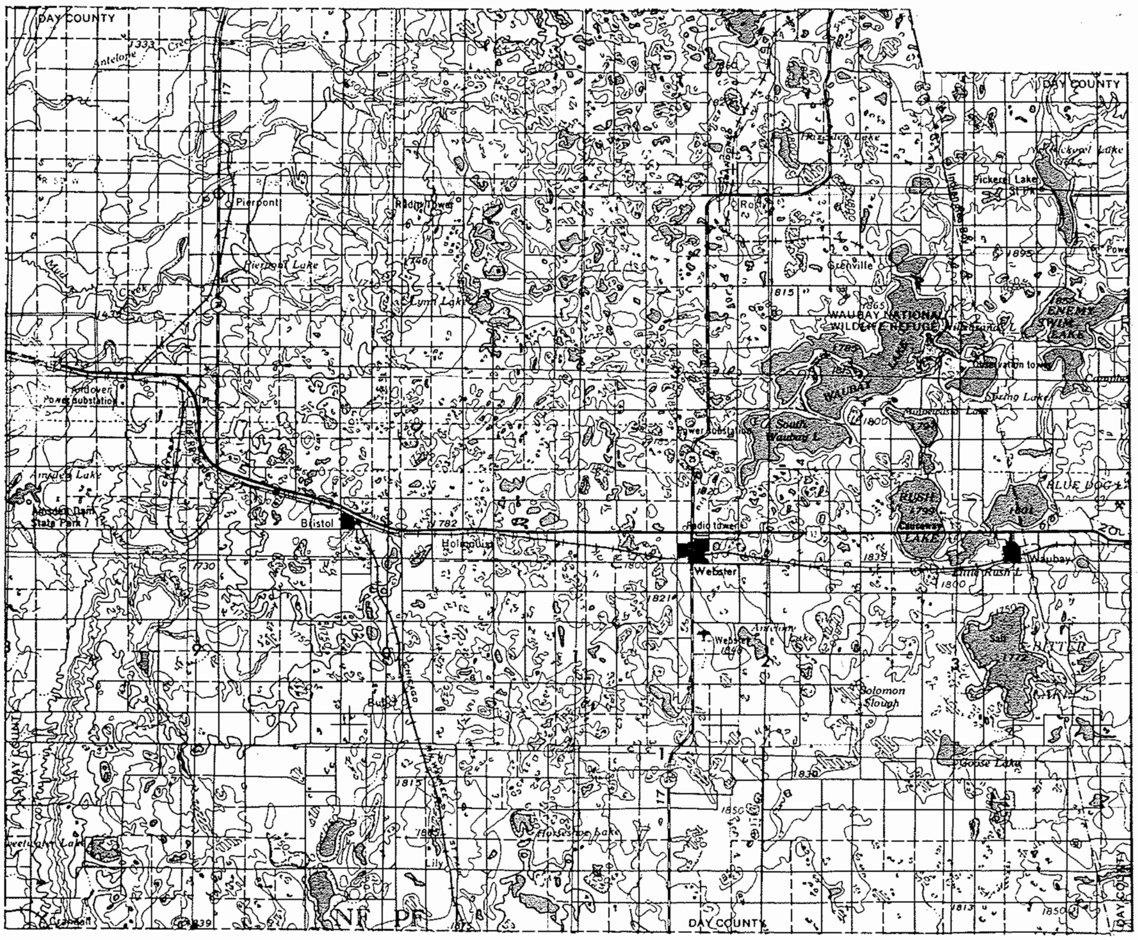
Bulletin 24

GEOLOGY AND HYDROLOGY OF DAY COUNTY, SOUTH DAKOTA

by Darrell I. Leap



Prepared in cooperation with the United States Geological Survey,
East Dakota Conservancy Sub-District,
and Day County

DEPARTMENT OF WATER AND NATURAL RESOURCES
DIVISION OF GEOLOGICAL SURVEY
1988

STATE OF SOUTH DAKOTA
George S. Mickelson, Governor

DEPARTMENT OF WATER AND NATURAL RESOURCES
John J. Smith, Secretary

DIVISION OF GEOLOGICAL SURVEY
Merlin J. Tipton, State Geologist

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Science Center
University of South Dakota
Vermillion, South Dakota

1988

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ABSTRACT

Day County includes an area of approximately 1,013 square miles in northeastern South Dakota; most of the County lies within the Coteau des Prairies. Physiographically the County is included within the Central Lowlands Province.

The climate of Day County is sub-humid with average lows in temperature of 7.3 degrees Fahrenheit in January and average highs of 70.2 degrees Fahrenheit in August. Precipitation averages about 21.5 inches annually.

Bedrock above the Precambrian basement consists of 1,000 feet of Cretaceous rocks from the Dakota Formation to the Pierre Shale on top. Three major channels are incised into the surface of the Pierre Shale.

Drift from at least three glaciations lies on the Pierre Shale and varies from a few feet to 800 feet in thickness. Advance I drift and Advance II drift are both pre-late Wisconsin in age. Both glaciations came from the east while the last, the late Wisconsin, came from the west. The presence of buried oxidized zones helped to delineate the drifts. The first two glaciers were stopped by a Pierre Shale bedrock ridge in the western part of the County. The terminus of the late Wisconsin glacier is the Waubay Moraine along the eastern side of the County. The surface of this drift is characteristically of stagnant ice origin as evidenced by moraine plateaus, shear moraines, disintegration ridges, kames, prairie mounds and vast outwash deposits which are economic sources of sand and gravel.

Lakes cover about 6 percent of the County's surface and surface drainage is mainly internal with a minor amount leaving the County. Chemical composition of lake water varies from less than 200 to almost 23,000 parts per million of total dissolved solids; greatest concentrations are in areas of discharge of regional and intermediate ground-water flow.

Four aquifer systems within the drift contain at least 53 known aquifers. Regional ground-water flow in all is east to west. Drift water is characteristically a calcium-magnesium sulfate type while Dakota Sandstone water contains mainly sodium sulfate.

Ground water will meet present stock, domestic, and municipal needs, but is of limited use for irrigation because of chemical quality and low well yields. Major lakes will provide at least 10,500 to 21,000 acre-feet of irrigation water per year, but not without some secondary environmental impact.

INTRODUCTION

Purpose of Investigation

In July 1967, the South Dakota Geological Survey and the U.S.Geological Survey began a 5-year cooperative study of the geology and water resources of Marshall, Day, and Brown Counties. This study is part of a cooperative program of the geology and water-resources evaluation in South Dakota.

This investigation was undertaken at the request of the Day County Commissioners and funded through the South Dakota Geological Survey, the U.S. Geological Survey, Day County, and the Oahe Conservancy Sub-District. The purpose of the investigation was to determine the potential mineral and water resources of Day County as well as to gain basic knowledge concerning the geology and geologic history of the County. Hydrologic investigations were instigated to determine sources of water, the amount available and the chemical quality for purposes such as domestic, industrial, stock-watering, and irrigation. The basic data collected and used in preparation of this report is contained in the appendices. This report was extended to serve as a Ph.D. thesis for the author through the Pennsylvania State University.

Location and Size of Area

Day County is located in the northeastern section of South Dakota and includes an area of approximately 1,013 square miles. It is bounded by Marshall County to the north, Roberts County and Grant County to the east, Codington and Clark Counties to the south, and Spink and Brown Counties to the west (fig. 1).

Methods of Investigation

Data for this report were obtained during the summers of 1967, 1968, 1969, 1970, and 1971, and involved field mapping on vertical air photographs having a scale of approximately 1 inch to 1 mile. In addition, data from 289 borings drilled expressly by the South Dakota Geological Survey, geophysical logging data of 64 test holes, data from 78 private drillers' logs, and interviews of owners of wells in the County were also used. Later, the data were transferred to a base map of a scale of 1 inch to 1 mile, prepared by the South Dakota Department of Highways. All cuttings from test holes drilled by the Survey were examined and described in the field; selected samples were studied and analyzed in the laboratory.

