STATE OF SOUTH DAKOTA
Joe Foss, Governor

STATE GEOLOGICAL SURVEY
Allen F. Agnew, State Geologist

REPORT OF INVESTIGATIONS

No. 85

GEOLOGY AND SHALLOW GROUND WATER RESOURCES of the WATERTOWN-ESTELLINE AREA, SOUTH DAKOTA

by

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CONTENTS

ILLUSTRATIONS

TABLE	PAGE

ERRATA

Page ii..."Deep Water", "Sand and Gravel","Oil and Gas Possibilities", and "Clay" are on page 21 not 18.

Page 2...Last paragraph, "absorbent" not "absorbant".

Page 4...Last paragraph, "R. H. Benson" not "H. Benson".

Page 7...Under "Approximate Thickness", sixth line, "5-60 feet" not "5-6 feet".

Page 15...Lines 5 and 8, "absorbent" not "absorbant".

GEOLOGY AND SHALLOW GROUND WATER RESOURCES

OF THE

WATERTOWN-ESTELLINE AREA, SOUTH DAKOTA

ABSTRACT

The Watertown-Estelline area is in northeastern South Dakota in the north-central part of the Coteau des Prairies of the Central Lowlands Physiographic Province. The area occupies about 650 square miles and is drained by the Big Sioux River.

Precambrian granite and metamorphic rocks underlie the entire area, and are overlain in part of the area by the Sioux formation also of Precambrian age. About 900 to 1000 feet of Cretaceous sedimentary rocks overlie the basement; in ascending order, these are the Dakota Group, and the Graneros, Greenhorn, Carlile, Niobrara, and Pierre Formations. Mantling the bedrock are glacial deposits of Pleistocene age. The Wisconsin Stage is represented by Iowan(?), Tazewell, and Cary drifts.

Shallow ground water is stored in the glacial outwash sands and gravels. The principal source of recharge is precipitation, and the major discharge is through wells and through evaporation and transpiration by plants. The calculated water resources of the area are about 270 billion gallons. The volume of sand and gravel in the glacial deposits is 7 3/4 billion cubic yards

In general, recharge exceeds discharge in the gravels and the movement of the ground water is southward. The quality of water for irrigation is good to excellent, and thus the future of irrigation and/or industrial use of water in the Watertown-Estelline area is favorable.

INTRODUCTION

General Statement

The Watertown-Estelline area is in the Central Lowlands Physiographic Province of northeastern South Dakota (Fenneman, 1938). The area is in the north-central part of the Coteau des Prairies upland. It includes the Watertown, Hayti, and Estelline 15-minute quadrangles, and contains about 650 square miles in parts of Codington, Hamlin, Kingsbury, Deuel, and Brookings counties (fig. 1).

The climate in the Watertown-Estelline area is characterized by long, cold winters and short, hot summers, with rapid fluctuations in temperature. The highest and lowest temperatures recorded between 1904 and 1957 by the United States Weather Bureau at Watertown are 110° and -40° F., in 1934 and 1916 respectively, (fig. 2 and Table 5, Appendix). The maximum annual precipitation between 1904 and 1957 was 29.12 inches (1953) and the minimum was 12.32 inches (1933). However, the average annual rainfall was 20.93 inches (fig. 2 and Table 5, Appendix).

The rural population of the area is fairly dense, with approximately 1.5 dwellings per square mile. The city of Watertown (pop. 12,699, 1950 census) and the towns of Estelline (760), Castlewood (498), Hayti (413), Lake Norden (373), and Dempster (150), contain the remainder of the population.

The Watertown-Estelline area is served by U. S. Highways 77, 81, and 212, and by State Routes 20, 21, 22, 23, and 28. In addition to the main routes, nearly every section line is marked by gravel roads. The Great Northern, the Chicago and North Western, and the Minneapolis and St. Louis railroads serve the area, converging in Watertown. Commercial air service to the city of Watertown is provided by Braniff and North Central Airlines.

Several soil types are recognizable in the area. In general, the soil developed on the rough topography is dark clayey moisture retaining material (clay and silty clay-loam), which ranges in thickness from two inches to three feet. A lighter, more absorbant soil (silt and sandy loam) is present on the "bottom-land". A third type of soil is present in areas covered by recent stream alluvium. This soil is richer in humus than the others and is locally so coarse that it contains coarse sand and pebbles. All the soils are productive where adequate water is available. The major crops grown in the area are corn, wheat, barley, oats, sorghum, alfalfa, soybeans, and flax.

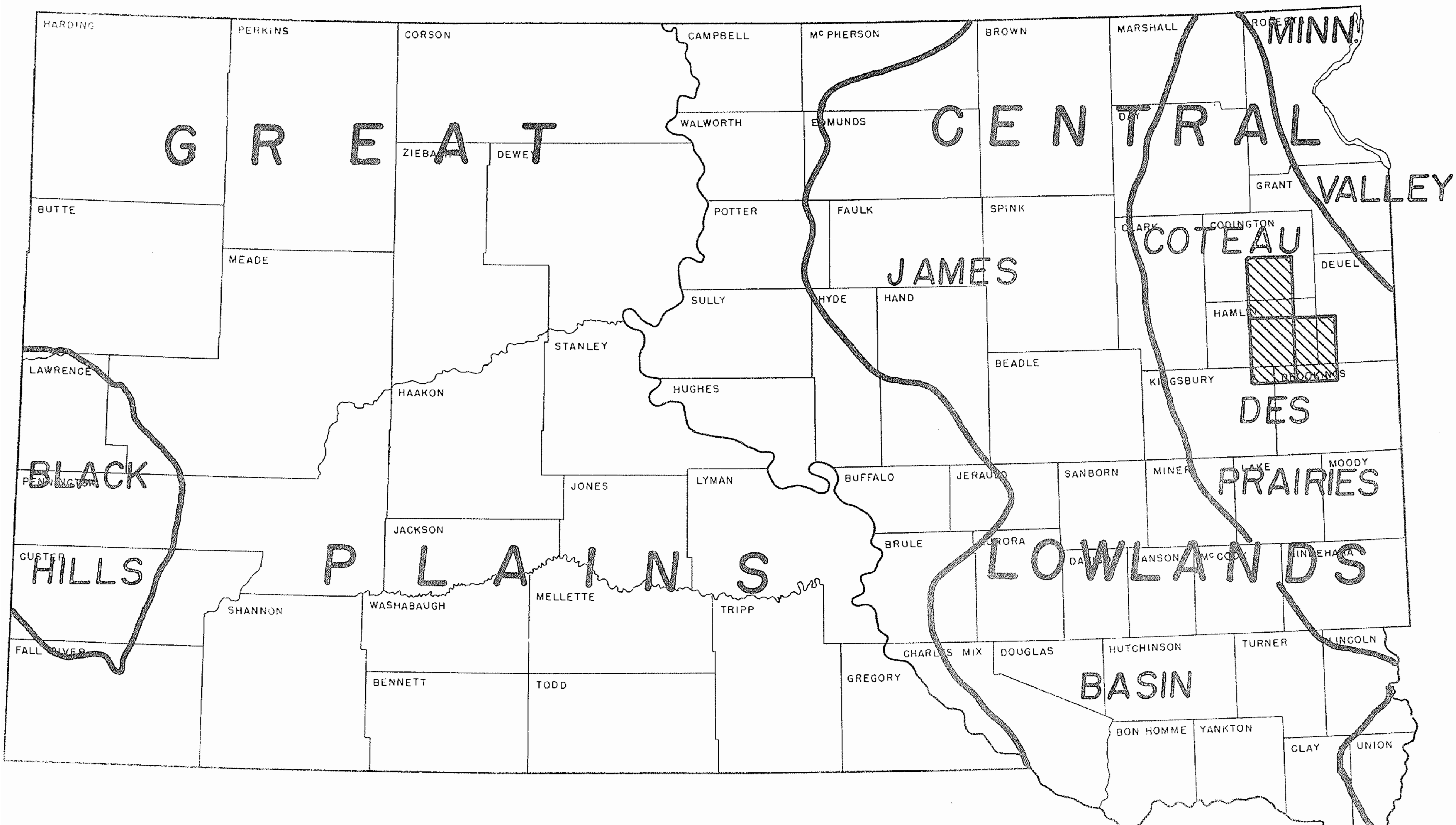


FIG. I. MAJOR PHYSIOGRAPHIC DIVISIONS OF SOUTH DAKOTA (AFTER ROTHROCK, 1943)

