuate depression which lies along the eastern margin of the Coteau du Missouri escarpment. The depression extends southeastward from the central part of T. 33 N., R. 3 W., Knox County, to the vicinity of Crofton; from there the channel trends northeastward, rejoining the Missouri River trench opposite Yankton. The topographic depression is about 4 miles wide and 50 to 100 feet deep. The bedrock floor is cut into the upper part of the Ogallala formation and lies at an altitude of about 1,535 feet in the NE cor. SE¼ sec. 33, T. 33 N., R. 3 W., Knox County. This is about 345 feet above the present Missouri River flood plain. The eastern end of the channel is cut into the Niobrara formation, and in the SW cor. sec. 18, T. 33 N., R. 1 E., Cedar County, the floor is an altitude of roughly 1,225 feet. The gradient of the channel is thus about 13 feet per mile.

The floor of this abandoned channel is nearly flat except where thickly mantled with loess or dissected, and even in dissected areas flat-topped remnants remain. In the western part of the channel the floor is underlain by sand and gravelly sand that locally contain considerable pink feldspar which probably was reworked from the Grand Island formation or a similar deposit. Scattered igneous boulders of northern provenance within the gravel indicate a glacial origin of part of the material. In the vicinity of Crofton much of the deposit conists of fine- to medium-grained sand, and near the lower (eastern) end of the channel the fill appears to consist chiefly of silt and fine-grained sand. The thickness of the fill is not known. West of Crofton the channel fill is mantled by moderate amounts of grayish-orange, post-Iowan pre-Mankato loess believed to be of Cary age. Elsewhere in the channel loess is patchy or absent.

The upper part of the channel is occupied by Devils Nest Creek and is transected by Weigand Creek; the lower part is occupied by Beaver Creek. Neither Devils Nest Creek nor Beaver Creek is large enough to have cut the channel. The three creeks have dissected Crofton channel so thoroughly at each end that the surface profile is difficult to recognize from within the channel; from either side, however, the topographic form is generally distinct.

This diversion route is of inferred Cary age because the alluvium and loess that occupy it are inferred from lithologic character and field mapping to be of Cary age. The possibility exists, however, that the channel was first cut at some earlier date.

WEST BOW CREEK CHANNEL

Crofton lies at the northeastern edge of a wind gap about 150 feet deep and a mile or more wide. This gap crosses the Coteau du Missouri escarpment at its lowest part and connects Crofton channel with the valley of West Bow Creek to the southeast. The floor of the gap is at an altitude of about 1,450 feet, or 25 feet above the floor of Crofton channel, and grades eastward to the valley floor of West Bow Creek.

Upstream from the gap West Bow Creek valley turns southward and narrows rapidly; downstream the valley floor trends east and widens to about half a mile at Fordyce and about 1½ miles at the town of Bow Valley. The floor is underlain by sand, mantled locally by yellowish-brown loess of probable Cary age.

At present West Bow Creek turns northeastward through a narrow, youthful valley to join Bow Creek near its confluence with the Missouri River. The main valley of West Bow Creek, however, trends slightly south of east from Fordyce and opens into the valley of Bow Creek at the SE cor. sec. 10, T. 31 N., R. 2 E., Cedar County, where the difference in altitude between the floors of Bow and West Bow Creeks is now about 70 feet. During Cary time Bow Creek drained northward into the Missouri River trench as it does now; the Missouri River at that time must have been flowing 70 feet above its present level, probably owing to ice in the trench somewhere down stream.

East of Crofton a number of large draws enter the valley of West Bow Creek from the northwest; these were channels formed by the melt water that deposited Cary outwash in the area to the north. One of the largest of these tributaries is Second Bow Creek, which in Cary time probably entered the Missouri trench in the vicinity of the present mouth of Bow Creek. Apparently the drainage of West Bow Creek was captured by a tributary of Second Bow Creek at some time after West Bow Creek ceased to serve as a diversion channel.

ST. HELENA TERRACE CHANNEL

Partly dissected remnants of a strath terrace cap the south bluff of the Missouri trench at two localities. One locality is about 5 miles upstream from Yankton, in SW¼ sec. 7, T. 33 N., R. 1 E., Cedar County, and the NW¼NE¼ sec. 13, T. 33 N., R. 2 W., Knox County. The second locality extends downstream from SW cor. sec. 18, T. 33 N., R. 1 E., Cedar County, to and beyond the community of St. Helena which is on this, the largest, remnant. The terrace is cut into the Niobrara formation and near St. Helena is from half a mile to more than a mile in width. The cut surface generally is mantled by 3 to 10 feet of silty sand of glacial origin, which is overlain by two sheets of loess with a now-buried soil profile developed on the upper part of the lower loess (measured section 7). The outwash-bedrock contact is at an altitude of about 1,250 feet in sec. 24, T. 33 N., R. 1 E., Cedar County; farther west at the first locality it attains an altitude of approximately 1,285 feet. The gradient is thus about 3 feet per mile. The terrace appears to be at nearly the same altitude as, but a little lower than, the down stream end of Crofton channel and is about 85 feet above the Missouri River flood plain. Because the alluvium and loess mantling the strath surface of the large remnant are thin and vary in thickness, the underlying Niobrara formation is shown on the geologic map.

The large terrace remnant is inferred to have been part of the Crofton diversion channel from a time shortly after the maximum of Cary glaciation until ice within the trench had thinned sufficiently to permit the return of drainage to it. Until that time melt water and Missouri River discharge were trapped between the ice and the bedrock that now lies along the southern edge of the terrace. This segment narrows at St. Helena and ends in the vicinity of the mouth of Bow Creek; the diverted drainage may have returned to the trench at this point or a downstream extension of the terrace may have been cut away by post-Cary meandering of the Missouri River.

When Cary ice within the trench had thinned enough to permit the diverted drainage to abandon Crofton channel, the Missouri River returned to the trench and, escaping along the contact of the ice and the bedrock wall, cut a terrace in the Niobrara formation at a maximum altitude of about 1,285 feet. The only remnants of this terrace are those at the first locality described above. Downstream the escaping water is inferred to have flowed across the large St. Helena remnant. Further thinning of the glacier allowed the Missouri River to return to its former course wholly within the trench.

The reconstruction of events related to the Crofton channel, West Bow Creek channel, and the St. Helena terrace channel is as follows: (1) At the time of maximum extent of the Cary glacier ice tongues entered and filled the Missouri River trench at both ends of Yankton Ridge and may have covered briefly the highest part of the ridge. (2) Melt water from ice occupying the trench spilled across the southern edge and deposited a sheet of Cary outwash over much of the terrain. (3) Ice dams diverted the flow of the Niobrara, Ponca, and Missouri Rivers. At the maximum position of the ice this discharge was diverted along the base of the Coteau du Missouri escarpment. Escape was found through a gap at Crofton into the valley of West Bow Creek. (4) When Cary ice in the Missouri River trench thinned a little the diverted drainage ceased to escape along West Bow Creek and instead flowed through the lower part of Crofton channel and across the large remnant of the St. Helena terrace, returning to the trench downstream from St. Helena. (5) Further thinning of ice in the trench allowed the water to return to the trench and escape along the contact of the ice and the trench wall, cutting and modifying the St. Helena terrace to its present form. (6) Further thinning of the ice permitted the Missouri River to return to its former course wholly within the trench.