A three-dimensional model was constructed to summarize drill-hole data. Drill holes were represented by wooden dowels approximately spaced on a base map. Pertinent geological formations and drift lithologies were represented by colored sections of the dowels placed at the proper elevations. Colored strips of tape

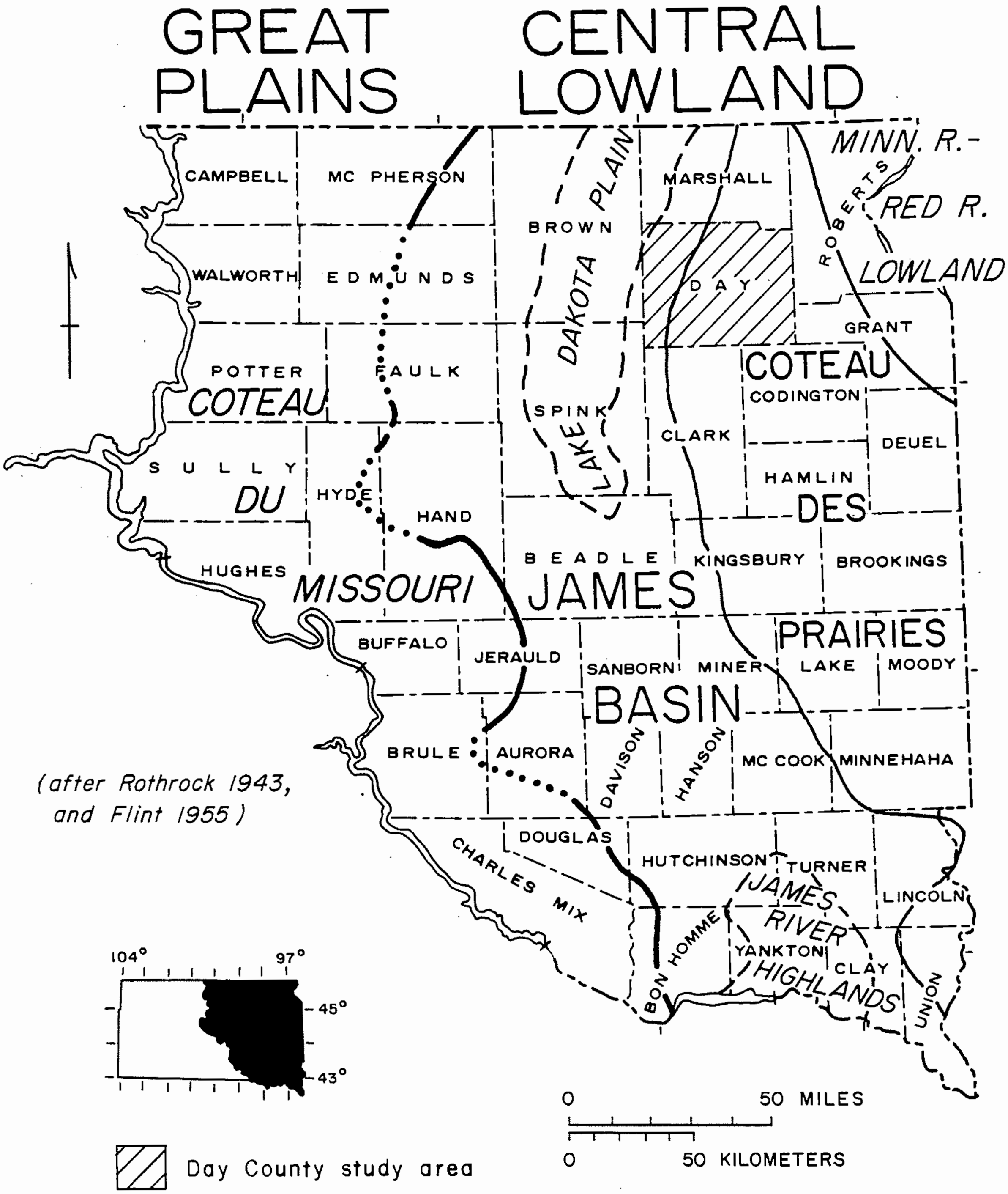


Figure 1. Map of eastern South Dakota showing locations of Day County and physiographic divisions.

were used to join formations and correlate drift units from hole to hole giving a concise and readily available three-dimensional representation of the geology of the County (fig. 2).

A computer program was prepared and a series of vertical drift variability models were generated by computer to describe the statistical distribution of aquifers throughout the County. The models are described and shown in the appendices. Another computer program was written to speed up drill-hole data handling and preparation of illustrations. The program, CROSEC, (Leap, 1974) plots out lithologic logs of drill-hole data in the form of a diagrammatic cross-section which is later hand drafted. Figure 3 shows the locations of all holes for which geologic and hydrologic data are available.

Transmissivities of the various aquifers were determined by 3 pump tests, 19 slug-injection tests, and grain-size analyses of 91 samples of aquifer materials.

Chemical analyses of 135 lake water samples taken over a 3-year period provided information for determining quality of water of the lakes. Quality of ground water was determined by chemical analyses of 203 well-water samples. Sodium absorption ratios were computed for all lake samples and for well-water samples for which sodium analyses were available.

A computer program, CUFREQ (Leap, 1974), was written to compute and plot cumulative frequency curves of grain-size analyses of aquifer materials in order to provide parameters for computing transmissivity. Another program, STAT (Leap, 1974), was also written to actually compute the transmissivities from these parameters.

Finally maps were made showing thicknesses, elevations and areal extent of all significant aquifers in the County.

Previous Investigations

The first known scientific description of the geology of Day County was made by Chamberlin, in 1881-1882 (Chamberlin, 1882). Later, Darton (1909) conducted a survey of water supplies in South Dakota which included some descriptions of artesian water supplies of Day County. The first report of the geology and hydrology specifically for Day County was published by Rothrock (1935). Also, Rothrock (1943) gives a brief geological description of parts of Day County. Flint (1955) mapped the glacial geology of all of eastern South Dakota including Day County. The Florence Quadrangle was mapped by Tipton (1958a) and includes a small part of southeastern Day County; Tipton (1958b) also mapped the Still Lake Quadrangle which includes a small strip along the Day County-Grant County line. Wood and Hedges (1964) conducted a ground-water study for the city of Langford and mapped a small section of the northwest corner of the County. Finally, a