WATERTOWN - ESTELLINE AREA

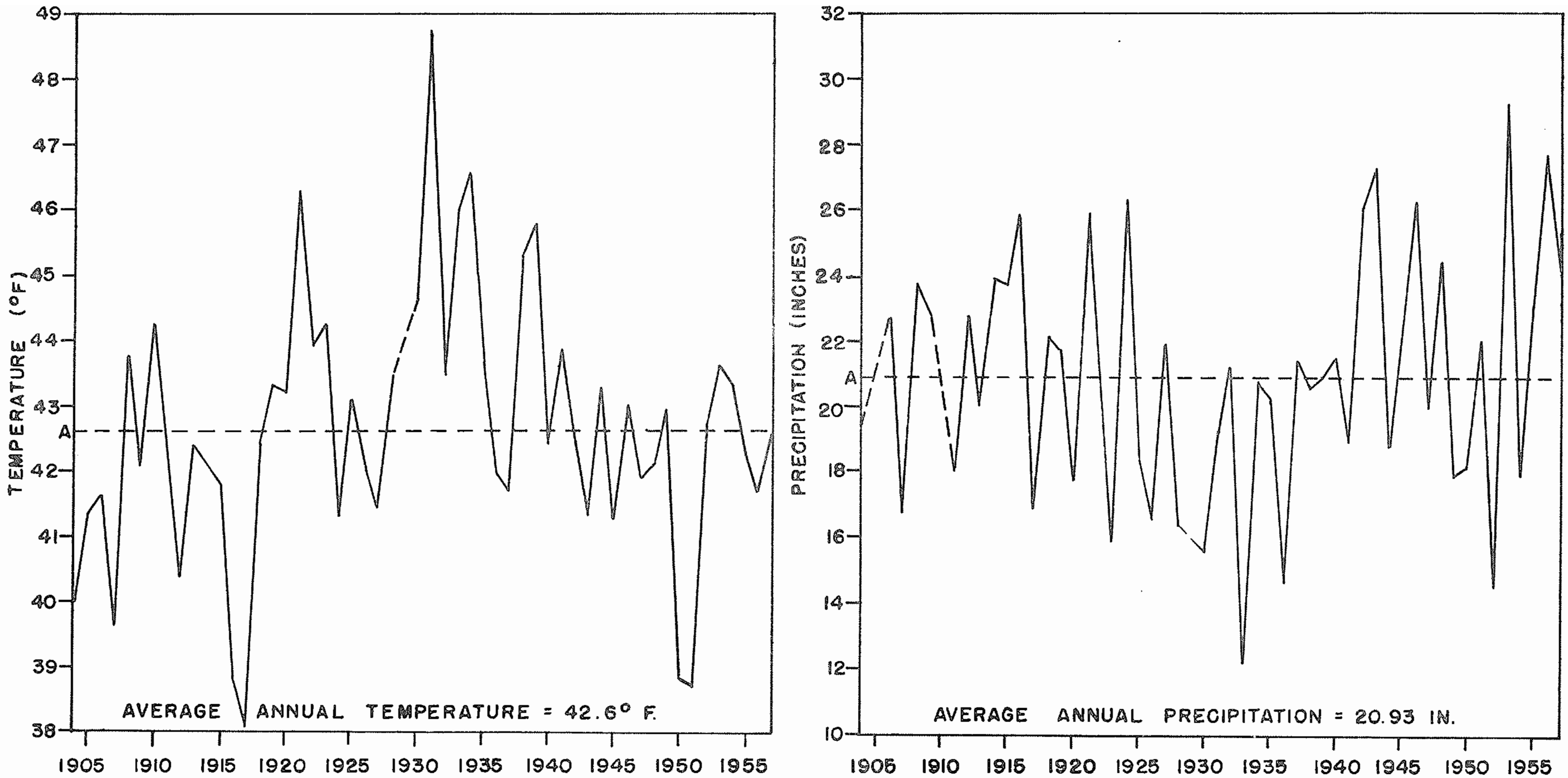


FIG. 2. DISTRIBUTION OF TEMPERATURE AND PRECIPITATION AT WATERTOWN, 1904 – 1957. (U.S. WEATHER BUREAU)

The center of industry in the area is the city of Watertown where meat packing, flax-straw processing, potato distributing, gravel quarrying, and resorts are important industries. In addition, dairy and beef cattle, hogs, sheep, and turkeys are raised. Some tree farms are maintained in the area.

Even though most of the land in the area is cultivated, much is virgin soil, especially in the rugged terrain. Hence, wild grasses, flowers, shrubs, and weeds grow profusely. Trees grow naturally only along major streams.

Topography and Drainage

Three major types of topography are present in the Watertown-Estelline area. The rugged, knob and kettle type is restricted to the area west of the Big Sioux River; the gently rolling well-drained topography east of the same river and in a narrow strip to the west; the third is the relatively level "bottom-land" adjacent to the Big Sioux River and some of its tributaries.

The maximum relief in the area is about 320 feet, measured by altitudes of 1640 feet where the Sioux River leaves the area and 1960 feet in the north-central part of the Estelline quadrangle. The local relief ranges widely; in the knob and kettle topography it is normally not more than 40 to 50 feet, but may be as high as 175 feet. In the gently rolling area the relief normally ranges from 10 to 30 feet, but reaches a maximum of 146 feet. The local relief of the "bottom-land" is less than ten feet, except in areas of collapsed outwash where it reaches 40 feet in places.

The drainage in the Watertown-Estelline area is controlled solely by the Big Sioux River, which flows southerly through the area. Its major tributaries are Willow, Stray Horse, and Hidewood Creeks.

Drainage is well developed in the area of gently rolling drift, and forms a pattern characteristic of late youth or early maturity. In the knob and kettle topography the drainage is very poorly developed; consequently, there are many small lakes but very few streams on its surface. The surface of the "bottom-land" outwash is, for the most part, well drained, owing to two factors. First, most of the surface water which enters the valley is absorbed directly by the porous soil. Second, any runoff that does not soak into the sands and gravels moves directly to the Big Sioux River and is carried downstream. There are, however, several localities where the surface of the outwash is covered by impermeable material, causing marshy areas.

Previous Investigations

Chamberlin (1881) made reconnaissance studies of the moraine systems of eastern South Dakota. Later, Todd (1894, 1899) wrote of the glacial geology of this part of the State. The glacial geology of northeastern South Dakota was mapped by Leverett and Sardeson (1932) as part of their study of Minnesota and adjacent States. The following year, Rothrock (1933) studied the water supplies of Lake Kampeska (Watertown quadrangle) and mapped the geology in the vicinity of the lake. Detailed geologic mapping of the area considered in this report was undertaken in 1951 and 1952 by Bolin, Rothrock, and Doran, who prepared manuscript maps of the three quadrangles and the Still Lake, and South Shore quadrangles, to the north and northeast (S. Dak. Geological Survey, Vermillion). Erickson (1954, 1955) reported on the artesian conditions in that part of eastern South Dakota which includes the Watertown-Estelline area. The most recent work was accomplished by Flint (1955) who prepared a reconnaissance map of the glacial geology of the eastern part of the State.

Present Investigation

The geologic mapping was accomplished on air photos in the summer of 1957, and was supplemented by plane table surveys. A hand auger was used to determine the character of the soil and subsoil so that the margins of the various surface deposits could be accurately plotted.

The thickness of outwash sands and gravels was determined by 113 holes drilled with a jeep-mounted auger. Sixty-two resistivity stations were occupied, but because of the anomalous results these were not used in the determination of outwash thickness.

The materials in the surficial deposits were examined in the laboratories of the State Geological Survey to determine the size distribution and rock composition (Tables 7, 8, 9, and 10, Appendix.)

Acknowledgments

Geologic work on which this report is based was done under the supervision of Dr. A. F. Agnew, State Geologist. The writer profited by many field conferences with his colleagues, M. J. Tipton and Dr. K. Y. Lee, and by one meeting with Dr. M. M. Leighton, Chief Emeritus, Illinois Geological Survey. The assistance of geophysicists S. G. Howell and Daniel Lum, and drillers and field assistants H. Benson, D. J. Buckmeier, J. C. Harksen, D. G. Jorgensen, G. E. Kroger, P. D. Lidel, R. H. Von Holdt, and R. C. Wilson, is gratefully acknowledged. The writer wishes to express his thanks to the local residents of the area who contributed information and otherwise aided in the completion of this work.

GEOLOGY

Surficial Deposits

Pleistocene Series

Eastern South Dakota was glaciated at least four times during the Pleistocene epoch. Deposits left by these four ice sheets are, from oldest to youngest, the Nebraskan, Kansan, Illinoian, and Wisconsin. The Wisconsin has been subdivided into four substages, in ascending order the Iowan, Tazewell, Cary, and Mankato (see fig. 3).

No positive features of pre-Wisconsin glaciation are preserved in the Watertown-Estelline area. However, wells that apparently penetrated more than one till imply that pre-Wisconsin drift underlies the Wisconsin.

Little is known of the method of advance of the pre-Wisconsin ice sheets. Glacial striae and other features in eastern South Dakota and western Minnesota (Baldwin, 1951), cause the writer to believe that these sheets entered South Dakota from the northeast. At least one of the pre-Wisconsin (Illinoian) ice sheets crossed the State as far as the present course of the Missouri River, and Warren (1952) has shown that at least part of the Missouri River in South Dakota is Illinoian in age. The Iowan has been mapped (Flint, 1955) as extending even farther south and west.

Because deposits of Wisconsin age are present at the surface of most of eastern South Dakota, much more is known about the direction of movement of the Wisconsin ice. The Iowan ice sheet apparently followed the course of the pre-Wisconsin sheets across the area. The succeeding Tazewell and Cary ice sheets entered the State from the north and apparently split into two lobes at the apex of the Coteau des Prairies (figs. 1, 3). As a result, the westernmost lobe passed west of the Coteau down the present James River lowland southward nearly to the present position of the Missouri River. The eastern lobe passed around the east side of the Coteau and flowed southward in the Des Moines River lowland to south-central Iowa.

Deposits of the Mankato ice were mapped by Flint (1955) far south in the James lobe. Similarly, Ruhe (1950) has shown that Mankato drift occupies much of the Des Moines lobe. Recent work, however, shows that this extreme southward extent of Mankato deposits in both lobes is questionable (Zumberge and Wright, 1956; Steece, Tipton, and Agnew, In Preparation).

The Watertown-Estelline area contains part of the eastern edge of the James lobe, the western edge of the Des Moines lobe, and the interlobate area between. Hence, deposits of Iowan(?),