CARY MELT WATER CHANNELS

Along the south flank of Yankton Ridge between sec. 8, T. 93 N., R. 56 W., Yankton County, and sec. 7, T. 93 N., R. 57 W., Yankton County, several short tributary valleys with gradients as steep as 170 feet per mile enter the Missouri River trench. These tributaries are distinctive because they possess a conspicuous valley-in-valley profile which is readily apparent in the upper part of their courses.

The broad valleys appear to have been a quarter of a mile to half a mile wide when formed and were cut in till; almost no outwash was deposited within them. The gradient of one typical broad valley is about 55 feet per mile. Headward, the broad valleys grade into surfaces of Cary end moraines and ground moraine; downstream they intersect the Missouri River trench at elevations 200 to 280 feet above the flood plain. The degree of dissection of the broad valleys differs from one channel to another; remnants of the broad-valley floors are common in the upper courses of most channels, but near the mouths the floors generally are represented only by subaccordant knolls and ridges. One notable exception is a large flat-topped remnant occupying most of the SW¼NE¼ sec. 17, T. 93 N., R. 57 W., Yankton County.

The V-shaped inner valleys are cut deeply into Pierre shale and the Niobrara formation, and slumping is general along the sides. The gradient of the inner valley in the tributary referred to above is about 170 feet per mile.

The broad valleys are melt water channels that originated at the margin of the Cary glacier and drained southward. They were probably graded to a pond caused by an ice dam at the eastern end of Yankton Ridge, an alluvial fill formed in such a pond, or a mass of ice filling the trench. The broad valleys probably originated when Cary ice lay on the south flank of Yankton Ridge, and they grew longer as the ice front receded northward. When the glacier covered only the north flank or the ridge, melt water drainage down these channels ceased. Erosion by the melt water was possible because of the steep gradient down which the streams flowed; this also explains the near-absence of outwash in the channels today.

The reconstruction of the sequence of events is as follows: (1) At the maximum of the Cary glacier the ice entered the Missouri River trench at both ends of Yankton Ridge; it may have briefly covered the highest part of the ridge. (2) As the ice front receded from the highest part, melt water channels were cut across the south flank of the ridge to the Missouri River, ponded between ice dams at either end of the ridge. (3) As more of the ridge was exposed, additional channels were cut at somewhat lower altitudes. (4) Melt water from the two ice tongues occupying the Missouri River trench and from the pond between spilled across the southern edge of the trench and deposited a sheet of Cary outwash over much of the terrain. This suggests that the pond between the two ice dams had become filled with outwash; otherwise, the sand and gravel would have settled out in the pond. (5) The melt water escaped by way of the West Bow (Bow Valley) Creek channel into the Missouri trench southeast of the blockading ice.

The Cary-Mankato interstadial was probably characterized by erosion, for no deposits of Cary age remain within the Missouri River trench. Whether the trench was cut to its post-Cary(?) depth of 1,132 feet at the Yankton Bridge during this interval or in post-Mankato time is not known.

DISRUPTION OF DRAINAGE BY THE MANKATO GLACIER

Tongues of the Mankato glacier entered the Missouri River trench at both ends of Yankton Ridge, but neither tongue was thick enough to force the river from its trench. The ice is inferred to have dammed the river however, for there are several exposures of laminated clay and silt at and upstream from the mouth of the Niobrara River. The deposits are as much as 60 feet above the level of the Missouri River and are apparently of lacustrine origin. Owing to their altitude, which is higher than that of known Recent deposits in the Yankton area yet lower than the St. Helena terrace, the beds are tentatively inferred to be of Mankato age; their lacustrine origin suggests that they may have accumulated behind an ice dam. There is no other evidence of the height of the ice dam; if escaping water cut terraces, they have been destroyed by post-Mankato erosion.

MANKATO MELT WATER CHANNELS

With the exception of the Cary melt water channels on the south flank of Yankton Ridge, nearly all streams and creeks north of the Missouri River trench originated as melt water channels during the Mankato substage, and in a general way reflect the position and trend of the margin of the Mankato glacier at its maximum and during its recession. This is particularly true of East and West Marne Creeks on the north flank of Yankton Ridge, and of Clay and Mud Creeks on the southwest flank of Turkey Ridge. These streams wee occupied by melt water caught between the advancing ice and the higher topography beyond, and plainly reflect in their courses the form of the terrain and the position of the ice front. The two largest melt water channels are distinctive geomorphically and deserve separate attention. These are the James River trench which is characterized by its smooth walls, and Beaver Creek valley which is striking because of its peculiar bilateral and cross-axial relation to James Ridge.

JAMES RIVER TRENCH

The James River flows in a smooth-walled trench from half a mile to a mile wide, and about 135 feet deep. The floor is underlain by 4 to 6 feet of fine alluvium over at least 80 feet of outwash ranging from layers of sand to beds of cobble gravel, and its profile is graded to the lower terrace of the Missouri River. The trench marks the axis of a broad valley once tributary to the pre-Illinoian valley of the Niobrara River. The oldest deposit exposed in the trench walls is Cary till; so the broad valley is clearly pre-Cary in age. Overlying the Cary till is outwash of Cary(?) age; it indicates that a valley coincident with the present James trench served as a melt water channel in Cary(?) time. Mankato till overlies the Cary(?) outwash and is overlain in turn by Mankato outwash. The latter forms constructional terraces which have steep gradients, are as high as 40 feet above the present trench floor, and grade upslope into Mankato end moraines. The outwash terraces indicate existence of a valley in Mankato time and indicate trenching took place in post-Mankato time.

The most significant features of the trench are the smoothness of the walls relative to those of comparable valleys in the region, and the fact that the flood plain grades into the bottom land terrace of the Missouri River trench. The first suggests that entrenchment of the James River took place more recently than the formation of the other valleys; the second suggests that when cutting and filling were completed, the Missouri River may have been as much as 10 feet higher than its present profile.

Flint (1955, p. 126–127) traced the floor of the James River trench upstream and found that it graded into the outlet of glacial Lake Dakota. From this he concluded that trenching began with breaching of the lake's morainal dam and concluded with cessation of discharge from melting ice in central and northern North Dakota.

BEAVER CREEK VALLEY

The valley of Beaver Creek is a tributary of the James River trench, and in most aspects the two have similar stratigraphy. Moreover, just as the course of the James River is influenced by its ancient pre-Illinoian valley, the course of the lower part of Beaver Creek is influenced by a segment of the pre-Illinoian valley of the Niobrara River; in addition it is likely that the upper part is influenced by some tributary of the ancient valley, although this is wholly conjecture.