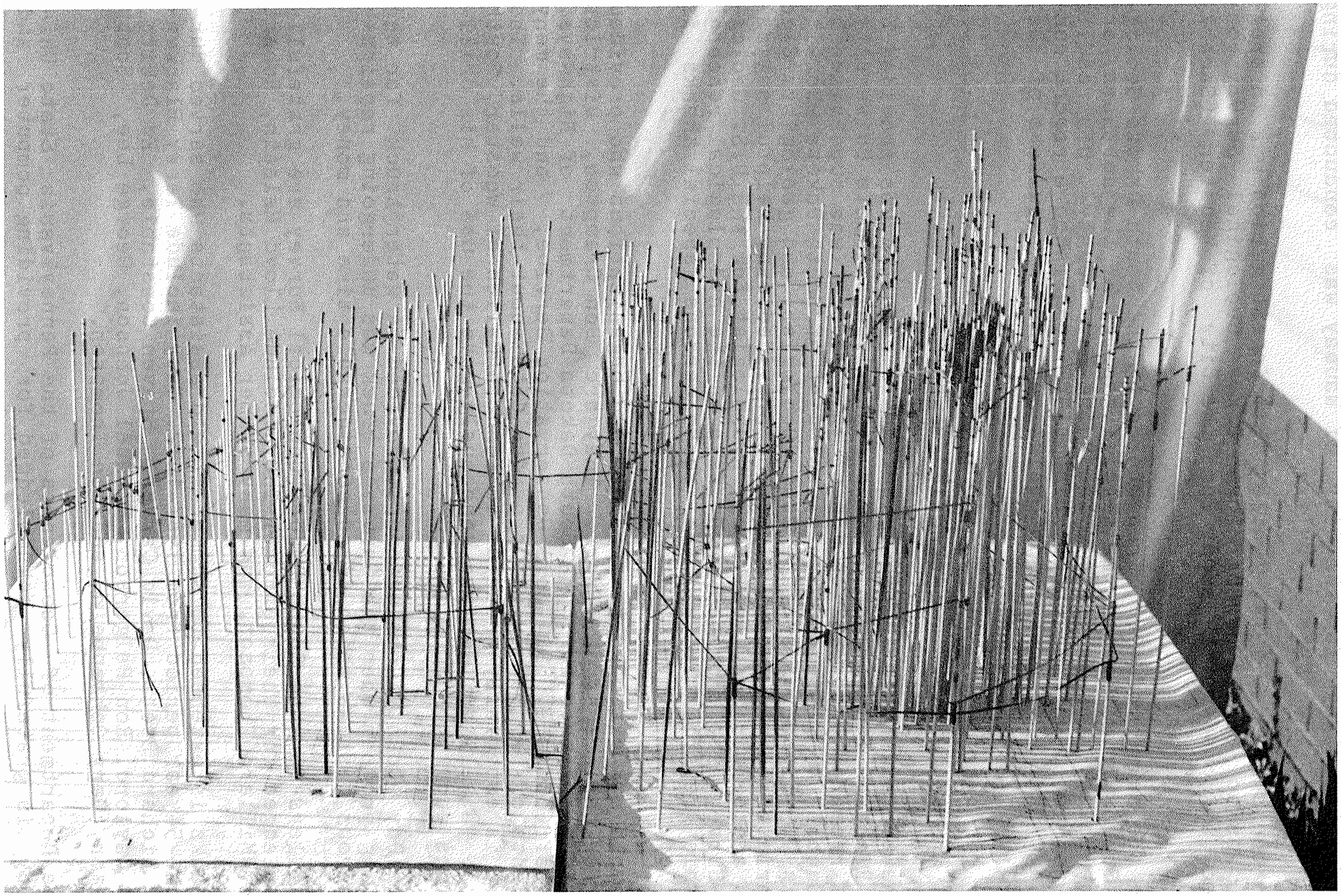


Figure 2. Photograph of three dimensional correlation model.

ground-water study for the City of Waubay was conducted during 1966 (Beffort and Hedges, 1967).

In the summer of 1971, while this investigation was in progress, Assad Barari of the South Dakota Geological Survey conducted a ground-water study for the City of Webster (Barari, 1974).

In the summer of 1966, Fred Steece of the South Dakota Geological Survey investigated the glacial geology of the northern part of the Coteau des Prairies, including Day County. His results have not yet been published. Leap (1972) published a report concerning sand and gravel potential and major aquifers of Day County.

Acknowledgments

The overall supervision of the thesis research was provided by Dr. Richard R. Parizek of The Pennsylvania State University. Field research and publication of this report was supervised by Dr. Duncan J. McGregor, State Geologist of South Dakota who with Merlin J. Tipton, Associate State Geologist, and geologists Cleo M. Christensen and Robert A. Schoon provided many helpful suggestions and criticisms. Neil Koch, hydrologist for the U.S. Geological Survey also provided much help in the hydrological research for this report. To all the above persons special thanks is extended.

Thanks are extended to persons and organizations who provided data for the research effort. They are Don Crampton, District Materials Engineer for the South Dakota Department of Highways, the staff of the U.S. Soil Conservation Service, and the many residents of Day County who provided data about their wells. The writer is especially grateful to Kenneth Callen of Webster, South Dakota, a well driller who generously gave the use of his drilling logs and records.

The Day County Commissioners provided a water truck for the drilling program when the Survey's truck was undergoing repairs--a generous gesture which saved considerable time and money.

Drillers for the South Dakota Geological Survey are gratefully acknowledged for their effort. They include Lloyd Helseth, Robert Stach, Millard Thompson, and many summer assistants.

Thanks is extended to summer field assistants who served during the 5-year period from 1967-1972. They include Terry Blankenship, Richard Bretz, David Carver, Steven Constable, Ed DeWitt, David Gaylord, Ron Helgerson, Michael Johnson, George Lee, Scott McGregor, Gary Ochsenbein, and Lon Thompson.

The Department of Geosciences of the Pennsylvania State University is gratefully acknowledged for providing computer and

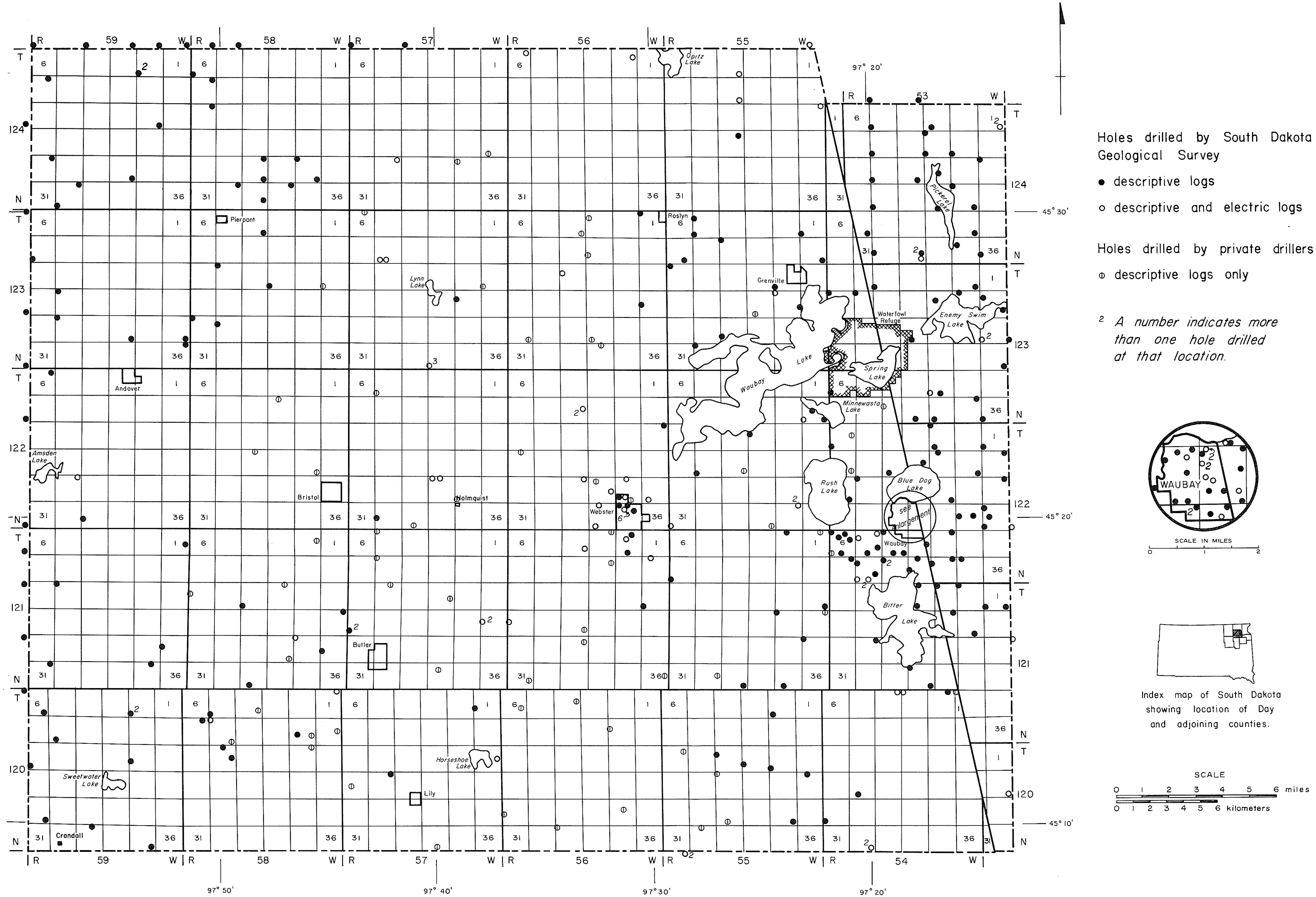


Figure 3. Location of drill holes with logs.

laboratory funds.

The author wishes to thank the many analytical chemists and laboratory assistants who helped in analyzing water samples and drill cuttings. Those persons with the South Dakota Geological Survey included Stephen Beach, Cathy Monk, Wayne Schroeder, and Fran Watkins. Laboratory personnel of the Pennsylvania State University included Paul Diehl, Judith Kamp, Mary Karandosovski, and Carl Palmer.

Thanks is extended to the following draftsmen: Dennis Johnson and Debra Moore Kummer of the South Dakota Geological Survey, and Thomas Kostick and Patricia Wilbur of the U.S. Geological Survey in Denver, Colorado.

Funding of this project was shared by the U.S. Geological Survey, the South Dakota Geological Survey, Day County, and the Oahe Conservancy Sub-District.

Well-Numbering System

Wells and test holes are located according to a numbering system based on the Federal land-survey system used in South Dakota (fig. 4). The location number consists of townships, range, and section numbers separated by hyphens, followed by a maximum of four letters that indicate, respectively, the 160-, 40-, 10-, and 2 1/2-acre tract in which a data point is located. A serial number following the last letter is used to distinguish between data points in the same tract. Thus, well 121-57-24cbbb (fig. 4) is in the NW 1/4 NW 1/4 NW 1/4 SW 1/4 sec. 24, T. 121 N., R. 57. W.