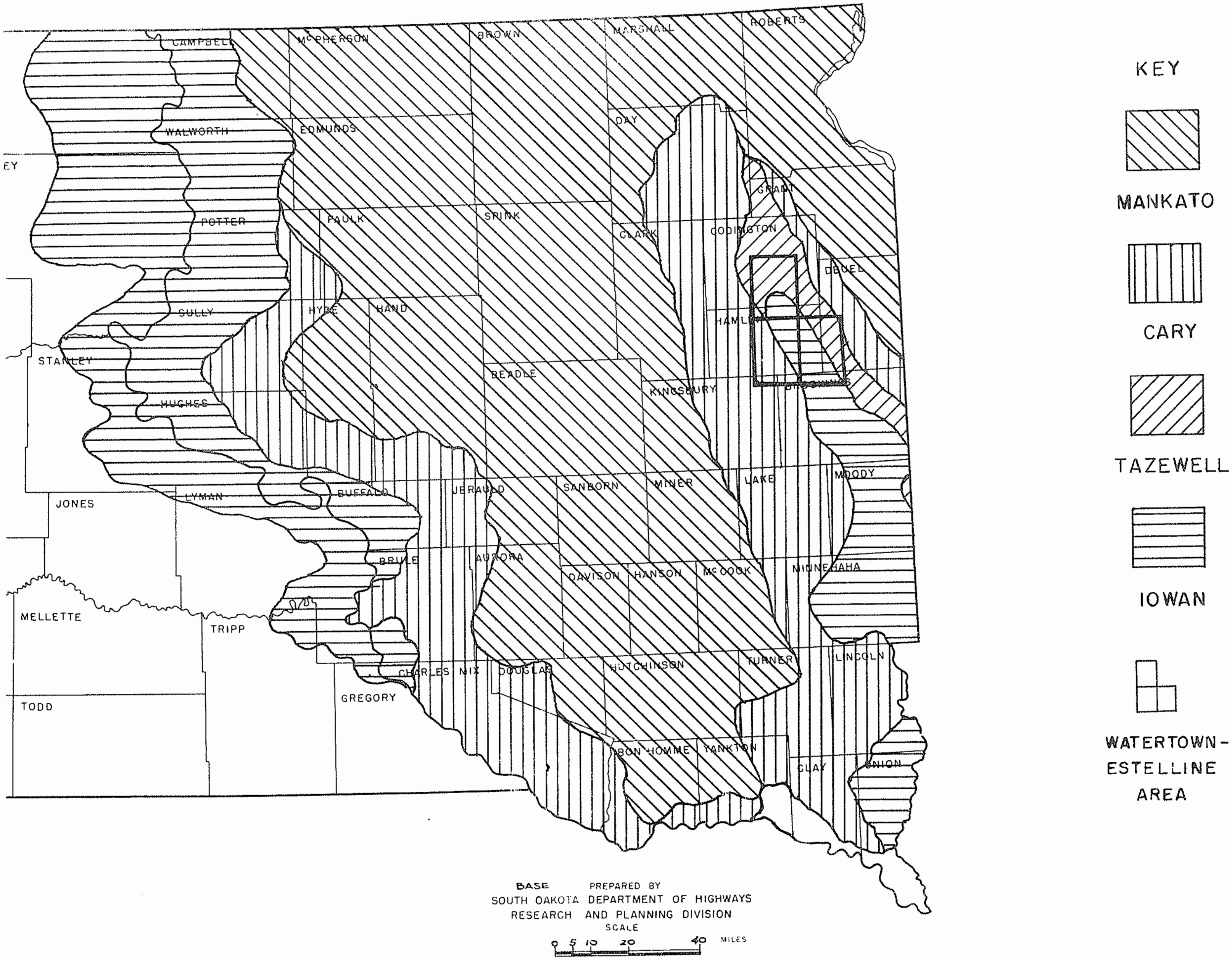


FIG. 3. THE REGIONAL DISTRIBUTION OF THE PLEISTOCENE WISCONSIN GLACIAL DRIFT SHEETS IN SOUTH DAKOTA (AFTER FLINT, 1955).

Tazewell, and Cary age have been recognized in this area (see Table 1).

Iowan(?).--Deposits formerly mapped as Iowan in this area are here recognized only as being older than Tazewell. Because they might be pre-Iowan rather than Iowan, however, they are termed "Iowan(?)". The Iowan(?) glacial deposits are till (boulder clay) that is characterized by level to gently rolling topography, upon which an intricate pattern of dendritic drainage is developed. The smooth surface of the till is due partly to a mantling of the former rough topography with a variable thickness of loess, presumably of Wisconsin age, and due partly to erosion after its deposition. The relief is very low, normally not more than 10 to 30 feet, but reaches a maximum of 146 feet on Hidewood Creek. The surface of the Iowan(?) drift is overlain by clay-loam or silty clay-loam soil that averages two feet thick, ranging from six inches to 3½ feet. No outwash deposits of Iowan(?) age are recognized in the area.

Tazewell.--Tazewell glacial deposits are till and outwash gravels. The till is typical boulder clay characterized by a more youthful topography than the Iowan(?). The Tazewell surface, although not as level as the Iowan(?), is nonetheless well-drained; however, it does not exhibit the intricate dendritic drainage pattern that is developed on the Iowan(?) till. The Tazewell surface is for the most part loess-mantled. The soil development on the Tazewell till and/or on the loess covering the till ranges from several inches to 2½ feet in thickness. The thickness of the Tazewell till is unknown, but at least 150 feet is preserved in the extreme northeastern corner of the Estelline quadrangle.

Tazewell outwash occupies level terrace positions along the Big Sioux River and its tributaries Willow Creek, Stray Horse Creek, and Hidewood Creek. These terraces are remnants of former Tazewell valley-fill material which was dissected by post-Tazewell streams. The terraces are generally small and occupy less than a square mile in area. A striking exception to this is the terrace northeast of Estelline, which covers about two square miles. The terrace gravels range from several feet to more than 60 feet in exposed thickness, but average about 15-20 feet.

The gravels have large percentages of carbonate and granitic rocks. Smaller percentages of shale, chalk, sandstone, and limonite concretions comprise the remainder (Table 7, Appendix). The gravels range from clay to boulders several feet in diameter, with the greatest percentage restricted to the ½-8 mm size (Table 8, Appendix). The Tazewell outwash has a sandy, silty soil (sandy loam) on its surface, which ranges from several inches to several feet in thickness.

Cary.--Till, outwash, and glacial lake sediments comprise the Cary deposits in the Watertown-Estelline area. The till is similar in composition and texture (Tables 9, 10, Appendix) to the Iowan(?) and Tazewell tills, but is differentiated from them

Table1--Generalized Pleistocene Geologic Section,
Watertown-Estelline Area

AGE				ROCK NAME	APPROXIMATE THICKNESS	DESCRIPTION
RECENT				Alluvium	4-20 feet	Fine to coarse detrital material, containing humic matter; black color
QUATERNARY	PLEISTOCENE	WISCONSIN	CARY	Glacial lake sediments	10-60 feet	Fine sand and silt; light-colored, well-bedded; contains fossils
QUATERNARY	PLEISTOCENE	WISCONSIN	CARY	Till	10-70 feet	Grayish to brownish boulder clay, may be unleached, and unoxidized; up to 3 feet of soil may be present
QUATERNARY	PLEISTOCENE	WISCONSIN	CARY	Outwash	8-96 feet	Coarse to extremely fine sand and gravel; unsorted, covered with up to 2 feet of sandy and silty soil. Contains water
QUATERNARY	PLEISTOCENE	WISCONSIN	TAZEWELL	Till	150 + feet	Grayish to brownish boulder clay, more or less unleached and unoxidized. May have soil and/or loess cover up to 3 feet
QUATERNARY	PLEISTOCENE	WISCONSIN	TAZEWELL	Outwash	5-6 feet	Terraces only. Along Big Sioux, Stray-Horse, Willow, and Hidewood Creeks. Poorly-sorted fine to coarse sand and gravel. No water
QUATERNARY	PLEISTOCENE		IOWAN?	Till	146 + feet	Grayish to brownish boulder clay, may or may not be leached and oxidized. Covered with up to 3 feet of soil and may have 2 feet ± loess overlying

by topography, by the absence of loess on the Cary till, and by the absence of well-developed drainage on the Cary surface. The Cary till is characterized by knob and kettle topography that contains many small lake-filled depressions. The local relief developed on the till differs markedly from ground to end moraine. In end moraine areas the terrain is more rugged, with as much as 80 to 100 feet of local relief. The ground moraine is also rough, but has less local relief, ranging from several feet up to 30 feet. The Cary till is 10 to 70 feet thick in exposures. Normally the till has a poorly developed soil on its surface; this soil is commonly less than six inches thick, although in places it reaches several feet in thickness.

Cary outwash sediments are expressed as three topographic types; valley train deposits, terrace remnants, and collapsed material. The more common valley trains are characterized by level to very gently undulating topography; they occupy low positions relative to the surrounding till uplands, and are confined to valleys in which present streams flow. The material in these is chiefly poorly sorted sand and gravel with carbonate rocks being predominate. Valley train outwashes range from 20 to 95 feet in thickness and average about 50 feet. Abundant supplies of shallow ground water are available from the valley train outwashes.

Remnants of older Cary valley fills are preserved as terraces along the Big Sioux River. These terraces are thin deposits of sand and gravel whose exposed thicknesses range from 8 to 20 feet; they are differentiated from Tazewell terraces on the basis of geographic position. Tipton (1958) has traced the corresponding older Cary terraces in the Still Lake quadrangle (directly north of the Watertown quadrangle) westward to their source in the easternmost (oldest) Cary moraine of the James ice lobe. The lower valley train outwash deposits can be traced westward to the second moraine system west of the Big Sioux, both in the Still Lake quadrangle and in the area of this report. Therefore, the terraces are Early Cary in age and the valley outwash deposits are Middle or Late Cary in age. This type of relationship holds for the Cary valley outwash in the major tributaries on the east side of the Big Sioux Valley where Tazewell rather than Early Cary terraces occupy upper levels. These Tazewell terraces can be traced northeastward to their source in the Bemis moraine (fig. 3), and nearly all of the Cary outwash deposits can be followed eastward beyond, to their sources in the Altamont moraine.

The third, or collapsed type of Cary outwash is difficult to distinguish from Cary till, for the surface of the former is rough and undrained, much like that of the Cary end and ground moraine. The surface of the collapsed outwash is closely underlain by sands and gravels in most places, whereas the till is composed chiefly of boulder clay, except where local knobs of sand occur in end moraine. The composition of the collapsed outwash is not entirely that of sands and gravels, but is a heterogeneous mixture that contains some till.

Cary glacial lake sediments are fine well-sorted (fig. 6) sand, silt, and clay, generally gray or brown and are commonly fossiliferous. These deposits are confined to topographically low areas in which recent alluvium has been deposited. The sediments range in thickness from several feet to 70 feet.

Recent

Alluvium.--Alluvial deposits of recent age are present along most of the streams in the Watertown-Estelline area, and are especially well preserved along the Big Sioux River and its major tributaries. Recent deposits occupy to a lesser extent the smaller streams and lakes. Alluvium consists generally of a heterogeneous mixture of gravel, sand, silt, and clay, with local sub-stratification. The alluvium contains a large proportion of humic material, which causes its dark color. These deposits range up to 20 feet in thickness and average about three feet.

Subsurface Rocks

No bedrock is exposed in the Watertown-Estelline area. However, data obtained from well logs in the vicinity reveal the presence of Precambrian rocks unconformably overlain by rocks of Cretaceous age, beneath the surficial deposits.

Precambrian System

Granite comparable with the Ortonville granite of the Milbank area, metamorphic rock (serpentine), and Sioux Formation, are all Precambrian in age and comprise the basement rocks of this area (fig. 4; also see Steece, 1953a).