Beaver Creek is characterized by the most unusual geomorphic feature in the vicinity of Yankton: an anomalous course which is in part cross-axial to, and in part longitudinal within, James Ridge, a remnant of a drainage divide between the ancient Niobrara and ancient James Rivers. The valley is at least pre-Cary in age, for kame-terrace deposits that are not older than Cary are present in the walls of Beaver Creek valley where the valley bisects the ridge longitudinally, and extend upstream through the ridge where the valley is cross-axial. Thus Beaver Creek valley must have acquired its present peculiar position prior to occupation by the glacier that deposited the kame-terrace gravelly sand. The valley is at least pre-Cary, therefore, but the direction of flow within it is not known.

The manner of origin of either the longitudinal or cross-axial segments of Beaver Creek valley is not known. It seems likely that the longitudinal segment originated as an interlobate melt water channel when some glacier flanked both sides of James Ridge. Origin of the cross-axial segment is more problematical. It may have been started by a consequent melt water stream divergent in course from the one that bisected the ridge, or the headward growth of the longitudinal stream may have been influenced by joints in the bedrock.

RECENT EPOCH

During Recent time geomorphic processes have been chiefly degradational but have resulted in construction of various landforms which include alluvial terraces, alluvial fans, sand dunes, and landslides. Missouri River terraces indicate that at least four times since the Mankato maximum the trench has been filled with sediments above the present river level. The first three fills were to elevations of 30 to 40 feet above the modern low-water profile and compose the older, higher, terrace 2. Each filling was followed by an interval of erosion, during which the terrace fills were dissected to an altitude at or a little below the present river level. The fourth period of filling was to only a few feet above the present level; this fill composes the lower, younger, terrace 1. Since that time the Missouri River has lowered its longitudinal profile to the present position. It seems most unlikely that five periods of alternate filling and dissection constitute the complete history of the Missouri River trench, but other periods are not recorded by identifiable remnants. The broad Missouri River has swept away most traces of its past.

SUMMARY

Anomalous features of the Missouri River trench and evidence of a former drainage pattern to the north thereof indicate that the Missouri River originated as a result of a glacial diversion of an ancient drainage system. The origin of that section of the Missouri River trench extending from Springfield to Yankton is inferred to have taken place during the maximum of Illinoian glaciation, and the date of entrenchment to the present bedrock floor, 135 feet below the river, is inferred to have been before Cary time. Other diversions are known or inferred to have occurred at earlier and later dates. During the Kansan glacial stage a temporary diversion of the existing drainage may have occurred through the route represented by the Creighton Channel of Todd. The same channel was used again as a temporary diversion route during the maximum of the Iowan glacier.

The Cary glacier entered the Missouri River trench and diverted the drainage southeastward past Crofton into West Bow Creek. Owing to thinning of ice in the trench, the water later escaped by way of Crofton channel and St. Helena terrace, and still later along the southern margin of the trench. During the Cary-Mankato interval erosion may have cut as much as 60 feet below the present Missouri River.

The Mankato glacier also entered the trench but did not force the Missouri River from it. The river was dammed to an unknown depth, and sediment accumulated to a depth of 60 feet in the resulting lake. After the Mankato glacier receded north of glacial Lake Dakota in central South Dakota, that lake breached its outlet and subsequent discharge cut the present James River trench. When discharge ceased, the Missouri River may have been about 10 feet above its present profile.

The land surface has been lowered gradually during postglacial time, and constructional features are of minor significance. The most important of these are two terraces in the Missouri River trench, the flood plain of the river, and a widespread mantle of colluvium.

GEOLOGIC HISTORY

The geologic history of an area is inferred from examination of the lithologic characteristics and physical relations of the rocks that lie beneath it. Reconstruction of the events that produced the rocks in their present state is limited chiefly by the incompleteness of the geologic record and by the extent of geologic knowledge. Thus, history inferred from pre-Pleistocene formations in the vicinity of Yankton is restricted largely to Cretaceous time, for little is known of Precambrian rocks, Paleozoic strata are absent, and Tertiary strata represent only a small part of that epoch. Similarly, events of Pleistocene time are inferred principally from deposits of the glacial stages and substages. In both cases it may be possible to infer from evidence exposed in adjacent areas the nature of events of which the record has since been destroyed by erosion.

PRE-PLEISTOCENE HISTORY

The only recognized formation present older than Cretaceous is the Sioux quartzite of Precambrian (Huronian) age. No information is available in the vicinity of Yankton that indicates the origin of this rock, although Baldwin (1949, p. 10) infers that it accumulated in a shallow marine or lacustrine environment. The record shows only that a quartz-rich sand was deposited, and at some later date precipitation of a siliceous cement in the interstices formed an orthoquartzite; there is no evidence of the source of the sand, the environment of deposition, or the date of cementation. Neither is there evidence as to whether the sand of the quartzite was deposited on, or was intruded by, the dark crystalline igneous rock reported in an early Yankton water well.

Subsequently both rocks underwent extensive subaerial erosion which cut a broad valley southward (Darton, 1909, pl. 10) in the Sioux quartzite and may have exposed the igneous rock. Weathering may have locally leached the siliceous cement from quartzite at the surface, leaving a sandy mantle. It also altered the upper part of the igneous rock to a greenish clay and may have resulted in deposition of secondary calcium carbonate in the partly weathered rock below. The date of erosion and weathering is not known. It clearly postdates the formation of the quartzite and its possible intrusion by the igneous rock, and it predates the deposition of the overlying sandstone of Early Cretaceous age. This leaves events of Paleozoic, Triassic, and Jurassic time unrecorded, for no rocks represent them. It is possible that the missing strata once were deposited, but if so, they have since been removed by erosion.

During the latter part of the Early Cretaceous epoch continental deposits accumulated on the eroded and weathered surface of the Precambrian rocks. These sediments consisted chiefly of sand with small amounts of silt and clay. Thin layers of carbonaceous matter intercalated with the clastics may indicate temporary swamps but some of the material may have been deposited by streams. Toward the end of the epoch the sediments became finer, chiefly light-colored clay with some sand and thin carbonaceous layers, but near the beginning of Late Cretaceous time they again became coarse. This sequence of strata comprises the lower sandstone member, middle shale member, and upper sandstone member of the Dakota sandstone. Molds of deciduous tree leaves indicate a continental origin of the sandstone beds, but the upper part of the middle shale member contains fragments of plant rootlets like those found in superjacent marine beds. These fossils suggest that an encroaching Cretaceous sea that later covered much of the western interior of North America may have first covered this area at the time during which the shale was deposited locally and receded before the deposition of the overlying, coarser strata.

The epicontinental sea, which may have occupied the area briefly a little earlier, covered it by the time deposition of Dakota sandstone ceased. In the shallow water several hundred feet of marine clay, marl, and a little sand were deposited prior to eventual recession. These marine strata comprise several formations of which the Graneros shale is the oldest and the Pierre shale the youngest, and their marine origin is established by the wealth of fossils they contain, including microfossils, a mosasaur, clams, and oysters. Layers of bentonite intercalated with these strata suggest that volcanic eruptions began during deposition of the Greenhorn limestone and occurred with increasing frequency through the accumulation of the Pierre shale.