PHYSIOGRAPHY

Day County can be divided into two distinct physiographic divisions (fig. 1). The highest part of the County covers about five-sixths of the total area and is part of the high tableland which was named the Coteau des Prairies (Hill of the Prairies) by the early French explorers. The Coteau in South Dakota is a long, flat-iron shaped feature which runs roughly north-south from northwestern Iowa and western Minnesota to its apex just inside the North Dakota line. The elevation at the north end of the Coteau is a little more than 2,000 feet above sea level. Within the boundaries of the Coteau, the land is very hummocky to rolling for the most part with occasional flatter areas marking the position of former Pleistocene lakes. In addition, many large lakes as well as thousands of kettles and ponds exist on the Coteau. In general, the topography of the Coteau resulted from stagnation of glacial ice during late Wisconsin time.

The remaining one-sixth of the County lies in the James Basin and is separated from the Coteau by a sudden change in slope (fig. 1). The southern part of this boundary, from Crandall to

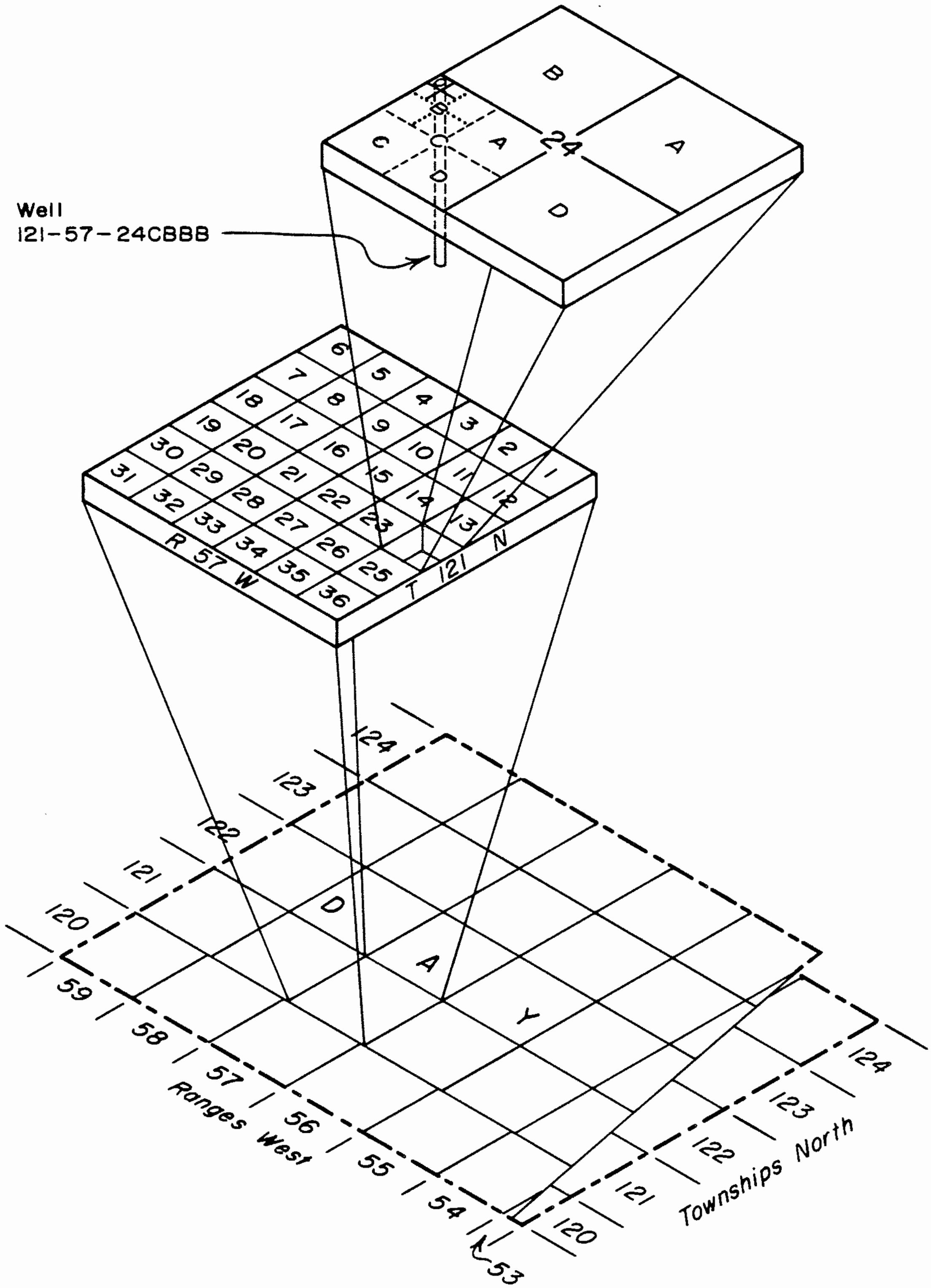


Figure 4. Diagram showing United States Bureau of Land Management method of land subdivision.

Amsden Lake, is characterized by a very abrupt and steep escarpment, which north of Amsden Lake becomes a more gentle slope but still distinct in gradient from the gently sloping James Basin. At the boundary between the Coteau and the James Basin, the Coteau escarpment rises to the east about 250 feet in 0.75 mile. Westward from the boundary the James Basin slopes at about 60 feet per mile for 1 mile and then flattens to an almost level plain. The escarpment, known as the Crandall Hills, is the result of thrusting of large sheets of glacial ice and is discussed in more detail later in the report.

The James Basin, in Day County slopes westward rather evenly toward the Ancient Lake Dakota bed, and in Day County, is characterized by recessional moraines of low relief which have been covered by silts deposited in temporary lakes formed behind ice receding from the Coteau during the latter part of the Pleistocene Epoch. The bed of Lake Dakota is found only in the extreme northwestern corner of the County, specifically in section 6, Township 124 North, Range 59 West.

Drainage in the County, particularly on the Coteau, is poorly developed for the most part. Only in the western part, where streams flow down from the western part of the Coteau, is drainage developed to any significant degree. On the steeper slopes of the Coteau escarpment and the James Basin the streams have cut valleys 40 to 50 feet deep, but as the streams approach the Lake Dakota Plain, many of the valleys disappear as their streams debouch onto the silts of Lake Dakota. The streams themselves flow only intermittently, but the downcutting of their valleys into the underlying bedrock has been extensive, indicating that at one time the flow volume of these streams was much greater owing to melting of late Wisconsin stagnant ice on the Coteau. In addition to many small streams flowing down the Coteau slope, the major ones are Antelope, Mud, and Pickerel Creeks (fig. 5). All are at present extending themselves by headward erosion into the interior of the Coteau. The present base level for streams flowing off the western edge of the Coteau is the James River to the west in Brown County.

Within the confines of the Coteau itself, internal drainage is the rule. Streams generally connect two or three potholes or kettles and carry water only during heavy rain or snowmelt or during periods of abnormally high water in the ponds--during which times spillover from one pothole may be carried to another via the streams. Absence of well-integrated drainage on the Coteau is a reflection of the extreme youth of the terrane, its hummocky character, and the existence of thousands of temporary local base levels provided by the ponds and lakes. On the eastern side of the County, a few streams breach the Waubay terminal moraine and are intermittent in character. South of Bitter Lake, these streams drain eastward to the headwaters of the Big Sioux River. North of Bitter Lake, a few intermittent streams drain westward to Pickerel, Enemy Swim, Blue Dog, and Bitter Lakes from the terminal moraine complex and outwash plain in Roberts and Grant Counties (fig. 5).

STRATIGRAPHY

The rock sequence overlying the Precambrian basement in Day County is comprised of approximately 1,000 feet of Cretaceous rocks and up to 800 feet of Pleistocene glacial drift. Figure 6 illustrates the general stratigraphic column that is known to be present in the area of study.

Precambrian Rocks

Relatively little is known of the composition or of the subsurface topography of the basement rocks in Day County. The South Dakota Geological Survey files contain the record of only three wells that have penetrated into Precambrian rocks. The cores and cuttings of the Precambrian that are available for study have not been dated by laboratory methods.

A map of the Precambrian surface of South Dakota (Steece, 1961) based on drilling data, indicates that the basement slopes westward into the Williston Basin, and with minor variations, rises in an eastward direction and crops out at the Milbank granite quarries in Grant County.