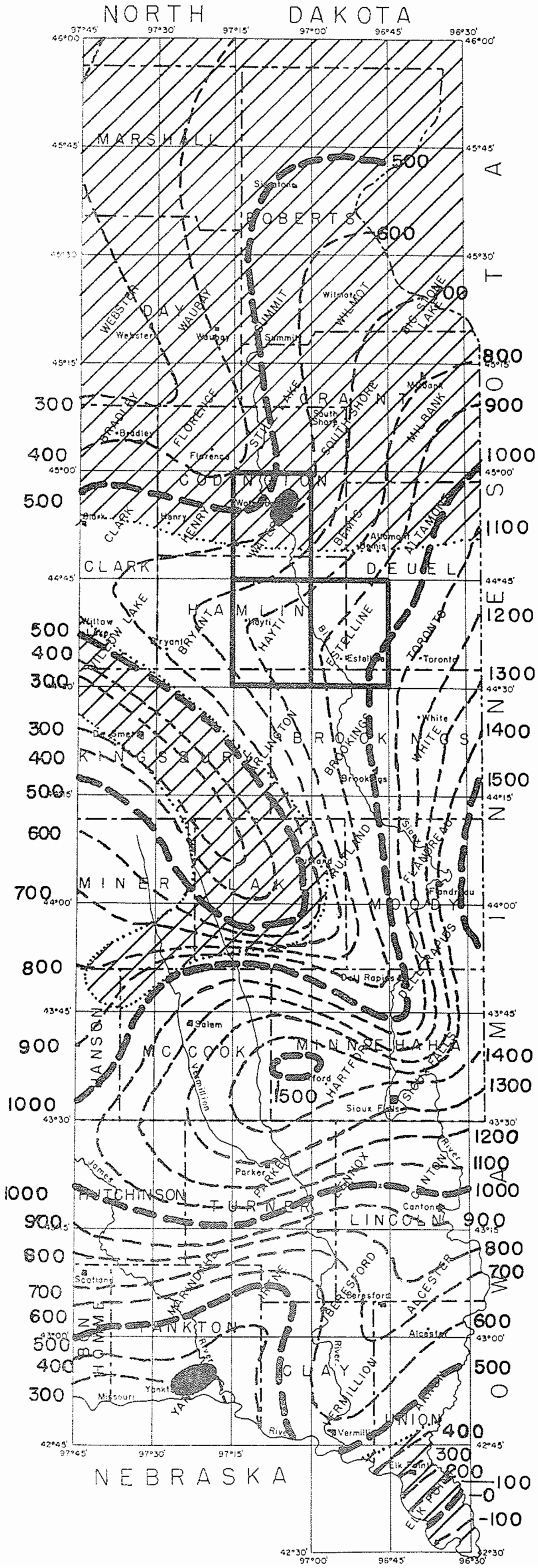
Ortonvile (Milbank) granite.--About 40 miles northeast of Watertown the Ortonville granite is exposed at the surface as roches moutonees (sheep rocks) amid the glacial deposits. The rock is deep-red biotite granite, composed mainly of orthoclase, microcline, quartz, and biotite. Microscopic characteristics of the rock are its microperthitic and myrmekitic textures (Steece, 1953b) and Thiel and Dutton, 1935). What is assumed to be this same rock was found in southeastern Day County in the Oil Ventures #1 Naessig oil test in NE$\frac{1}{4}$SE$\frac{1}{4}$ sec. 32, T. 121 N., R. 55 W.

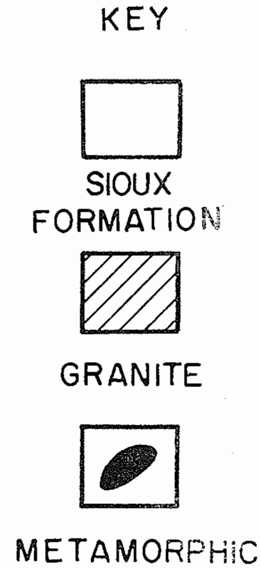
Metamorphic rocks.--Metamorphic rock has been found at one locality in this area. The well at the U.S. Bureau of Reclamation sub-station east of Watertown (SE$\frac{1}{4}$ sec. 3, T. 116 N., R. 52 W.) recovered bottom-hole samples of olive-green serpentine, magnetite, chlorite, biotite, and muscovite (Erickson, 1954, p. 49). Other metamorphic rocks have been discovered in wells both north and south of the area of study. It is likely that these rocks are confined to rather small areas of local Precambrian deformation.

Sioux Formation.--The Sioux Formation, of Precambrian age and younger than the granite that it overlies, is commonly called "Sioux Quartzite" (Baldwin, 1951). The Sioux Formation is a pink to red hard silica cemented sandstone (orthoquartzite); it is jointed, bedded and cross-bedded, and interbedded with red sericitic siltstone ("pipestone"), and conglomerate that is locally cemented with silica. The Sioux Formation is present as far north as southern Codington County (fig. 4). The rock has a maximum thickness of approximately 3000 feet (Baldwin, 1951).

Cretaceous System

Erickson (1955) mapped exposures of Pierre Formation 85 miles to the west, 100 miles to the northwest, and 100 miles to the north of Watertown, along both sides of the Coteau des Prairies. These are the nearest exposures to the area of study. Well logs in and around the Watertown-Estelline area have revealed the presence of the following Cretaceous rocks: Dakota Group and the Graneros, Greenhorn, Carlile, Niobrara, and Pierre Formations, arranged in ascending order.





SCALE IN MILES

10 0 10 20

STATE GEOLOGICAL SURVEY

VERMILLION, SOUTH DAKOTA

FIG. 4. DISTRIBUTION AND TOPOGRAPHY OF PRECAMBRIAN ROCKS IN EASTERN SOUTH DAKOTA.

Dakota Group.--Even though three separate formations of Early Cretaceous age have been recognized in the past, from oldest to youngest the Lakota, Fuson, and Dakota, Gries (1954) has shown evidence that the Lower Cretaceous sequence is rather complex. The Lakota, Fuson, and Fall River are recognizable units in western South Dakota and can be traced with continuity into the central part of the State. However, farther east they merge imperceptibly into a thick sequence of sands, shales, and coals in extreme eastern South Dakota, apparently losing their identity in the Dakota massive sands. An added complication is the Newcastle sandstone, which overlies and is separated from the Fall River sandstone by the Skull Creek shale; traced eastward from the Williston Basin, the Newcastle is also lost in the Dakota Group.

Because these individual units cannot be identified in eastern South Dakota, the terms Lakota, Fuson, and Dakota Formations have been discarded in that part of the State, and the sedimentary rocks formerly assigned to these formations are now given the name Dakota Group (A. F. Agnew, personal communication, May 1958).

The Dakota Group consists of cemented to unconsolidated, coarse to fine, massive to bedded and cross-bedded, buff red and white sands; massive varicolored bentonitic shales; and many lignite zones. The shales contain nodules of goethite, commonly termed "Fuson pellets". The average thickness of the Dakota Group in the area of study is about 150 feet.

Graneros Formation.--In the Watertown-Estelline area the Graneros Formation is chiefly shale, but locally is sandy. The thickness of Graneros Formation in the area averages 155 feet.

Greenhorn Formation.--The Greenhorn Formation is light- to dark-gray fragmental limestone and light- to dark-gray marl and marly shale. The limestone is dense and easily recognized both in well cuttings and in exposures. The Greenhorn produces a characteristic limestone curve on the electric log, and thus the formation is good structural datum. The thickness of the Greenhorn in this area averages 31 feet.

Carlile Formation.--The Carlile Formation consists chiefly of gray fissile shale; it has thin interbedded sands and impure limestones. The Codell sandstone persists near the top of the formation. The Carlile averages 196 feet in thickness, ranging from 77 to 277 feet.

Niobrara Formation.--The Niobrara Formation is mainly light- to dark-gray chalk and marl which weathers buff to white. The formation contains thin impure bentonite beds and a luxuriant microfauna (Bolin, 1952). The Niobrara is easily identified in well cuttings and, like the greenhorn, gives a characteristic curve on the electric log. The Niobrara ranges from 30 to 250 feet in thickness and averages 93 feet in the area of study.

Pierre Formation.--The Pierre Formation consists of light- to dark-gray fissile shale with many thin bentonites and concretionary layers of iron-manganese. The Pierre has been divided into six members along the Missouri River in South Dakota. However, it is difficult to correlate these members in the subsurface east of the Missouri River, because of the similarity of the rock chips in well cuttings. The thickness of the Pierre Formation is variable; in the Watertown-Estelline area the average thickness is 243 feet.

Structure

The Watertown-Estelline area is in the stable interior of the United States, where evidence of tectonic activity is small. The surface of the Precambrian (Steece, 1953a) shows an uneven topography with a general slope to the west-northwest.

The Cretaceous strata are relatively flat in the Watertown-Estelline area, as is shown by the altitude of the Greenhorn in three wells. In the Milbank city well the Greenhorn is 875 feet above sea level. It is present in the U. S. Bureau of Reclamation well east of Watertown at the same altitude. In the Oil Ventures #1 Naessig oil test the altitude of the Greenhorn is 794 feet above sea level. The dip of the Greenhorn is thus determined as less than a half degree, to the N. 54° W.

The contact between the Cretaceous strata and the Precambrian basement is unconformable, and in places a series of overlaps or stratigraphic "traps" undoubtedly exist.

ECONOMIC GEOLOGY

Ground Water

General Statement

The most important economic mineral resource in the Watertown-Estelline area is ground water. The monetary return from irrigating crops is, in most cases, sufficient to warrant the initial expense in establishing an irrigation system. Small industries, also, could find adequate water for their operations.

The pore spaces in the surficial deposits of the Watertown-Estelline area are filled with water below the water table. Because the outwash is more permeable than the surrounding till, and thus permits the water to move through the pores, supplies of water in them are available for use; the discussion is thus concerned primarily with the outwash deposits.

The water table is a surface that has irregularities much like the land surface, and it conforms roughly with the land surface. Where the land is high the water table is higher than elsewhere, although it does not reach the surface; where the land is low, however, the water may rise above the land surface as ponds and lakes. The average depth to the water table in the outwash gravels as determined by borings is twelve feet.

The surface of the outwash deposits slopes to the south. The water table surface should also slope to the south. There is thus a slow continuous movement of water through the sands and gravels from north to south in the Watertown-Estelline area. The rate of movement has not been determined.

Occurrence

Ground water in the Watertown-Estelline area occupies the interstices of all the unconsolidated Pleistocene deposits.The quantity of water in a particular deposit depends on several factors, among which are porosity, permeability, and extent of the materials.