Some strata in the Niobrara formation and Pierre shale appear to have undergone partial lithification before deposition of the overlying beds. This is indicated by shale pebbles, probably derived from the underlying Sharon Springs member, in the coarse layer at the base of the Gregory member of the Pierre, and by the growth of oysters on bedding planes of the Smoky Hill chalk member of the Niobrara.

The epeiric sea that had covered much of the western interior retreated at some time following deposition of the Mobridge member of the Pierre shale. Just when the Yankton area was exposed to subaerial erosion is not known, for the upper part of the Mobridge member is eroded, and there is no record that the marine Elk Butte member or the overlying Fox Hills sandstone found elsewhere were deposited here.

The first record of deposition in Cenozoic time is the Ogallala formation of Pliocene age; thus the break between the Mobridge member of the Pierre shale and the Ogallala formation represents part of Late Cretaceous and all of early Cenozoic time. The Ogallala formation indicates a complete change of regimen from that of the Cretaceous marine sequence, for the formation is a continental deposit of clayey silt, sand, and gravel laid down by shifting streams. These sediments were derived chiefly from the youthful Rocky Mountains, and in part from formations of the bordering lowlands across which the streams flowed. At some time after deposition a siliceous cement transported by ground water was precipitated locally in coarse facies of the formation forming lenses of greenish orthoquartzite.

PLEISTOCENE AND RECENT GEOLOGIC HISTORY

The close of the Pliocene epoch was marked by a change of regimen. Streams which had been depositing sand and gravel of the Ogallala formation ceased to do so, and instead began to deepen their channels, establishing more permanent courses. This interval of erosion continued for some time and was accompanied by a change to a cooler, more humid climate which foreshadowed the Nebraskan glaciation and which characterized much of Pleistocene time.

The Nebraskan glacier entered the easternmost part of Nebraska, but no evidence exposed indicates that the glacier reached the Yankton area. Neither is there evidence of the drainage diversion which must have resulted from ice damming the preglacial drainage system. Undoubtedly recession of the glacier accompanied warming of the climate and introduced the Aftonian interglacial stage. No deposits of this age have been found, nor is there evidence of prolonged weathering and dissection such as is found farther south in Nebraska.

At the close of Aftonian time the climate again cooled, marking the advance of the Kansan glacier. This ice sheet covered the Yankton area and reached its maximum extent approximately along a line drawn southeast from the present mouth of the Niobrara River. The regional drainage pattern was disrupted, and melt water from the ice, together with the discharge of ancient Ponca Creek and the ancient Niobrara River, is believed to have flowed southeast along the glacier margin, cutting the Creighton channel. During late Kansan time, following recession of the ice, drainage followed a course between Springfield and Yankton which approximately coincided with the present Missouri River. In this broad valley the river deposited sand and gravel, correlated with the Grand Island formation, to an altitude of nearly 1,600 feet. At the end of Kansan time the path of the river within the valley lay through the present communities of Tabor and Utica.

During the Yarmouth interglacial stage the region underwent extensive dissection, for the ancient Niobrara River lowered its valley floor to an altitude of about 1,140 feet. A small tributary that probably joined this river opposite the mouth of the ancient James River cut headward to the west, dissecting the Grand Island formation. The course of its headward erosion was influenced by the late Kansan channel in which the gravel had been deposited. No evidence of prolonged weathering like a buried soil profile observed farther south in Nebraska remains in the vicinity of Yankton.

A third cooling of the climate characterized the Illinoian glacial stage. The advancing glacier dammed the drainage system and partly filled the overridden valley segment with drift. The ice advanced onto the upland south of the valley and entered the tributary of Yarmouth age, depositing outwash containing gravel reworked from the Grand Island formation, then overriding it and mantling it with till. Sediment in melt water and east-flowing streams settled out in ice-dammed lakes; thus water which spilled over interfluves and around the ice front was capable of eroding the soft bedrock. Diversion channels had become entrenched enough by the time the glacier margin eventually receded so that drainage was not able to return to its earlier course, now partly drift-filled. This marked the origin of the Missouri River. Fine fractions of outwash from the receding glacier accumulated on flood plains of the river and were picked up by the wind and deposited on terraces and uplands as Loveland loess.

No deposits mark the Sangamon interglacial stage, for like other interglacial intervals it was characterized by erosion and weathering. The youthful Missouri River probably became further entrenched at this time, possibly to the depth of the present bedrock floor. As a result of the dissection, pre-Sangamon deposits not removed by Yarmouth erosion were largely stripped from terrain adjacent to the river. During the long interval of weathering under a mild climate, which was possibly somewhat more humid than the present, a mature reddish-brown (Sangamon) soil was formed.

Late in Sangamon time or early in Wisconsin time a minor glacial advance may have occurred well to the north of the Yankton area. Outwash from it reached the Missouri River, however, and the finer fractions reworked by the wind and deposited on the upland near the edge of the trench compose the Farmdale loess of Leighton and Willman. There formed on this loess an immature soil profile characterized by the same reddish-brown color that marks the soil on the Loveland loess.

The Wisconsin glacial stage consists of four glacial substages—or five if Leighton and Willman's Farmdale loess represents earliest Wisconsin time—separated by interglacial intervals. Pre-Wisconsin glacial ages may have been similarly subdivided, but there is now no evidence of that.

During the first, or Iowan, glacial substage the ice entered the Yankton area and crossed the Missouri River trench, depositing a mantle of till. The glacier margin at its maximum reached a position about 3 miles south of Coleridge; farther west it was a little southwest of the present mouth of the Niobrara River. The Missouri River was diverted from its trench, and at the maximum flowed southeastward from Niobrara through a diversion channel believed to have been cut first by Kansan melt water. The Iowan glacier probably did not remain long at its maximum position, for drainage through the diversion route did not cut deeply enough for the course to be retained after recession of the ice. During recession the glacier may have deposited stratified drift southwest of the Missouri River, and in late Iowan time, outwash in melt water channels served as the source of Iowan loess.

The relation of the Tazewell drift border to Iowan and Cary drift borders suggests that the Tazewell glacier failed to enter the Yankton area, a suggestion supported by the apparent lack of identifiable Tazewell drift. The fact that the Tazewell glacial substage is represented only by loess derived from Tazewell outwash indicates the glacier did enter the drainage basin. Locally there was no apparent time lapse between deposition of Iowan loess and Tazewell loess, for there is no physical discontinuity or buried soil profile within the deposit. Farther south in Nebraska where accumulation may have been slower, the lapse of time is indicated by a weak, discontinuous soil profile. The Tazewell-Cary soil which probably formed on the upper part of the undifferentiated Iowan and Tazewell loess during the Tazewell-Cary interval has been destroyed by erosion in the vicinity of Yankton, but it is found farther south in Nebraska. Near Yankton the interval is represented only by the eroded loess surface, locally marked by a band of lag pebbles.