Absence of Paleozoic Rocks

No Paleozoic rocks have been found beneath Day County and data from only three holes may not be justification for ruling out the existence of these rocks in the County. The relatively high elevation of the basement in the County suggests that this part of the State was not part of the basin of deposition (the Williston Basin) during Paleozoic time, and that Paleozoic rocks were never deposited here even though they are found in Brown County to the west.

Mesozoic Rocks

Resting directly on the Precambrian basement in Day County are Mesozoic rocks of Cretaceous age.

Absence of Triassic and Jurassic Rocks

During Mesozoic time the area that is now Day County was a highland (the western edge of the Canadian Shield) near the basin of Mesozoic deposition and probably never received Triassic and Jurassic sediments (Stokes, 1966, chap. 13).

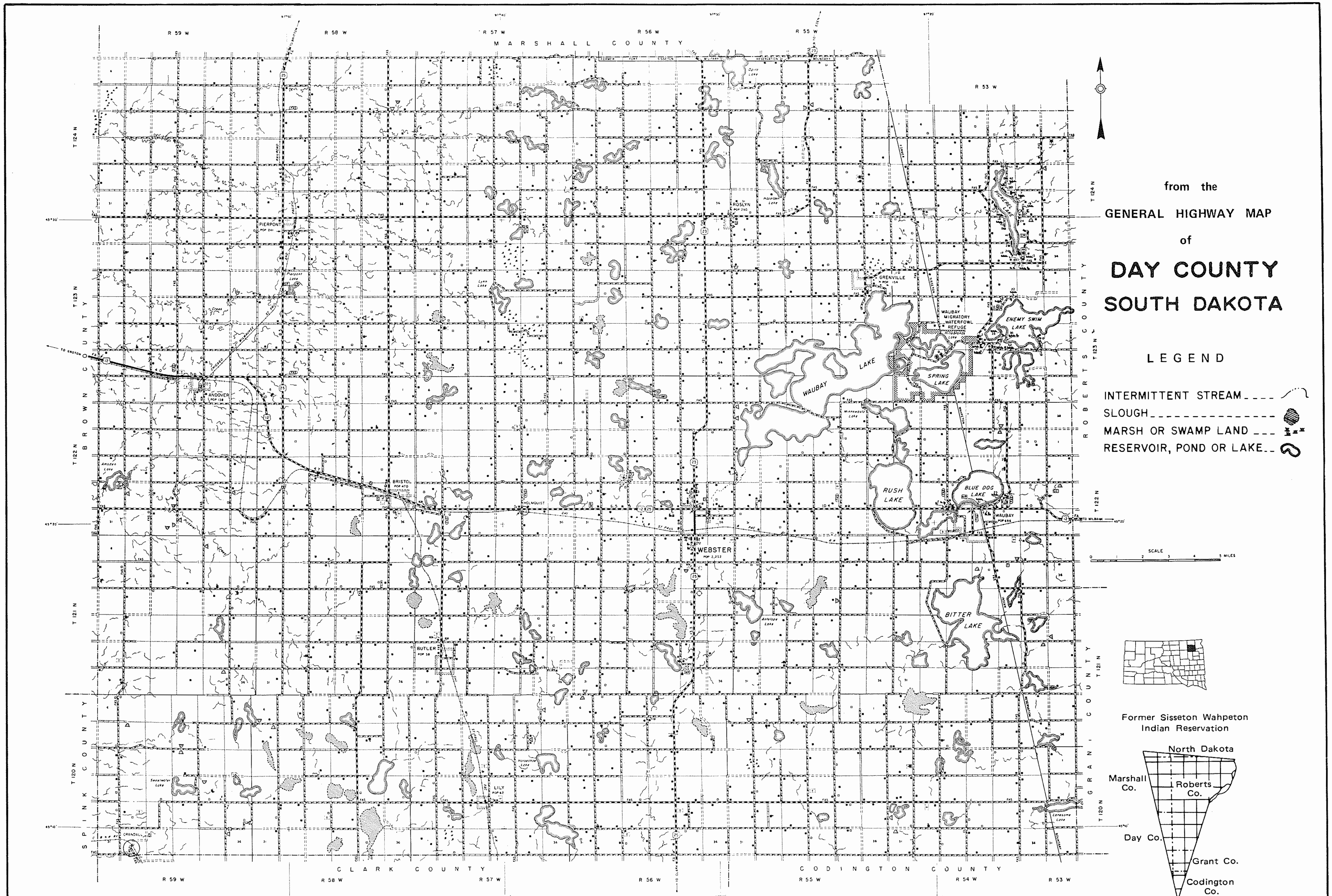


Figure 5. Map showing hydrographic and cultural features.

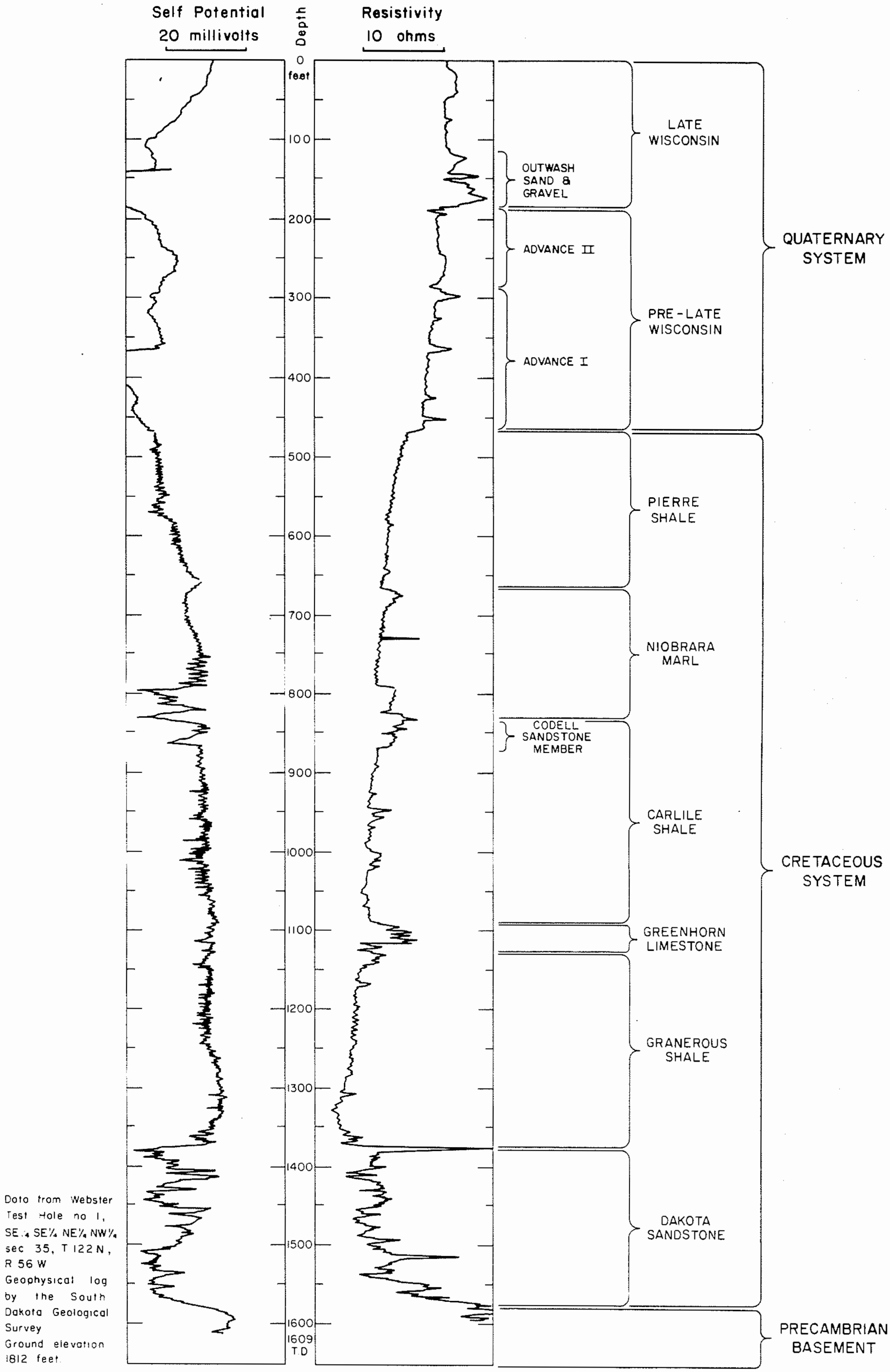


Figure 6. Typical electric log showing the stratigraphic column in Day County.