In general, coarse-grained unconsolidated material is more permeable than fine-grained material, depending on the arrangement of the grains (fig. 5). Porosity, however, is dependent not on grain size but on grain shape. The most permeable deposits in the Watertown-Estelline area are the sands and gravels of the

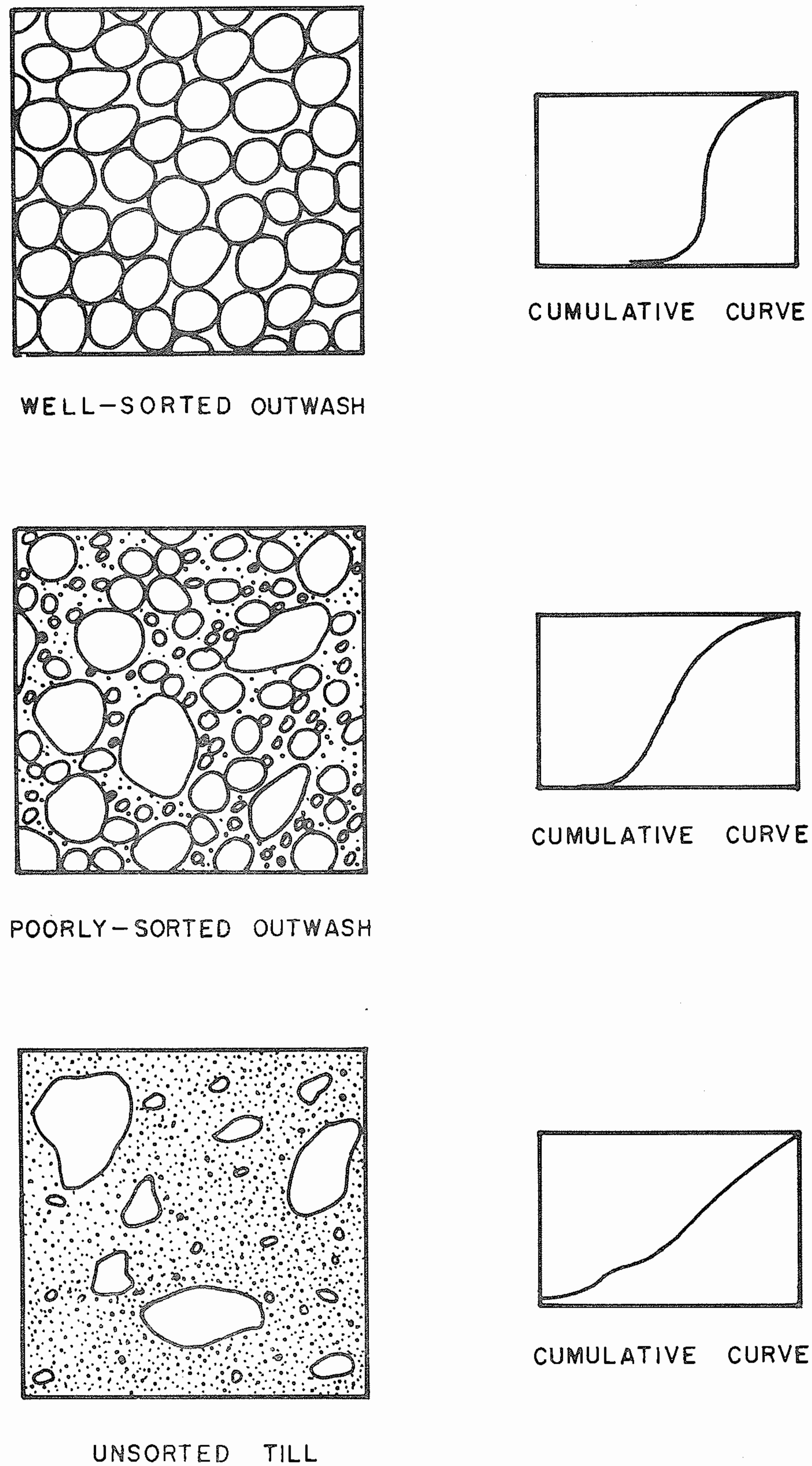


FIG. 5. PARTICLE SORTING AND ARRANGEMENT IN THREE IDEALIZED GLACIAL DEPOSITS.

outwash, for the tills are too poorly-sorted, and the lake deposits and loess are too fine-grained to have high permeabilities (fig. 6). All the deposits probably are nearly equal in porosity, with the lake deposits and loess having slightly higher porosities than the tills and outwashes. Therefore, the outwash contains the major shallow ground water resources in the area. The loess curve (fig. 6) shows that this material is very fine-grained (increase in Phi-Ø-values represents decrease in diameter of particles (Table 6, Appendix) and that it is fairly well-sorted, that is, most of the grains fall within a narrow range of sizes (About 50 percent of the grains in the sample shown fall between two Phi units). However, the grains are all small in diameter and whereas the porosity may be as high as 60 or 70 percent, the permeability is low.

The lake sand curve shows that more than 75 percent of the grains are restricted to two Phi units. This material has not only a higher degree of sorting, but also is somewhat coarser than the loess. Thus its permeability is greater. The average frequency-distribution of outwash gravel samples from the Watertown-Estelline area shows that it is a fairly well-sorted material (50 percent of the grains fall between two Phi units). Even though this material is not so well-sorted as the lake sand, it has a higher degree of permeability than the latter, because it is composed of coarser material.

The tills in the Watertown-Estelline area are unsorted (only about 20 percent of the grains fall within two Phi units). The curve shows that the tills contain some material that is coarser than that in the lake sand and loess, but that they have about the same median size as the outwash gravel. The tills have, however, a greater percentage of sand, silt, and clay that fill the openings between the larger grains and the permeability of the tills is lower than the other deposits.

Probably the most important factor affecting the occurrence of ground water in this area is the extent of the outwash deposits (pl. 1). The outwash sands and gravels cover approximately 168 square miles of the Watertown-Estelline area, and average 52 feet in thickness, resulting in 7,750,000,000 cu.yd. of sand and gravel. Much of this sand and gravel cannot be considered as a source of irrigation water because it is collapsed material that contains some till or because it is in unconfined terraces. Omitting the areas of collapsed outwash and unconfined terrace deposits, the remaining area of outwash sands and gravels is 112 square miles, which contains approximately 5,850,000,000 cu. yd. The average depth to water is 12 feet. By using the 40-foot thickness of saturated outwash, the resulting volume of saturated sand and gravel is 4,475,000,000 cu. yd. Using an average porosity of 30 percent for the outwash material, the total amount of available water in the outwash is 832,000 acre-feet or 271,000,000,000 gallons.

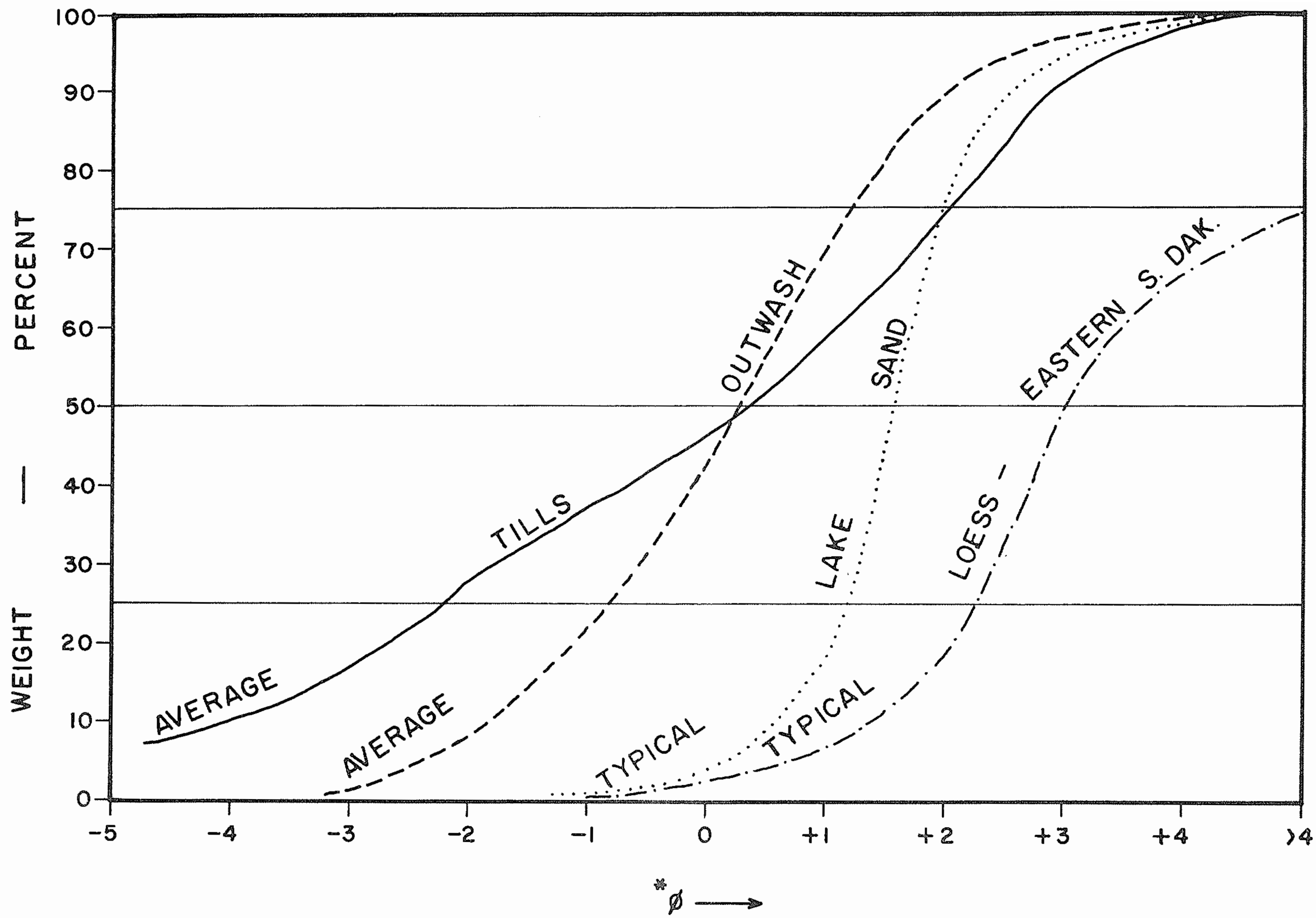


FIG. 6. COMPOSITE CUMULATIVE CURVES OF PLEISTOCENE DEPOSITS IN THE WATERTOWN-ESTELLINE AREA.

*SEE TABLE 6

Movement of Water

Recharge.--The principal means of recharge in this area is by direct absorption of precipitation on the surface of the outwash. The average annual precipitation at Watertown from 1904 to 1957 was 20.93 inches. Most of this rainfall filters directly into the outwash material through the absorbant soil, as only a small amount is lost by runoff. Surface runoff from the slopes bordering the outwash, however, contributes to its recharge, because the soil developed on the tills is not as absorbant as that on the outwash. A small amount of recharge is accomplished by percolation downward from streams flowing over the outwash deposits. This is especially true during periods of great precipitation and flood, when the surface of the outwash is covered by water.