The course of advance of the Cary glacier during the Cary substage was strongly influenced by the James River lowland. The ice crossed James and Turkey Ridges, may have covered Yankton Ridge, and stopped at or just beyond the Missouri River trench. If the ice did cover Yankton Ridge entirely, the margin soon must have retreated from the crest, then built several small end moraines about the resulting reentrant. As recession of the ice front from the south side of Yankton Ridge proceded, melt water cascaded down the steep flank and eroded a succession of broad, high-level channels graded to a local baselevel as much as 280 feet above the present Missouri River profile. While the ice stood at or near its maximum, melt water deposited a sheet of outwash somewhat similar to an outwash plain beyond the margin. Part of this melt water at first escaped directly into Second Bow and West Bow Creeks, the rest joined the diverted waters of the Missouri River and flowed along the Crofton channel to Crofton. For a brief time the water passed through a gap in the Coteau du Missouri escarpment at Crofton into West Bow Creek, reentering the Missouri River trench southeast of St. Helena. After the ice receded slightly, the water escaped along Crofton channel and cut part of St. Helena terrace channel.

The lack of alinement among Cary end moraines on the north flank of Yankton Ridge indicates that recession of the Cary glacier was not uniform. During its retreat the glacier deposited stratified ice-contact material just north of Yankton, left a valley train or similar deposit in the forerunner of Beaver Creek valley, and left an extensive mantle of ground moraine. When the ice margin lay against the northeastern flank of James Ridge, short tongues of ice occupied a valley in the ridge, and outwash from these tongues probably constructed the kame terraces against the valley walls and along the ridge flank farther northwest. As before, glacial outwash was the source of loess which accumulated thickly on River terraces and the uplands.

Like comparable intervals the Cary-Mankato interstadial was characterized by erosion and weathering. The erosion removed all earlier deposits from the Missouri River trench to a depth of about 60 feet below the present low-water profile, and the weathering formed a weak soil profile locally observed on Cary loess.

During the last, or Mankato substage, the course of the James, or Dakota, lobe of the Mankato glacier was controlled entirely by the James River lowland. At its maximum the glacier covered the crest of James Ridge at an altitude of about 1,500 feet but halted at that altitude against the north flank of Yankton Ridge, and at an altitude of 1,300 to 1,400 feet against the southwest flank of Turkey Ridge. Tongues of ice encircled the ends of Yankton Ridge and entered the Missouri River trench. Lacustrine sediments upstream from Yankton indicate that the river was dammed to an altitude of at least 1,225 feet. Evidence of the exact altitude or course of escape of the water has since been destroyed. To the west the ice margin reached a maximal position along Emanuel Creek.

The ice soon receded from its position along Emanuel Creek and built an end moraine about 10 miles east. Further recession of the glacier was

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interrupted by brief pauses or slight readvances during which chains of end moraines were formed. The retreat was apparently uniform, for the ground moraine lacks convolute pattern and end moraines and groups of swales are commonly subparallel. The ice melted back last from the north flank of Yankton Ridge, on which it had been the thickest. As the glacier receded from the inner Mankato drift border the retreat was irregular enough to produce rough ground-morainal topography. Other deposits included ice-contact stratified materials and outwash which partly filled Beaver Creek valley and the James River trench. Outwash in these and other channels was the source of Mankato loess, but loess accumulation may have ceased about the time the glacier margin stood at the inner Mankato drift border. Still later the morainal dam of glacial Lake Dakota was breached and escaping water retrenched the James River and caused comparable downcutting in Beaver Creek valley.

The Recent epoch began essentially at the end of Cary time for that part of the area not later covered by Mankato drift, and at the end of Mankato time for parts so covered. Downcutting of the Missouri River trench during the Cary-Mankato interval induced rejuvenation of the tributaries. Some of these have cut deep, V-shaped valleys into the floors of the high-level melt water channels of Cary age on the south flank of Yankton Ridge. Landslides began along the over-steepened walls, and sliding probably has been continuous ever since. Other processes have caused the accumulation of alluvium, colluvium, and swale deposits, and the erosion of deposits already formed. Two constructional terraces in the Missouri River trench postdate the maximum of Mankato glaciation, and the higher of the two indicates a series of fillings and cuttings. Construction of the lower terrace was complete after downcutting in the James River trench ceased. Dunes along the edge of this terrace, scattered alluvial fans, and flood plain alluvium are all of Recent age. Weak soil profiles representing early Recent and late Recent (thermal maximum) time probably are present in the area but have not been identified. In general the surface of the Yankton area is being lowered as it was during interglacial intervals.

ECONOMIC GEOLOGY

The geology of the Yankton area has had an important influence on economic development in the past and will continue to do so in the future. Geology has received little credit for the part it has played, however, largely because there has been essentially no industrial exploitation of available natural resources, and because many people fail to realize the importance of geology to agriculture. The subject of mineral resources is of more popular interest, for it includes both metallic and nonmetallic resources; the latter includes construction materials, fuels, and water resources. All these are described briefly.

CONSTRUCTION MATERIALS

Construction materials may be divided into two groups, those readily available, and those that require thorough economic investigation before production begins. The first group includes sand, gravel, till, and argillaceous limestone of the Niobrara formation for fill, loess and silty sand for asphaltic-paving filler, sand and gravel for concrete aggregate, plaster sand, and road metal, and argillaceous limestone for restricted use as riprap and building stone. The second group includes Pierre shale and argillaceous limestone of the Niobrara formation for portland cement, Pierre shale for expanded light-weight aggregate, and loess for sintered light-weight aggregate. Despite the variety of material and quantities present, high-quality construction materials are not easily obtainable, for deposits are commonly small and irregular, and large accumulations are generally overlain by valuable agricultural soils. If a specific product is obtainable it probably will require processing. Construction materials available in the Yankton area are summarized below according to use and geologic unit. More detailed information regarding the physical nature, distribution, and engineering characteristics of the various materials is given in the descriptions of geologic units in the chapter on "Stratigraphy," and on the geologic map.

ROAD METAL

Gravel suitable for road surfacing is in continual demand in the vicinity of Yankton owing to the large number of unpaved roads and to loss each winter caused by snow plows. Road metal has been obtained at one time or another from most gravel deposits. In general, outwash yields the best material available, in the largest quantities, and throughout the greatest part of the area. Individual deposits differ considerably as to the size of material, but in general range from fine to coarse gravel. Most outwash is used pit-run, but for many Federal and State contracts crushing and screening are necessary. The coarsest deposits are of

Mankato age and range from medium to coarse gravel containing beds of boulders to gravelly sand. Cary outwash is generally finer, ranging from a silty to coarse sand south of the Missouri River to a medium gravel north of the river. Iowan(?) outwash is coarser and ranges from a medium gravel to a cobble gravel. Illinoian gravel belonging to both the glacial and the reworked facies, the Grand Island formation, and gravel lenses in the Ogallala formation are chiefly fine gravels.