Cretaceous Rocks

Table 1 is a compendium of information on holes completely penetrating Cretaceous rocks. It includes only those holes drilled by private firms for which the information is felt to be reliable. Figure 7 shows the locations of the holes listed in table 1.

The Cretaceous rocks in Day County, from oldest to youngest are the Dakota Formation, Graneros Shale, Greenhorn Limestone, Carlile Shale (including Codell Sandstone Member), Niobrara Marl, and the Pierre Shale.

The Dakota Formation was first defined by Meek and Hayden in 1856 (Meek, in, Hayden, F. V., 1876, p. 23) as Formation No. 1 of the Cretaceous consisting of 90 feet of sandstone and clay. Shortly thereafter, in 1861, Meek and Hayden revised the nomenclature of Cretaceous rocks and employed the geographical term Dakota to include 400 feet of "yellowish, reddish, and occasionally white sandstone, with at places alternations of various colored clays and beds and seams of impure lignite . . ." that cropped out in the "Hills back of the town of Dakota." (Meek, in, Hayden, F. V., 1876, p. 24-25). The development of the nomenclature of the term Dakota can be traced by interested readers by referring to Darton (1896, 1901, and 1909), Tester (1931) and Gries (1954). At the present time the South Dakota Geological Survey (Schoon, 1971, p. 8) restricts the term "Dakota Formation" to include "the first relatively continuous sandstone below the Greenhorn Limestone and extending downward to the top of the Skull Creek Shale in western and central South Dakota. Where the Skull Creek is absent the Dakota overlies Precambrian rocks and to a minor extent, rocks of the Inyan Kara Group."

As thus defined the Dakota consists of approximately 195 feet of a relatively continuous sand interval in the Webster municipal water well (fig. 6). In this well the Dakota unconformably overlies the Precambrian basement at a depth of 1,575 feet and has a transitional contact with the overlying Graneros Shale at an approximate depth of 1,375 feet. These contact relationships exist throughout the County.

The term Graneros Shale was employed by G. K. Gilbert in 1896 (Gilbert, 1896, p. 564) to define a 210-foot thickness of laminated agrillaceous gray shale with very little limy or sandy material. As generally accepted the Graneros includes, in ascending order, the Newcastle Sandstone, Mowry Shale, and the Belle Fourche Shale. Gries (1952, p. 75-76) recommended abolishing the term Graneros and raising the aforementioned units to formational rank. Subsequently D. E. Hattin (1965) restricted the term Graneros to include the shale sequence between the Greenhorn Limestone and the Dakota Sandstone. The South Dakota Geological Survey recognized the terminology of Hattin in southeastern South Dakota but also recognized that the terminology suggested by Gries has greater merit where formation boundaries can be accurately

TABLE 1. Description of holes penetrating Cretaceous strata in Day County

Number	Location	Elevation of land surface	Total depth of hole	Depth to Pierre Shale	Depth to Niobrara Marl	Depth to Codell Sandstone	Depth to Carlile Shale	Depth to Greenhorn Limestone	Depth to Graneros Shale	Depth to Dakota Sandstone	Depth to Precambrian Basement
1.	SW SW sec. 29, T. 122 N., R. 57 W.	1800±25	1966	370*	620	800	850	1050	1100	1350	1500
2.	SE sec. 19, T. 120 N., R. 59 W.	1461	1174	31*	440	580	620	706	756	1020	not reached
3.	SE sec. 15, T. 124 N., R. 59 W.	1340	1180	28	?	312	347	570	620	880	not reached
4.	Sec. 35, T. 122 N., R. 56 W.	1812	1609	465	665	845	870	1090	1150	1375	1575

* Approximate depths; no data in logs, depths from bedrock map.

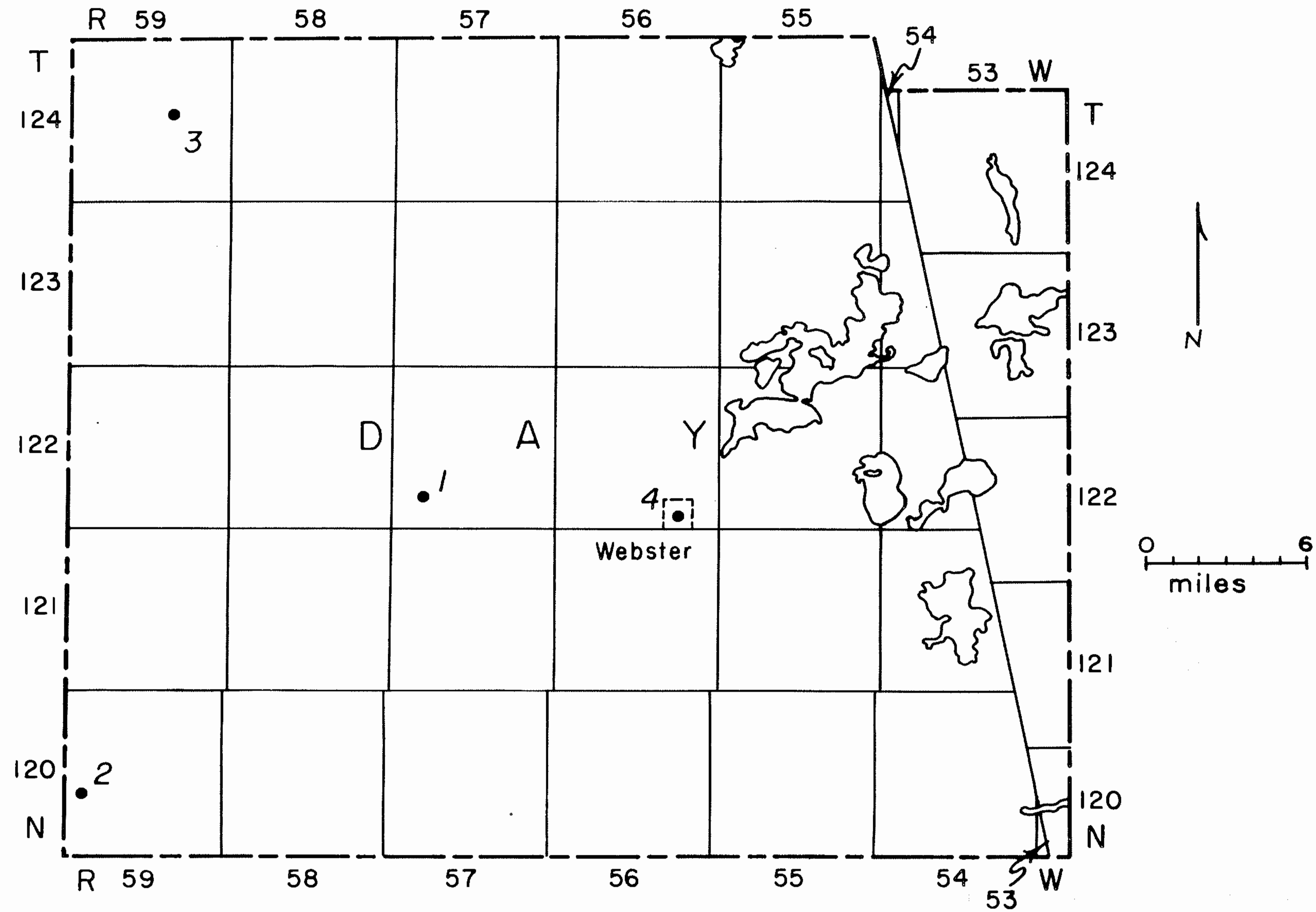


Figure 7. Map of Day County showing locations of holes listed in table 1.

established. Day County is in the "gray" area where in practice the nomenclature of both Hattin and Gries may be employed about equally well. Where the Belle Fourche Shale is separable from the Mowry Shale the top of the Mowry bentonite marker is considered the common contact of the two shale units. The top of the Belle Fourche Shale is usually marked by an interval of calcareous, white-speckled, gray shale which is very similar in appearance to the Niobrara Marl. The contact of the Belle Fourche with the Greenhorn Limestone is conformable.