Recharge is also accomplished by underflow, slow percolation of water through the outwash material from up-stream areas.

Discharge.--Discharge is the removal of water from the outwash and is dependent on several factors, including the position of the water table, the number of wells in the reservoir, and the relationship of the streams to the outwash.

The greatest amount of discharge in the Watertown-Estelline area is by wells, as more than 250 domestic wells draw water from the outwash of this area. The wells range in depth from eight to 80 feet, averaging 20-25 feet. The water table in most of the wells stands within 10 or 20 feet of the surface.

Natural discharge by underflow from the outwash down the gradient accounts for some water loss. This discharge depends on the amount of water in the stream, the rate of flow in both stream and outwash, and the relation of the stream to the outwash; however, this amount of discharge is believed to be insignificant in the over-all ground water picture.

Transpiration of water by plants, and direct evaporation of water to the atmosphere account for some loss of water from the outwash reservoir. The exact amount is unknown, but the loss by evapo-transpiration is small in general aspects.

Recovery.--When a pump discharges water from a well the surface of the water table is lowered around the well and a hydraulic gradient is established from all directions toward the well, forming a cone of depression. As pumping continues this cone of depression increases in diameter until discharge and recharge have reached equilibrium. Wells which lie in the area influenced by the cone of depression are affected markedly; their water levels decline to correspond with the declining water table. When pumping ceases the water table recovers its normal level, and the wells which were affected by the lowered water table also return to normal.

The rate of recovery depends on the permeability and the amount of water contributed as recharge.

Quality of Water

Water which falls as rain and snow is relatively pure. As soon as it reaches the land it begins to react chemically with the material with which it comes in contact. The amount and kind of mineral matter that it dissolves depend on several factors, including the chemical and physical composition of the materials the water has contacted, the atmospheric temperature and pressure, the duration of the water-land contact, and the amount of minerals already in solution.

In the Watertown-Estelline area the mineral content of the water is derived from the gravels. Limestone dissolves and produces ions of Calcium (Ca) and Carbonate (CO_3) in the water. Similarly, basic igneous rocks produce iron (Fe), and magnesium (Mg) ions and suspended silica (SiO_2) particles in the water. Sodium (Na) and Potassium (K) are derived from the solution of the feldspar minerals.

Table 2 shows the analyses of selected water samples in the Watertown-Estelline area. In general the following constituents when found in excessive concentrations are considered deleterious to its use in irrigation.

Boron.--Concentrations of more than 0.4 ppm of boron are considered toxic to most plants. According to the State Chemist, however, South Dakota waters are so very low in this constituent that it may be neglected (Don Mitchell, State Chemist, personal communication, April, 1958).

Sodium.--Waters containing high percentages of sodium have adverse effects on the physical structure of soil. Among these effects are: 1) soils become difficult to work, 2) water penetration to the rootzone is retarded, and 3) leaching of salts from the rootzone is impeded. Generally, a small amount of sodium is tolerable.

Calcium, Magnesium, and Potassium.--Waters high in calcium are preferred to those high in either magnesium or sodium. Some magnesium is essential to plant growth. Potassium is usually not in sufficient concentration in natural waters to cause harmful effects.

Carbonate and Bicarbonate.--The presence of carbonate in water indicates alkalinity and is an undesirable constituent. As soils become more alkaline, phosphate becomes less available and symptoms of chlorosis (blanching of green parts) is more prevalent. Bicarbonate has an uncertain significance in regard to plant development but is not considered to be as toxic as carbonate or as chloride or sulfate.

Table 2.--Analyses of Water Samples from Watertown-Estelline Area

PPM Constituent \ Well	1*	2	3	4	5	6	7	8	9	Watertown city Well #2	Estelline town well #1	Hayti town well #1	Castlewood town well #2	Lake Norden town well #1
Calcium	58	214	62	94	80	188	86	122	65	61	92	98	145	147
Magnesium	28	116	45	38	29	63	43	92	51	23	35	37	48	53
Sodium	13	468	12	18	10	30	20	50	17	16	24	24	68	24
Potassium	3	12	6	3	4	6	2	4	3					
Bicarbonate	235	210	260	265	255	280	245	405	315	218	334	281	410	381
Carbonate	20	10		50	40	40	10	40						
Sulfate	30	1650	83	160	65	433	150	290	55	64	56	150	150	326
Nitrate	5	3	5				6	1	1	.2	12	2	40	
Chloride	10	43	5	5	10	10	15	33	18	11	18	32	59	9
Iron	4.8	.15				1		.1		.06		.02		.24
Silica	22	28	26	24	23	22	24	24	23					
Dis. Solids										310	525	581	892	845
Hardness	260	1015	340	390	320	242	390	684	368	243	376	396	560	584
Alkalinity M.O.	255	210	260	315	295	320	245	445	315					
Alkalinity P.P.	10	10		25	20	20	10	20						
Conductivity	660	3510	705	930	705	1400	840	1420	800					
% Sodium	1.2	58.7	7.1	12.0	6.5	8.2	10	18.9	12.8	12.5	15.9	15.1	26.0	10.7
pH	Average pH = 7.5													
Class	1	3	1	1	1	2	1	2	1	1	1			2
Source	Outwash	Iowan till	Outwash	Cary till	Out-wash	Collapsed outwash	Out-wash	Iowan till	Iowan till	Outwash	Outwash	Collapsed outwash	Outwash	Cary till
Depth (feet)	25	495	20	82	20	46	20	125	35	27	26	51	20	24

*For location of samples 1 - 9, see Plate 2, Pocket

Samples 1 - 9 analysed by O. Olsen, Head Station Biochemistry, South Dakota Agricultural Experiment Station, State College, Brookings, South Dakota, 1957

Samples from city wells analysed by Division of Sanitary Engineering, South Dakota State Board of Health, Pierre, South Dakota, 1956

Sulfate and Chloride.--A small amount of sulfate is essential to plant growth, but few soils are deficient in this constituent. In general, higher concentrations of sulfate can be tolerated if higher concentrations of calcium are present.

Chloride is not essential to plant development. In fact, increase in chloride in the soil solution and increase in sulfate above that required results in retardation of plant growth.

During irrigation the waters concentrated in the soil around the plant roots may be three to eight times as concentrated as the irrigation water, as a result of transpiration by plants and evaporation to the atmosphere. The concentration of ions in the rootzone thus exceeds by many times that in the irrigation water, as a result of inadequate leaching of the rootzone by 1) insufficient volume of water, 2) improper methods of application, 3) impermeable soils, and 4) the presence of hard-pan layers at the base of the soils.

Therefore, in evaluating the probable effects of water upon crops, consideration must be given to the fact that plants are not subjected to the ionic concentrations as they exist in the water supply, but rather to the concentrations as they exist in the soil solution of the rootzone. It is evident, then, that in any classification of water supply, general terms must be used and the optimum limits of concentration ranges must be arbitrary. Table 3 is such a classification.

The United States Public Health Service (1946) has established standards of water used for human consumption. Table 4 is a tabulation of these data.

In addition to the limits set forth in Table 4, the following requirements should be met for chemically treated drinking water, i.e., water which is lime softened or softened with zeolites or other ion-exchange treatment: 1) phenolphthalein alkalinity (as calcium carbonate) should not exceed 15 ppm plus 0.4 times the total alkalinity; 2) the normal carbonate alkalinity should not exceed 120 ppm; and 3) if alkalinity is produced by chemical treatment the total alkalinity should not exceed the hardness by more than 35 ppm (calculated as calcium carbonate).

Suggestions for Development of Irrigation

Owing to higher circulation rates of water from the reservoir to the soil and back to the reservoir by percolation in the pumping season, a greater danger of salt accumulation is imminent at this time. Periodic analyses of the water should be made and corrective measures should be taken to prevent excessive accumulation of salts.

Because of the sandy and silty nature of the soil developed on the outwash sand and gravel, water can pass through it fairly easily. This, plus the fact that the land on the outwash is generally level, would suggest the use of sprinkler rather than ditch type irrigation in the Watertown-Estelline area.

Table 3.--Qualitative Classification of Irrigation Waters

Classification	Per-cent Sodium	Boron (ppm)*		Chloride (ppm)	Sulfate (ppm)
		Sensitive Plants	Tolerant Plants		
Class 1 Excellent to Good	0-40	Under 0.4	Under 1.00	Under 71	Under 192
Class 2 Good to Injurious	40-70	0.40-1.00	1.00-2.00	71-213	192-576
Class 3 Injurious to Unsatisfactory	70-100	1.00+	2.00+	213+	576 +

*ppm - Parts per million

Table 4.--United States Public Health Service Standards for Drinking Water

Constituent	Standard Limits (ppm)
Copper (Cu)	3.0
Iron and Manganese (Fe) and (Mn) together	0.3
Magnesium (Mg)	125
Zinc (Zn)	15
Chloride (Cl)	250
Sulfate (SO_4)	250
Lead (Pb)	0.1
Fluoride (F)	1.5
Nitrate (NO_3)	10.0
Arsenic (As)	0.05
Selenium (Se)	0.05
Hexavalent Chromium (Cr)	0.05
Phenolic Compounds	0.001
Total Solids	500*

*Total solids may exceed 500 ppm to a maximum of 1000 ppm if the water having this concentration is the only water available.

Each irrigation well should be deep enough so that it completely penetrates the sands and gravels of the outwash. Because the gravel thicknesses range up to 96 feet, the depth of the wells will range accordingly. The wells should be located generally in the body of the outwash and not near the till borders. Normally, wells should not be located in areas of collapsed outwash or in unconfined terrace deposits, as these cannot be considered predictable as water sources.

Deep Water

Several subsurface formations in most parts of the State supply adequate quantities of water for most domestic uses. These formations include the Dakota Group, the Codell sand member of the Carlile Formation, the Niobrara ("Chalkrock") Formation, and the Sioux Formation. The waters from these formations vary widely in chemical quality and are unsuited for irrigation. Many wells in the area draw water from sand and gravel lenses in till, but this water is usually very hard and the quantity is not great.

Although little information is available on the subject, the possibility of drawing water from buried stream channels has been suggested. Flint (1955) has mapped the course of several of these in eastern South Dakota.

Sand and Gravel

Sand and gravel is obtained from many pits throughout the area (Pl. I). Much of this washed and graded material is used as concrete aggregate, and nearly every secondary road in the area is surfaced with gravel. In general, the gravels are of fairly good quality for aggregate and road metal, except locally where abundant chalk and shale are present in the material. Table 7 shows the composition of selected gravel samples from the Watertown-Estelline area. An estimated reserve of 7,750,000,000 cubic yards of gravel is present in the Watertown-Estelline area. The average thickness of the deposits is 48 feet.