There is little choice in composition among the various deposits. Outwash deposits are for the most part similar and consist chiefly of a variety of igneous and metamorphic rock fragments, but the reworked facies of Illinoian outwash, the Grand Island formation, and gravel lenses in the Ogallala formation are composed principally of a single igneous rock type. Many outwash stones contain mica which has weathered selectively, thereby weakening the rock and causing more rapid breakdown in use and a large amount of fine material when crushed. The igneous pebbles of the Grand Island formation and reworked facies of Illinoian outwash contain considerable feldspar; feldspar is characterized by cleavage planes in three directions, and this structurally weakens the pebbles.

The largest deposits are those of Mankato outwash which underlie the floor of the James River trench and the tributary valley of Beaver Creek. These deposits probably contain millions of cubic yards and are covered by 5 to 20 feet of alluvium and colluvium. No comparable deposits are found south of the Missouri River. The next largest deposits are gravel of the Grand Island formation along the southern flank of Yankton Ridge, and northwest from Crofton. These deposits contain many thousands of cubic yards each; those south of the river are mantled generally by as much as 15 feet of loess, and those north of the river, although well exposed for considerable distances, are in part overlain by 10 to 15 feet of till. Deposits of Illinoian outwash are of similar size and are either well exposed or mantled by 5 to 15 feet of loess. They are found only north of the Missouri River. Lenses of gravel in the Grand Island formation are well exposed but known only beyond the western margin of the Yankton area. The Grand Island deposits commonly contain only a few thousand cubic yards, and several have been worked out. Pockets of Iowan(?) gravel are also very small and appear to be nearly exhausted.

CONCRETE AGGREGATE

The present demand for concrete aggregate in the Yankton area is almost wholly for light construction, chiefly poured foundations for homes and rural outbuildings, and for moulded construction block. For heavier construction, and paving in some communities, crushed Sioux quartzite is shipped in from Alexandria, S. Dak. Among locally available materials, gravel of the Grand Island formation and the reworked facies of Illinoian outwash are generally preferred. These gravels are too rounded to make good aggregate, but outwash generally is even more rounded unless it is crushed. Crushed aggregate is not normally available. The sorting, composition, size, cover, and distribution of deposits are about as described for road metal.

Blending sand may be obtained by screening gravel of the Grand Island formation and the reworked facies of Illinoian outwash or by screening and possibly washing outwash or gravel lenses in the Ogallala formation. Blending sand may also be available on a pit-run basis from the Cary(?) kame-terrace deposits in James Ridge and the James River trench.

MINERAL FILLER

Large quantities of loess and silty sand (Cary outwash) are available south of the Missouri River for use as a mineral filler in asphaltic road surfacing. To my knowledge neither has been used in this way within the Yankton area, but loess has been used extensively in Kansas with good results. Removal of overburden rarely will be a problem, for the lower slopes of hills are mantled only with very slightly humified colluvial material; if the land has not been farmed, sod may be present.

PLASTER SAND

Plaster sand is obtained from the Grand Island formation or from the reworked facies of Illinoian outwash by screening. The product is not as angular as desired but is more free from fine grade sizes than is a similar product of processed outwash. Pit-run outwash sand is commonly used in rural areas, but it is not generally favored because of dark iron and manganese stains.

BUILDING STONE

The sole source of building stone is the Niobrara formation. Although this argillaceous limestone was used extensively in the early days of Dakota Territory, it has had little use during recent years. The rock is easily quarried and shaped by hand- or power-saws, and limited mass-production of cut block is possible. The Smoky Hills chalk member of the formation is thinly bedded, a feature that would facilitate excavation and would reduce the number of faces to be cut by one-third. The underlying Fort Hays limestone member is more dense and massive, however, and probably would make better blocks. Fresh rock weathers rapidly to a light gray and in a short time attains an attractive yellow color. The exterior may be plastered for protecton or appearance if desired. Several two-story buildings in and near Yankton are constructed of this stone and, after 75 years or more, are still in good condition. The best sites for possible quarries in the Smoky Hills chalk member are along the north wall of the Missouri River trench between Yankton and the Hutterite Colony; a possible site for a quarry in the Fort Hays limestone member is the south wall of the trench near St. Helena.

FILL AND SUBGRADE

Several sources of fair to good fill and subgrade are found in the area. They include the Grand Island formation, outwash deposits, ice-contract stratified deposits, and till. Other materials that are less available or less desirable are the Niobrara formation and loess. Unsuitable materials include Pierre shale, most colluvial and fine alluvial materials, and swale deposits. With the exception of outwash, alluvial gravel, and possibly of ice-contact material, compaction during emplacement is important in reducing the effect of settling and frost heaving. Compaction by vibration or inundation of material obtained from the Grand Island formation, outwash deposits, and ice-contact stratified deposits is advantageous, for it will reduce the amount of settlement. The engineering characteristics of the several materials relative to their use as fill or subgrade are outlined in the table below; it must be emphasized that the data in the table are at best only subjective, for the lithologic variation within a given deposit is commonly as great as variation within the geologic unit as a whole.

Principal geologic materials and their engineering characteristics relative to use for fill and subgrade

Geologic material	Dry tensile strength	Value for subgrade	Value for base course	Frost heave	Contraction and expansion	Drainage
Grand Island formation	None	Excellent	Excellent	None	Negligible	Excellent.
Outwash	None	Good to excellent.	Fair to excellent.	None to low	None to slight	Good to excellent.
Ice-contract stratified deposits	None	Good	Poor	Slight to medium.	Slight	Fair to good.
Niobrara formation	Medium to high.	Fair to good	Poor to fair	Slight to medium.	Medium to low.	Poor.
Loesses	Low	Poor to fair	Not suitable	Medium to high.	Medium	Fair.
Till	Medium	Good	Poor to fair	Slight to medium.	Slight	Poor to negligible.
Pierre shale	Medium to high.	Poor	Not suitable	Slight to medium.	High to low	Poor.
Swale deposits	Medium to high.	Poor to very poor.	Not suitable	Medium to high.	High	Negligible.

RIPRAP

There are two potential sources of coarse riprap, the Niobrara formation and glacial erratics; neither is ideal. Of the two, the Niobrara formation is more readily available in the greater quantities. The lower member of the formation is somewhat more dense and a little harder than the upper member and would be preferable for riprap. The rock is subject to destruction by frost action, waves, and currents, but its cost would be so much less than riprap shipped in, that it could possibly be replaced profitably after a few years use. Glacial erratics are available in field-run piles; these generally lie north of the Mankato drift border, but they are most numerous north of the inner Mankato end moraine and on Turkey Ridge. Stones generally range from 6 to 24 inches in diameter, are rounded, and are chiefly composed of various igneous rock types. Few of the piles contain more than from 1 to 3 cubic yards of stones.

Finer grained riprap can be obtained from the coarser fraction of the Grand Island formation, and various outwash and ice-contact deposits. The coarsest material underlies the floors of the James River trench and Beaver Creek valley and forms a fill terrace in the E½ sec. 29, T. 95 N., R. 55 W., Yankton County.