The Greenhorn Limestone (Gilbert, G. K., 1896) is a white to light medium-gray, impure limestone that may be, in large part, composed of beds of fossil Inoceramus labiatus. Interbedded with the limestone are thin seams of calcareous, white-speckled, gray shale which, again, is very similar in appearance to the Niobrara Marl. The Greenhorn has a very pronounced increase in resistivity on the resistivity log (fig. 6) and serves as an excellent marker bed. In Day County the Greenhorn is approximately 25 feet thick and conformably underlies the Carlile Shale.

The Carlile Shale (Gilbert, 1896, p. 565) in Day County consists of approximately 200 feet of medium gray shale which is quite similar in appearance to the Graneros Shale but is more plastic. The Carlile conformably overlies the Greenhorn Limestone.

The Codell Sandstone member (Bass, 1926, p. 28, 64) near the top of the Carlile Shale ordinarily consists of fine-grained sandstone associated with varying amounts of medium-dark gray shale. In southeastern South Dakota this sandstone is consistently present and usually well developed. The resistivity log of the Webster municipal well indicates that a sand unit may exist from 845 feet to 870 feet (fig. 6). The gamma ray log of the same interval also indicates clean (or shale free) sediments. However, a study of the sample cuttings from the 845-870 interval yielded only a few chips of sandstone. In view of this the presence of the Codell is questionable because the gamma ray and resistivity log may indicate a calcareous unit. In either case, the upper contact of the Carlile (or Codell) with the Niobrara appears to be conformable in Day County.

The Niobrara Marl (Niobrara Chalk) was originally described by Meek and Hayden (Meek, F. B., and Hayden, F. V., 1862, p. 419-422) for exposures of "lead-gray calcareous marl" occurring in southeastern South Dakota. In Day County the Niobrara consists of approximately 180 feet of medium-dark gray chalk. There appears to be a definite tripartite subdivision of the formation on gamma-ray, resistivity, self-potential and sonic logs, but the lithology appears to be quite uniform. In view of this, the Niobrara has not been subdivided in this report. The top of the Niobrara is at the base of a white, to light tan bentonite (bottom of the Pierre Shale) that is present throughout much of the State. This bentonite occurs at a depth of 655 to 665 feet in the Webster municipal well (fig. 6) and for this reason the contact between the Niobrara Marl and the Pierre Shale is believed to be conformable in Day County.

The Fort Pierre Group (Meek, F. B., and Hayden, F. V., 1862, p. 419-424) was named for a sequence of dark gray shales that is 700 feet thick in Nebraska (which at that time included Wyoming, Montana, and North and South Dakota). The name was shortened to Pierre as early as 1896 (Darton, N. H., 1896). The Pierre Shale is the uppermost bedrock formation in Day County (fig. 8). In the Webster municipal well it underlies the glacial drift at a depth of 465 feet. In the preceding paragraph mention was made of the presence of a bentonite bed at the base of the Pierre. Owing to the fact that this bentonite is included in only 200 feet of Pierre, it is apparent that only the lower part of the Pierre is present in Day County. Information concerning the Pierre Shale in the area does not permit subdividing the formation into members.

Cenozoic Rocks

Absence of Tertiary Rocks

No Tertiary rocks have been found in Day County. The area that now comprises Day County was located on the eastern edge of a depositional basin in early Tertiary time--the Cannonball Seaway (Stokes, 1966, chap. 14).

Tertiary deposits have been found along the Missouri River 150 to 200 miles southwest of Day County (South Dakota Geological Survey staff, personal communication). Hedges (1972, p. 7) found rocks which may be of Tertiary age across the Missouri River just west of Campbell County about 150 miles west of Day County.

The paleogeographical location of Day County on the edge of the Cannonball Seaway and the great distance from the County to the nearest Tertiary outcrops suggest that the area was undergoing erosion during Tertiary time rather than deposition.

Pleistocene Deposits

CLASSIFICATION OF PLEISTOCENE DEPOSITS

In the midwestern United States four major advances or stages of glaciation have been recognized and classified along with the interglacial warm periods which separate them as follows:

Glacial Stage	Interglacial Period
	Post glacial
Wisconsin	
	Sangamon
Illinoian	
	Yarmouth
Kansas	
	Aftonian
Nebraskan	

(after Flint, 1971, p. 543).

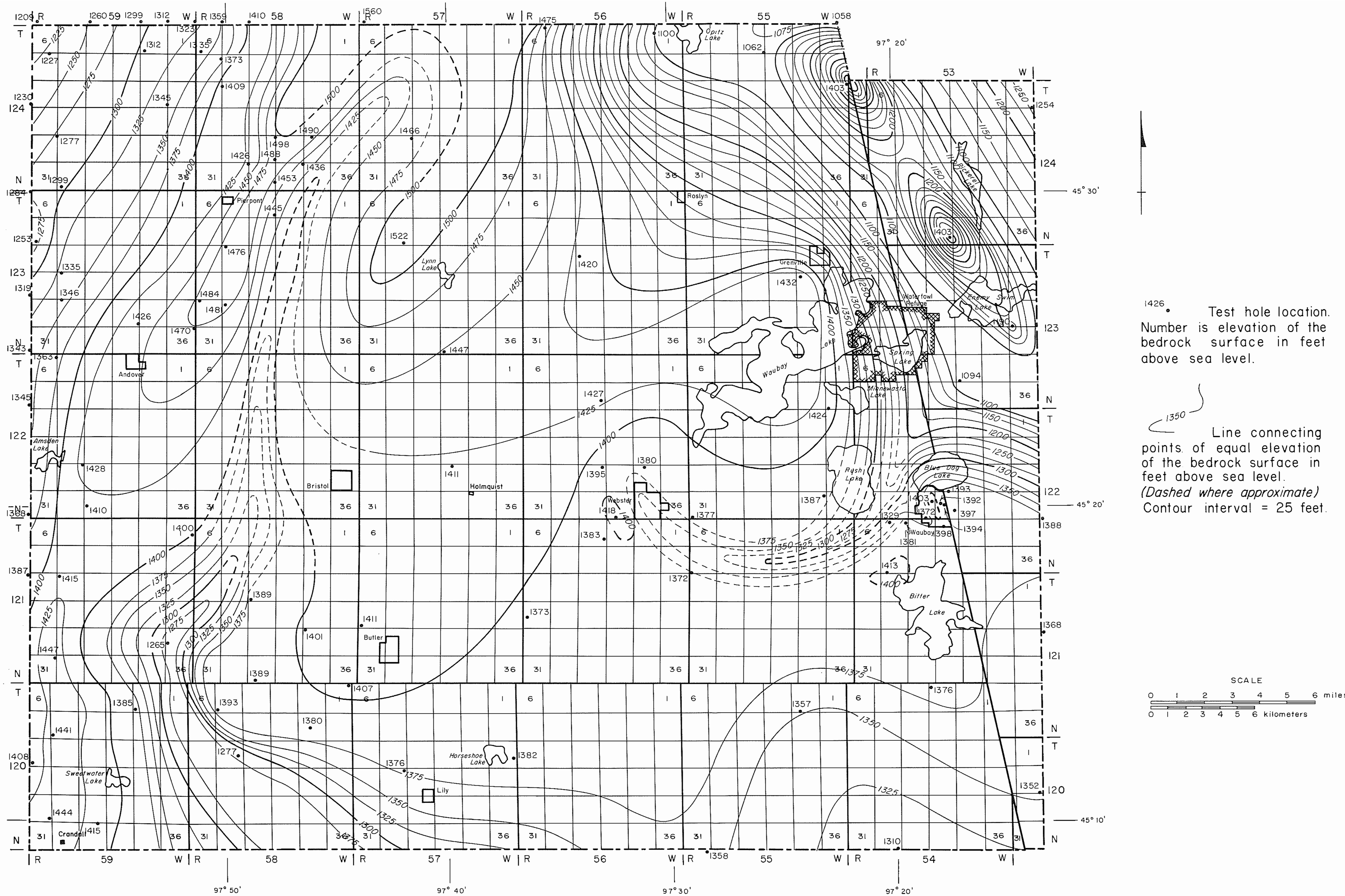


Figure 8. Bedrock map of Day County, South Dakota.

The above classification is quite broad and is generally accepted as the framework for classification of Pleistocene stratigraphy throughout the midwest.

The first glacial stage, the Nebraskan was named by Shimek (1909, p. 8) from outcrops near Omaha, Nebraska, in the Missouri River trench. The next stage, the Kansan was named by T. C. Chamberlin (Geikie, 1894, p. 755) from exposures in northeastern Kansas. Leverett proposed the Illinoian (Chamberlin, 1896, p. 874), and Chamberlin named the Wisconsin stage (Geikie, 1894, p. 763).