Oil and Gas Possibilities

Petroleum has not been found in commercial quantities in eastern South Dakota. Several shows have been reported in borings south of Sioux Falls, but none in the northeastern part of the State. The possibility exists that the stratigraphic "traps" formed by Cretaceous rocks lapping the Precambrian basement in this area could yield commercial oil if the conditions of migration and accumulation had been fulfilled in past geologic ages.

Clay

The tills in the Watertown-Estelline area are composed of from 40 to 60 percent of clay size particles. Clays of similar character have been used successfully in the manufacture of bricks in various parts of the State and could be used in the Watertown-Estelline area. Other sources of clay are loess and lake deposits, although these are not so widespread as the tills.

SUMMARY

The Watertown-Estelline area, in northeastern South Dakota, covers an area of about 650 square miles in the northern part of the Coteau des Prairies.

Pleistocene deposits of the Wisconsin glacial stage mantle the surface of the area and are classed as till, outwash, lake beds, and loess.

The till is chiefly clay; it is sandy and contains rock fragments up to boulder size. Loess and lake bed deposits are likewise fine-grained. The outwash consists of coarse and fine sand and gravel, and contains large quantities of water. The total value of outwash sand and gravel in the area is 7,750,000,000 cu. yd., containing 832,000 acre-feet or 271,000,000,000 gallons of water.

The quality of the water in this area is generally good to excellent for irrigation, but periodic analyses should be carried out during the pumping season.

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APPENDIX

Table 5.--Temperature and Precipitation at Watertown South Dakota from 1904-1957 (U. S. Weather Bureau)

Year	Temperature (°C)			Precipitation (inches)		
	Mean Annual	High	Low	Annual Total	High	Low
1904	39.8	95	-36	19.44	5.08	0.01
1905	41.3	93	-38			
1906	41.6	93	-19	22.62	4.30	0.26
1907	39.6	91	-29	16.72	2.80	0.00
1908	43.8	96	-20	23.80	6.12	0.25
1909	42.1	95	-29	22.94	4.56	0.10
1910	44.3	98	-21		3.17	T
1911	42.21	100	-28	17.96	4.24	0.14
1912	40.4	96	-38	23.30	5.16	T
1913	42.4	98	-23	20.58	4.30	0.10
1914	42.1	98	-30	23.91	8.99	T
1915	41.8	90	-29	23.66	5.49	0.10
1916	38.9	97	-40	25.93	7.40	0.02
1917	38.1	108	-35	16.98	3.03	T
1918	42.3	94	-29	22.29	4.73	0.35
1919	43.3	99	-30	21.69	6.50	0.02
1920	43.2	95	-20	17.66	3.72	0.15
1921	46.3	97	-20	26.07	7.22	T
1922	43.9	99	-26	20.47	3.49	0.35
1923	44.3	94	-20	15.88	5.29	0.15
1924	41.3	90	-32	26.31	5.86	0.13
1925	43.1	97	-23	18.52	7.27	0.08
1926	42.0	101	-29	16.62	3.58	0.06
1927	41.4	94	-27	22.08	5.11	0.16
1928	43.4	100	-32	16.41	4.41	0.18
1929	Incomplete					
1930	44.7	106	-32	15.57	3.42	0.02
1931	48.7	107	-15	19.27	8.16	0.03
1932	43.5	101	-24	21.56	5.31	0.02
1933	46.0	108	-28	12.32	2.65	T
1934	46.6	110	-20	20.93	5.65	0.04
1935	43.8	101	-29	20.34	4.61	0.17
1936	42.0	106	-36	14.56	3.06	0.30
1937	41.7	102	-23	21.44	4.62	0.36
1938	45.2	101	-22	20.64	4.05	0.12
1939	45.8	102	-26	20.93	6.11	0.02
1940	42.4	109	-28	21.52	5.40	0.12
1941	44.0	103	-23	18.88	8.88	0.09
1942	42.4	94	-29	25.84	6.80	0.02
1943	41.3	98	-33	27.32	5.65	T
1944	43.3	97	-20	18.71	3.21	0.11
1945	41.3	99	-20	21.66	5.22	0.32
1946	42.9	96	-20	26.32	6.00	0.07
1947	41.9	104	-20	20.03	4.18	0.03
1948	42.1	98	-31	24.54	5.63	0.06
1949	43.0	99	-26	17.82	4.55	0.01
1950	38.8	93	-27	18.21	6.14	0.03
1951	38.7	91	-31	22.06	5.00	0.08
1952	42.6	96	-28	14.55	5.10	T
1953	43.7	96	-20	29.12	8.15	0.12
1954	43.3	98	-30	18.04	3.74	0.02
1955	42.4	99	-28	22.97	4.74	0.16
1956	41.7	98	-25	27.63	6.25	0.13
1957	42.5	99	-25	23.00	5.68	0.21

T.--Trace of precipitation.

Table 6.--Conversion Units for Phi (Ø) Scale

Wentworth's Limits (mm)	Phi (Ø) Units	A.S.T.M. Screen Size
32-64	-5	1¼
16-32	-4	5/8
8-16	-3	5/16
4-8	-2	# 5
2-4	-1	#10
1-2	0	#18
½-1	+1	#35
¼-½	+2	#60
1/8-1/4	+3	#120
1/16-1/8	+4	#230
1/32-1/16	+5	
1/64-1/32	+6	
1/128-1/64	+7	
1/256-1/128	+8	
1/512-1/256	+9	
1/1024-1/512	+10	

Table 7.--Lithologic Analyses of Gravel Samples in the Watertown-Estelline Area (Number - Percent)

Sample No.	G-1 Cary	G-3 Cary	G-4 Taz.	G-6 Taz.	G-7 Cary	G-8 Cary	G-9 Cary	G-10 Cary	G-11 Cary
Location / Rock Type	NWNW sec. 23, T.113 N., R. 53 W.	NWNW sec. 26, T.114 N., R.52W.	SWNW sec. 24, T.113 N., R.51W.	NESE sec. 33, T. 117 N., R. 52W.	N¼ corner sec.15, T. 116N., R. 52 W.	NW sec.25, T. 117 N., R. 53 W.	SE sec.21, T. 115 N., R. 52 W.	SE sec.20, T.114 N., R. 51 W.	SW sec.13, T.112 N., R. 51 W.
Limestone	18.4	19.9	22.8	27.1	24.6	18.8	12.5	22.9	22.8
Dolomite	34.2	22.2	32.4	31.6	21.3	18.2	27.1	30.5	22.8
Chalk	0.5	--	0.6	0.4	--	--	1.0	--	--
Red Granitic	12.9	11.9	7.9	7.6	13.1	14.9	10.4	13.4	9.1
Lt.colored Granitic	17.3	22.7	19.2	14.2	14.7	17.6	22.9	12.7	15.9
Other Igneous & Metamorphics	13.3	8.5	7.2	6.7	18.0	13.0	18.8	8.3	11.4
Shale	0.5	3.9	4.3	7.5	1.6	5.8	--	5.7	13.6
Sandstone	1.9	6.8	3.6	--	4.4	3.2	--	3.2	2.3
Secondary Silica	0.9	2.3	0.6	1.3	2.2	3.9	4.2	--	--
Secondary Calcium Carbonate	--	--	--	0.4	--	--	--	--	--
Limonite	--	3.17	1.3	3.1	--	4.5	3.1	2.5	2.3
TOTAL	99.9	99.9	99.9	99.9	99.9	99.9	100.0	99.2	100.2

Table 8.--Textural Analyses of Gravel Samples in Watertown-Estelline Area (weight-percent)

Location	No.	Diameter in Phi (Ø) Units											Total weight percent
		-5	-4	-3	-2	-1	0	+1	+2	+3	+4	<+4	
NW,NW sec. 23, T. 113 N.,R.53W. Hamlin County	G-1 Cary	--	10.8	15.3	19.4	18.3	12.3	11.5	7.5	2.9	1.0	1.4	100.4
NW,NW sec. 23, T.115N.,R. 52 W. Hamlin County	G-2 Taz	--	5.1	13.6	18.1	15.8	16.4	13.7	9.9	4.1	0.9	2.5	100.1
NW,NW sec. 26, T.114 N.,R.52 W. Hamlin County	G-3 Cary	--	16.1	18.6	18.6	14.0	14.8	10.7	4.6	1.2	0.4	0.8	99.8
SW,NW sec. 24, T.113 N.,R.51 W. Hamlin County	G-4 Taz	19.7	4.8	12.5	14.7	13.1	13.7	12.3	5.5	1.8	0.5	1.2	99.8
NE,NW sec. 20, T.114 N.,R. 50W. Deuel County	G-5 Taz	17.7	2.1	6.2	7.6	11.1	17.0	23.0	11.1	2.8	0.5	0.8	99.0
NE,SE sec. 33, T.117 N.,R.52 W. Codington County	G-6 Taz	--	5.6	8.1	8.2	11.6	17.5	22.0	17.5	6.1	1.4	2.0	100.0
N¼ cor. sec.15, T.116N.,R. 52 W. Codington County	G-7 Cary	7.2	4.4	6.7	8.9	13.6	18.3	21.0	13.9	4.3	0.9	0.8	100.0
NW sec. 25, T. 117 N., R.53 W. Codington County	G-8 Cary	--	1.7	6.6	8.1	8.2	11.5	20.9	26.5	13.3	2.0	1.3	100.0
SE sec. 21, T. 115N., R. 52 W. Hamlin County	G-9 Cary	--	--	--	5.5	15.1	20.0	27.2	22.2	6.8	0.8	1.8	99.4
SE sec. 20, T. 114N., R. 51 W. Hamlin County	G-10 Cary	--	--	3.1	11.5	16.5	21.0	25.0	15.6	4.8	0.6	1.3	99.4
SW sec. 13, T. 112 N.,R. 51 W. Brookings County	G-11 Cary	--	--	0.7	3.1	11.6	21.0	30.2	18.7	10.3	1.8	2.3	99.7

Table 9.--Lithologic Analyses of Till Samples in the Watertown-Estelline Area (Number-Percent)