PORTLAND CEMENT

A quarry (pl. 4*B*) and a tall chimney in the NE cor. sec. 17, T. 93 N., R. 56 W., Yankton County, are all that remain of a once-important cement industry that supplied cement for construction of the Panama Canal. Curtiss (1950, p. 33–60) has studied the portland cement resources near Yankton and gives a brief history of the abandoned plant, its production, and compression-test results of concrete test cubes found at the plant site. According to Curtiss, the plant began operation in 1891 and closed in 1910 after producing an estimated 1,900,000 barrels of cement; test cubes of cement and sand gave an average compressive strength of 6,060 pounds per square inch.

Using chemical analysis published by Curtiss (p. 42) I calculated the approximate ratio of argillaceous limestone from the Niobrara formation to Pierre shale necessary to produce Type I[16] portland cement that would compare favorably with the Type I product of contemporary cement plants. The data used were weighted to yield a composite analysis for the uppermost 83 feet of the Niobrara formation and the basal 37 feet of the Pierre shale at the cement plant site.

The weighted composite analyses, in percent are as follows:

	Niobrara formation	*Pierre shale*
SiO_2	5.04	53.60
Fe_2O_3	3.89	2.19
Al_2O_3	1.78	17.41
CaO	49.03	5.27
MgO	.55	2.49
SO_3	1.20	.25
Volatile matter	36.78	10.84
Moisture	2.09	2.30
	100.36	94.35

Calculations based on these analyses indicate that 106.75 tons of Type I portland cement can be produced from 130 tons of argillaceous limestone, 30 tons of shale, and 2½ tons of gypsum. Theoretical analysis of the product would be as follows:

	Percent		*Percent*
SiO_2	21.2	MgO	1.4
Fe_2O_3	5.5	SO_3	1.4
Al_2O_3	7.0	Alkalies (allowed)	1.4
CaO	62.2		
			100.1

Volatile matter and moisture are lost on calcining.

This analysis compares favorably with that of other portland cements. Shreve (1945, p. 197) averaged 102 analyses of Type I portland cements and obtained the following percentages:

	SiO_2	Fe_2O_3	Al_2O_3	*CaO*	*MgO*	SO_3	*Alkalies*
Minimum	18.58	1.53	3.86	61.17	0.60	0.82	0.66
Maximum	23.26	6.18	7.44	66.92	5.24	2.26	2.90
Average	21.06	2.86	5.79	63.85	2.47	1.73	1.40

The alkali content of the Niobrara formation and Pierre shale is not indicated in the analyses published by Curtiss. Portland cement with an alkali (Na_2O and K_2O) content less than 0.6 percent is known as low-alkali cement and is preferred for use with aggregates containing undesirable quantities of certain deleterious components; these components react with the alkalies and cause a weakening of the concrete. Three spot samples from the Niobrara formation are said (James B. Smith, executive secretary, Yankton Chamber of Commerce, oral communication, 1951) to contain 0.10 to 0.19 percent Na_2O, and 0.15 to 0.60 percent K_2O, but the analyst is unknown; no data are available for the Pierre shale. In the theoretical computation above, an alkali content of 1.4 percent was allowed arbitrarily as Shreve found it to be the average of the 102 analyses he studied (see above), and the figure seems reasonable in view of the few data available.

Natural gas, transportation, water, and labor are available at Yankton, and possible sites for production of portland cement are located along the bluffs of the Missouri River trench. Most of these sites would require the stripping of 25 to 50 feet of cover from the Niobrara formation, but part of this is shale that would be used in cement production. The nearest competitive product is produced at Louisville, Cass County, Nebr., 150 miles south; other plants are operating at Rapid City, S. Dak., Duluth, Minn., and Mason City, Iowa.

LIGHT-WEIGHT AGGREGATE

The production of light-weight aggregate from Pierre shale or loess appears to be possible. Of the two source materials, shale probably has the greater potential. Tremendous tonnages of shale are readily obtainable by stripping along both walls of the Missouri River trench, and extensive, thick deposits of loess are found to the south. Natural gas and shipping facilities are available at Yankton and the nearest competitive product is sintered loess at Kansas City, Mo., and expanded shale at Rapid City, S. Dak. It may prove feasible to produce both crushed and calcined agricultural lime for use in calcium-poor soils in States to the east with the same equipment used in production of expanded aggregate.

WATER RESOURCES

A complete study of water resources of the Yankton area is not within the scope of this report. Information regarding supplies of surface water may be found in publications of the U.S. Geological Survey.[17] The data are composed almost wholly of

[16] Definitions and standard specifications for portland cement are found in: American Society for Testing Materials, 1955, Standard specifications for Portland cement; ASTM Designation C 150–55 *in* 1955 Book of ASTM Standards, pt. 3, p. 1–4.

[17] All reports and maps published by the U.S. Geological Survey before May 1958, are listed and indexed in: U.S. Geol. Survey, 1958, Publications of the Geological Survey.

discharge measurements of the Missouri River made at Yankton since installation of a gaging station there in 1931, and of both the Missouri and James Rivers made at gaging stations in the region since an even earlier date. Condra (1908) briefly describes the discharge of smaller streams in Knox and Cedar Counties, and waterpower produced by them, but the information is now largely outdated.

Information regarding supplies of underground water have been published by both Federal and State Geological Surveys. U.S. Geological Survey publications include reports by Todd (1900, 1903a, and 1903b), Condra (1908), and Darton (1909). That part of these reports which generalizes the geology of the sources of supply and shows drillers' logs is valid still, but lists of known artesian wells showing owner, location, diameter, depth, date of drilling, pressure, yield, and temperature, and of representative shallow wells by owner, location depth, diameter and general quality of water are now of limited usefulness; yields of springs as given by Condra are outdated. The South Dakota Geological Survey has more recently published reports (Caddes, 1947; Barkley, 1952; and Rothrock and Ullery, 1938) on the ground water of the southeastern part of the State. These data include records of water-level fluctuations in shallow wells in and near Yankton, changes in altitude of the piezometric surface in the past 45 years, and chemical analyses of samples of water from artesian wells.

The principal source of surface water is the Missouri River. Large supplies are available, for the average daily discharge of the river at Yankton from 1931 to 1953 was 27,080 cubic feet per second, or 53,700 acre-feet. Within the area the river is the source of supply only for the community of Yankton.

The most important sources of subsurface supplies are alluvium in the Missouri and James River trenches and the ancient Niobrara River valley, and the lower (Lakota? equivalent) and upper sandstone members of the Dakota sandstone of Cretaceous age. Minor sources include alluvium in smaller valleys such as those of Beaver Creek (S. Dak.) and East Marne Creek, the Ogallala formation of Pliocene age, and Pleistocene sand and gravel. Numerous small springs, which are economically important in the area, commonly mark the exposure of the Ogallala formation with the underlying Pierre shale, or of Pleistocene deposits with either till or Pierre shale.

The largest supplies of ground water are those available from alluvium underlying the flood plain and bottom land terrace of the Missouri River trench. The amount of discharge through the alluvium is not known, and the source is drawn upon only by farm wells. Moderate or possibly large supplies probably are available from stratified drift partly filling valleys of the ancient Niobrara and James Rivers, but replenishment of this source may be slower than that of alluvium in the Missouri River trench. The communities of Tabor and Utica are supplied by wells in stratified drift in the ancient Niobrara River valley, and a few farm wells in each valley use this source also.

Mineralized supplies obtained from artesian wells within the upper ("first flow") and lower ("second flow") members of the Dakota are small, and are drawn upon by many farm wells and a few small municipalities. Multiple wells properly spaced and pumped could produce considerably larger supplies. Evidence indicates that in the vicinity of Yankton the rate of consumption has exceeded the rate of replenishment. In July, 1950, the New England Distillery Company drilled a third artesian well at the plant at 2nd Street and Walnut Avenue, Yankton. The well was 562 feet deep and had 29 feet of 4-inch perforated pipe at the bottom. On completion it yielded 251 gallons per minute from the Lakota(?) sandstone equivalent, at a pressure of 15¼ pounds per square inch and temperature of 60° F. This pressure indicates that the piezometric surface of the Lakota(?) stands at about 1,235 feet altitude at Yankton. Barkley (1952, piezometric map) showed the piezometric surface of the upper sandstone number of the Dakota to be somewhat lower, only a little over 1,200 feet altitude. Darton (1909, pl. XI) showed the piezometric surface for these formations to be 1,300 feet. Thus the piezometric surface has been lowered approximately 65 feet in about 45 years, and flowing wells now are found only within the valleys of the Missouri and James River.

Springs and surface runoff supply water held by the many small pasture dams; the yield of a typical spring was found to be 3 gallons a minute in early summer. Springs are not generally a source of water for human consumption, but they are reported to supply the village of Crofton. Unpublished chemical analyses of water from different sources in the Yankton area are given in the following table; data were supplied by H. L. Weil (written communications, November 18, 1949, and January 25 and July 5, 1950), Corps of Engineers.

Chemical analyses of water supplies

[In parts per million except pH and stain test]

	Missouri River [1]					Shallow well in Missouri River alluvium	Artesian wells in—	
	Low-water stage (16 analyses, July to December, 1949, 1950)			High-water stage				
	min	max	avg	April, 1950	June, 1949		"1st flow" [3] Dakota sandstone	"2nd flow" [4] Dakota sandstone
Suspended solids	72	940	456	7,531	1,041	241	11	58
Dissolved solids (residue at 103°C)	420	5,201	556	422	349	847	1,297	1,594
Organic matter (loss on on ignition, total solids)	120	212	148	635	166	....	....	....
Alkalinity to phenolthalein, as $CaCO_3$	0	9.30	2.26	.00	.00	.00	.00	.00
Alkalinity to methyl orange as $CaCO_3$	108	205	150	98	108	448	162	130
Total hardness as $CaCO_3$	172	279	236	174	145	715	734	956
Calcium (Ca)	49	81	56	55	38	197	226	307
Magnesium (Mg)	12	20	17	9	12	54	41	46
Sodium (Na)	50	89	66	48	48	39	76	68
Potassium (K)	7.0	18.0	9.0	26	6	15	28	23
Iron (Fe)	.01	.07	.03	.03	.44	.29	.25	.38
Aluminum (Al)	.00	.37	.12	.00	.06	.24	.15	.20
Manganese (Mn)	.00	.00	.00	.00	.00	.00	.00	.00
Sulfate (SO_4)	163	272	213	185	131	336	665	843
Chloride (Cl)	4.6	56.0	17.9	6.9	7.4	12	64	85
Nitrate (NO_3)	1.3	5.3	2.5	6.9	2.5	2.7	.25	.75
Bicarbonate (HCO_3)	133	237	178	120	132	547	198	159
Carbonate (CO_3)	.00	5.60	1.36	.00	.00	.00	.00	.00
Phosphate (PO_4)	....	....	....	....	....	.00	.00	.00
Fluoride (F)	....	....	....	....	....	.60	3.00	2.40
Silica (SiO_2)	12	41	23	18	16	40.0	9.5	19
pH	7.2	8.4	8.0	7.9	7.9	7.2	7.1	7.2
Stain test [5]	Slight	Moderate	....	Moderate	Slight	....	....	....

[1] Samples collected in the SE¼NW¼ sec. 21, T. 93 N., R. 56 W., Yankton County.

[2] Sample from shallow farm well in the SE¼SE¼ sec. 16, T. 93 N., R. 56 W., Yankton County; depth of well: 20 ft.

[3] Sample from well in the NW¼SE¼ sec. 17, T. 93 N., R. 56 W., Yankton County. Well reported to be 350 ft. deep [835 ft. altitude at bottom] and producing from the "first flow" (upper member, Dakota sandstone). The well is probably 450 ft deep, with its bottom at an altitude of 735 ft, for the reported depth would have the well producing from the Graneros shale, a very unlikely condition.

[4] Sample from well in the SW¼NW¼ sec. 17, T. 93 N., R. 56 W., Yankton County; well reported to be 602 ft. deep [or 593 ft. altitude at bottom] and producing from the "second flow" (lower member, Dakota sandstone).

[5] Stain test specifications are CRL–C 401–48, Corps of Engineers, U.S. Army.

FUEL RESOURCES

No indication of or potential trap for oil or gas was found during the present investigation. In a thesis prepared for the University of Nebraska, J. J. Schulte (written communication, 1952) shows a series of subparallel structural highs and lows that trend north-northeast across Knox County; the axes end south of the Missouri River, but one of the highs enters the extreme southwestern part of the Yankton area. Structure contours on the map are drawn on a 50–foot contour interval. Schulte stated:

> Numerous small structural features, some with small closure, appear when mapped on a smaller structure-contour interval, such as an interval of ten feet. Many minor structural features fall within the larger 50-foot contour interval.

The bituminous shale that forms the lower part of the Sharon Springs member of the Pierre shale is not more than 6 feet thick near Yankton and is overlain by a thick shale section; the deposit is not considered economic.

METALLIC RESOURCES

There are no significant deposits of metallic minerals in the area. Minute amounts of gold are said to be present in the glacial drift, but no attempt has ever been made to extract them, and it is extremely unlikely that such an undertaking would prove profitable. The bituminous shale at the base of the Sharon Springs member of the Pierre shale and other exposed bedrock formations and selected exposures of Pleistocene and Recent deposits show no significant radioactivity.

AGRICULTURAL GEOLOGY

A valuable geologic resource of the Yankton area is the surficial material and the soil formed upon it, for the productivity of the soil is an important factor in the economy of the region. In the future the geologic characteristics of soils will determine in part areas where new or different farming methods can be profitably employed. Probably the next major advance in local farming practice will be irrigation of terraces that compose the floor of the Missouri River trench. These are underlain by rich, well-drained silts and fine sand; the bottom land terrace is the more extensive and consists of deep humic loam that commonly produces 60 to 80 bushels of corn per acre. Because of the permeability of the soil, the nearly level surfaces of the terraces, and the dependable large supplies of water available from shallow wells in the alluvium or from the river itself, irrigation appears geologically practical, and if economically feasible should increase production considerably.

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INDEX

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