Sample No.	T-1 Iowan	T-2 Cary	T-3 Cary	T-5 Iowan	T-6 Iowan	T-7 Iowan	T-8 Iowan	T-9 Iowan	T-10 Iowan
Location / Rock Type	S$\frac{1}{4}$ cor. sec.23, T.115N., R. 52W.	NW,NW sec.16, T.114N., R.52 W.	NW,NW sec.36, T.113N., R.52 W.	SE,SE sec. 4, T.115N., R. 52W.	NW,NW sec. 26, T.116N., R.52 W.	S$\frac{1}{4}$ cor. sec.31, T.118N., R. 53W.	SW,SW sec. 6, T.114N., R.50 W.	SW,SE sec. 6, T.114N., R. 50 W.	NW,SW sec.6, T.115N., R. 49W.
Limestone	16.8	12.7	21.6	16.3	16.0	26.9	15.2	19.5	17.5
Dolomite	39.9	18.0	25.2	44.0	43.0	16.3	39.2	32.5	36.0
Chalk	0.5	0.1	0.4	1.3	--	--	--	--	--
Red Granitic	8.2	8.9	9.0	5.7	8.1	8.7	8.6	5.1	5.9
Light colored Granitic	11.4	9.6	10.8	7.6	6.7	13.9	7.3	8.4	6.7
Other Igneous and Meta-morphic	7.5	10.1	10.4	7.6	5.9	10.6	7.6	6.7	6.7
Shale	9.2	23.5	13.5	9.7	14.7	17.3	13.6	19.5	16.9
Sandstone	1.9	5.3	4.1	2.5	2.6	2.4	4.7	5.9	5.3
Secondary Silica	1.9	1.1	0.9	1.2	2.3	0.5	1.9	0.6	0.6
Secondary Calcium Carbonate	1.9	0.7	--	1.8	0.5	0.9	--	0.3	1.1
Limonite	0.7	10.3	4.1	1.8	0.3	2.4	1.9	1.6	3.2
Caliche	--	--	--	0.2	--	--	--	--	--
TOTAL	99.9	100.3	100.0	99.7	100.1	99.9	100.0	100.1	99.9

Table 10.--Textural Analyses of Till Samples in Watertown-Estelline Area (weight - percent)

Location	No.	Diameters in Phi (Ø) Units											Total weight percent
		-5	-4	-3	-2	-1	0	+1	+2	+3	+4	<+4	
S¼ corner sec. 23, T. 115 N., R. 52 W. Hamlin County	T-1 Iowan			16.6	11.1	9.3	10.3	12.3	15.5	16.1	6.9	1.9	100.0
NW,NW sec. 16, T. 114 N., R. 53 W. Hamlin County	T-2 Cary			6.5	6.2	5.8	8.2	13.0	20.6	24.2	11.5	4.2	100.2
NW,NW sec. 36, T. 113 N., R. 52 W. Hamlin County	T-3 Cary			1.4	4.5	5.7	8.4	13.2	21.2	27.1	13.3	5.0	99.8
SE,SW sec. 20, T. 114 N., R. 52 W. Hamlin County	T-4 Cary	11.2		2.2	4.7	6.8	8.6	12.4	18.4	22.1	10.0	3.5	99.9
SE,SE sec. 4, T. 115 N., R. 52 W. Codington Co.	T-5 Iowan		11.5	5.0	4.6	4.3	6.4	9.9	16.8	25.7	12.4	3.5	100.0
NW,NW sec. 26, T. 116 N., R. 52 W. Codington Co.	T-6 Iowan		17.6	8.3	3.8	3.9	5.4	9.0	14.3	22.2	11.1	4.2	99.8
S¼ corner sec. 31, T. 118 N., R. 53 W. Codington Co.	T-7 Iowan		7.2	4.3	8.0	7.4	8.5	12.8	21.7	22.0	6.4	1.9	100.2
SW,SW sec. 6, T. 114 N., R. 50 W. Deuel County	T-8 Iowan				0.7	2.2	4.4	10.5	22.4	37.8	17.7	4.4	100.1
SW,SE, sec.6, T. 114 N., R. 50 W., Deuel County	T-9 Iowan		5.8	5.0	7.1	5.8	7.7	11.3	18.8	23.6	12.0	3.2	99.8
NW,SW sec. 6, T. 115 N., R. 49 W., Deuel County	T-10 Iowan			2.9	4.8	6.0	7.7	12.1	21.5	26.6	14.2	4.1	99.9
NE, sec. 6, T. 114 N., R. 50 W., Deuel County	T-11 Iowan			5.5	5.4	5.5	8.5	14.6	22.2	23.6	9.5	4.9	99.7

Table 11.--Drill Hole Information, Watertown-Estelline Area

Test Hole No.	Description	Surface Elevation	Thickness sand&gravel (feet)	Depth to water (feet)	Over-burden (inches)
1	Till, sandy	1725	--	--	--
2	Gravel, sandy, clayey	1715	70	16	24
3	Coarse, silty sand	1718	85	10	36
4	Medium-coarse gravel and sand	1720	20+	--	36
5	Clayey sand and gravel	1730	16 +	--	36
6	Fine-coarse clayey sand	1696	58	5	24
7	Coarse sand-fine gravel	1715	58½	--	18
8	Coarse sand-fine gravel	1713	58	12	24
9	Medium gravel, sandy	1721	13+	--	24
10	Collapsed outwash	1706	17+	--	36
11	Medium-coarse gravel and sand and clay	1710	54	44	12
12	Till, sandy	1751	65	12	--
13	Medium-coarse sand and silt	1717	63	8	24
14	Medium-coarse sandy gravel	1749	61	9	48
15	Till, sandy	1763	37½	--	42
16	Till	1782	37	--	36
17	Medium sand and coarse gravel	1738	63	5	24
18	Silty, sandy gravel	1839	64'5"	23	7
19	Fine-medium gravel	1795	64½	12	6
20	Fine sand, silt, clay	1786	30	25	5
21	Coarse, sandy gravel	1747	64½	12	7
22	Coarse, silty sand and gravel	1743	64½	25	5
23	Coarse sand-medium gravel	1720	44½	13	5
24	Silty sand and gravel	1719	44½	12	8
25	Gravel and till	1743	25+	--	4
26	Fine to medium gravel	1787	64½	11	5
27	Fine silty gravel	1721	54½	6	6
28	Fine gravel and medium sand	1726	48	9	24
29	Fine to coarse silty sand	1706	87	8	36
30	Coarse gravel and medium sand	1750	50	5	48
31	Till	1805	30	--	12
32	Till	1761	30	--	12
33	Gravel, silty	1746	10	--	--
34	Till	1762	30	--	--
35	Till	1803	29	--	12

Test Hole No.	Description	Surface Elevation	Thickness sand&gravel (feet)	Depth to water (feet)	Over-burden (inches)
36	Fine silts and sand	1757	73	35	24
37	Coarse sand and gravel	1702	45½	8	7
38	Fine to coarse gravel	1710	60	9	7
39	Medium sand to coarse gravel	1694	56	6	48
40	Coarse sand-medium gravel	1706	63	35	24
41	Coarse sand-medium gravel	1699	56	13	13
42	Coarse sand-medium gravel	1714	54	12	8
43	Coarse sand and gravel	1713	24	13	36
44	Fine to coarse silty sand	1758	70	40	9
45	Sand and medium gravel	1744	95	30	8
46	Silty gravel	1745	15	--	36
47	Coarse silty sand and gravel	1721	92½	12	8
48	Medium sand-coarse gravel	1748	12	--	36
49	Silty, coarse sand	1752	19½	9	9
50	Fine sand-medium gravel	1747	62	3	36
51	Sandy gravel	1750	65	--	6
52	Medium sand to gravel	1752	12	--	12
53	Fine to coarse sand	1621	89½	6	6
54	Fine sand to fine gravel	1680	38½	11	4
55	Fine clayey and silty gravel	1694	64½	12	4
56	Coarse sand and very coarse gravel	1677	70	24	--
57	Sandy coarse gravel	1674	75	6	4
58	Silty coarse sand	1688	65	27	120
59	Fine sands and coarse gravel	1666	58	12	24
60	Fine to coarse gravel	1670	50	12	--
61	Silty, sandy, gravel	1671	22½	15	30
62	Silty sand	1655	72	10	36
63	Coarse sand-medium gravel	1691	69½	20	6
64	Sandy, silty, medium gravel	1697	60	20	60
65	Silty, sandy, fine gravel	1683	70	12	10
66	Medium sands and coarse gravel	1688	66	40	48
67	Fine-coarse sandy gravel	1685	39½	42	8
68	Silty coarse sand	1655	28	3	24
69	Sandy fine gravel	1657	10	--	4
70	Lake silts and clays with shells	1686	65	10	60
71	Till	1711	35	--	--
72	Till	1706	35	--	--
73	Silty, fine gravel	1674	33	26	24
74	Till	1696	35	--	--
75	Till	1697	35	--	--

Thickness (feet)

Locality H-2.--$NW\frac{1}{4}NW\frac{1}{4}$ sec. 16, T. 114 N., R. 53 W., Hamlin County

Soil, brownish-black, leached.......................... 0.5

Till, dark olive-brown, friable, calcareous, streaks of iron-oxide, profuse limonite concretions, caliche joint fillings....................16.5

Locality H-3.--$NW\frac{1}{4}NW\frac{1}{4}$ sec. 36, T. 113 N., R. 52 W., Hamlin County

Soil, brownish-black, slightly calcareous............... 1

Till, dark yellowish-brown, friable, calcareous, abundant caliche, few limonite concretions, sparse pebbles..12.5

Locality E-1.--$SW\frac{1}{4}SW\frac{1}{4}$ sec. 6, T. 114 N., R. 50 W., Deuel County

Soil, brownish-black, slightly calcareous............... 1

Loess, medium-yellow, clayey, calcareous, discontinuous... 1.5

Till, upper 15 feet exposed, dark orange-brown, friable, calcareous, streaked with gray near base, abundant limonite concretions, sparse pebbles, weathered rock fragments......................22

Locality E-2.--$SW\frac{1}{4}SE\frac{1}{4}$ sec. 6, T. 114 N., R. 50 W., Deuel County

Gravel, clean, unsorted, fine to medium................. 0-2

Till, dark orange-brown to dark olive-brown, calcareous, sandy near top, becoming clayey at base, iron staining on close-set poorly developed joints, abundant limonite concretions.........10-15

Locality E-3.--$NW\frac{1}{4}SW\frac{1}{4}$ sec. 6, T. 115 N., R. 49 W., Deuel County

Loess, yellowish-brown, calcareous...................... 0-2

Till, lower 41.5 feet exposed, medium- to dark-gray at base grading to dark olive-brown above, slightly calcareous, compact at base grading to friable at top, iron staining on wide-set indistinct joints...121