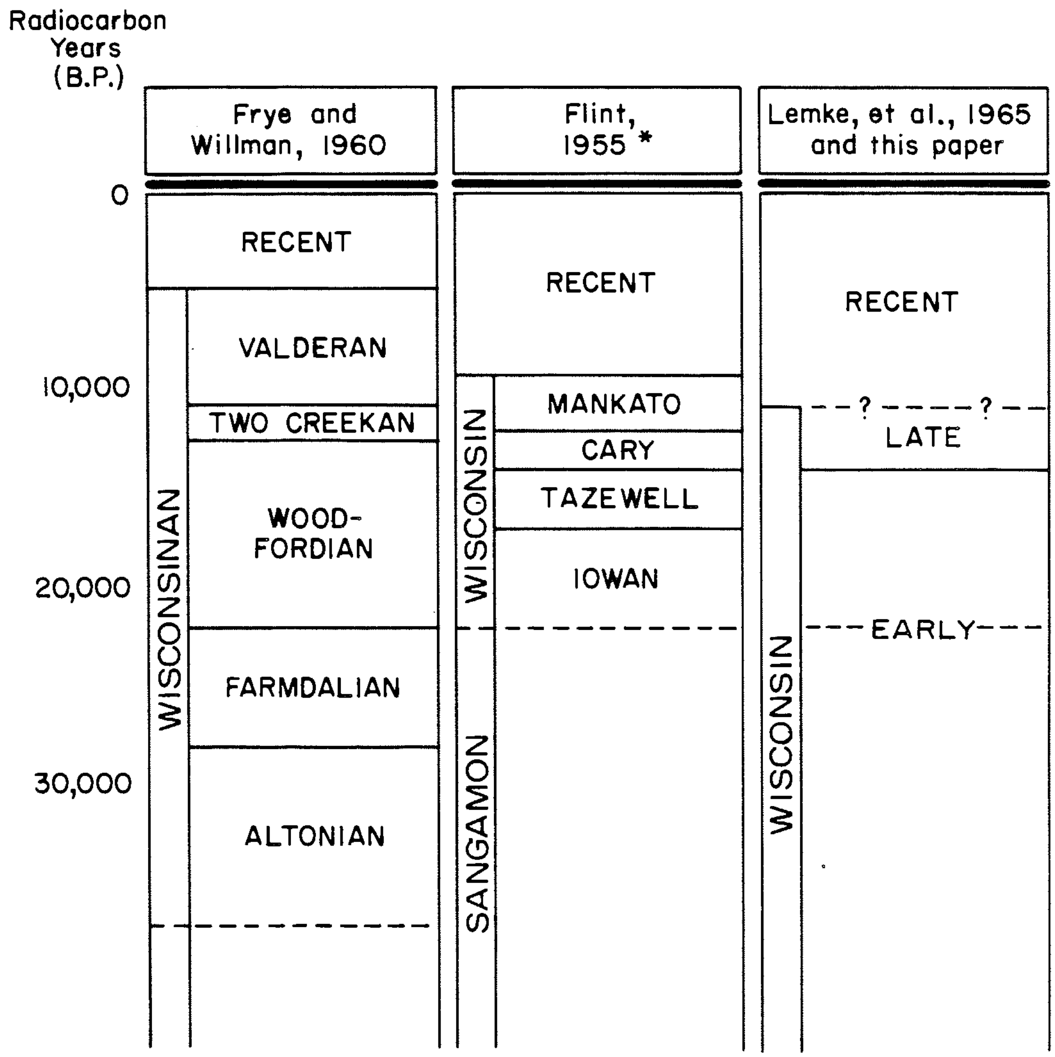
The Nebraskan and Kansan glaciations are known to have covered western Iowa, southeastern Minnesota, and eastern Nebraska (Flint, 1971, p. 545), and both have been mapped in southern South Dakota (Steece, Tipton, and Agnew, 1960, p. 1-5). The northern boundaries of the Kansan and Nebraskan glaciations are not known although Leverett believed that the bulk of the Coteau des Prairies was formed by Kansan glaciation (Leverett, 1932).

The northermost known exposure of Illinoian aged drift in South Dakota is located 2 miles north and 1 mile west of Dell Rapids in Minnehaha County, approximately 100 miles southeast of Day County (Tipton, 1959a and b). It is not known for certain how far north the Illinoian-aged drift continues beneath the deposits of the late Wisconsin glaciation although there is a large area of pre-late Wisconsin drift between end moraines of the late Wisconsin stage in the north-central part of the Coteau des Prairies. In addition, unnamed pre-late Wisconsin drift has been found by drilling in Sanborn County (Steece and Howells, 1965), in Marshall County (Koch, personal communication) and in Day County while investigations for this report were being carried out. Radiocarbon dates of organic material from the uppermost of two buried drifts in Day County exceed 30,000 years B.P. which does not help in determining if the buried drifts are early Wisconsin, Illinoian, Kansan, or Nebraskan in age. This age is too great to be late Wisconsin (fig. 9). It is certain, however, that no glacial deposits older than late Wisconsin have been found in drill holes in Brown, Edmunds, McPherson, and Faulk Counties to the west of Day County, and it is also fairly certain from drilling for the Day County investigations that both earlier drifts do not extend westward beyond the western third of the County.

The temporal and stratigraphic relations within the Wisconsin stage have been studied in more detail and classified more precisely than any of the preceding advances because it is the last of the midwestern glacial advances and is exposed over a wide area of the United States.

Leverett (1929) classified the Wisconsin stage into three subdivisions--early, middle, and late.

Later, Leighton (1933) classified the Wisconsin stage into four substages which are, from earliest to latest, the Iowan,



* The classification used by Flint was first proposed by Leighton (1933) in naming subdivisions of the Wisconsin glacial age.

Figure 9. Pleistocene classification in South Dakota and vicinity.

Tazewell, Cary, and Mankato. Subsequent to this classification, two other substages were added: the Valders was added above the Mankato as the latest of the Wisconsin substages by Thwaites (1943), and the Farmdale substage was placed below the Iowan to take the place of the earliest Wisconsin advance (Leighton and Willman, 1950). A seventh substage was named the Cochrane by Antevs (1925), but this term rarely appears in the literature - the latest Wisconsin substage being accepted as the Valders. It must be pointed out that the above names have been proposed for the midcontinent region and their extrapolation into South Dakota has caused severe difficulties in stratigraphic classification because many of the substages proposed simply did not fit the glacial geology as mapped for the State.

Todd (1909) described what he believed to be two advances of ice down the James Basin (the Antelope advances) but assigned no age to them.

Using Leverett's classification, Rothrock (1935) mapped the geology of Day County and described Iowan and Wisconsin aged deposits.

In 1955, Flint, borrowing the classification of Leighton (1933) mapped the glacial geology of eastern South Dakota, and in Day County described deposits of Tazewell, Cary, and Mankato age (Flint, 1955). Also following the classification of Leighton (1933), Tipton (1958a and b) mapped the glacial geology of a small part of southeastern Day County and recognized the presence of Cary drift.

Within the past 10 years a number of radiocarbon dates in North Dakota, eastern South Dakota and western Iowa have cast considerable doubt on the time-stratigraphic and to some extent, the geomorphic interpretations of the above investigators. Based on these dates and other information, the South Dakota Geological Survey has adopted a classification by Lemke and others (1965) which gives a better interpretation to the events of the Pleistocene glaciation in this region (fig. 9). In this classification, the Iowan and Tazewell are grouped together into early Wisconsin age, and the Cary and Mankato substages into late Wisconsin. It was with this classification that the Pleistocene stratigraphy of Day County was correlated and described for this report.

METHODS OF CORRELATION

Radiocarbon dates obtained from surficial material in Day County and surrounding counties indicate that the late Wisconsin drift comprises the entire surface of the County and was laid down by the ice of the James Lobe with one small exception in the extreme northeast corner of the County section 1, Township 124 North, Range 53 West. Here, end moraine from the Des Moines Lobe covers about one-half square mile. Thus, correlation of surface deposits presented little difficulty.

Correlation of subsurface data was possible using a three-dimensional model based on information from drill holes and geophysical logs. Correlation was greatly aided by the widespread occurrences of two buried oxidized zones which formed on the paleosurfaces of drifts deposited during earlier glacial advances. The results of these analyses and correlations, and the presence of the two paleosurfaces indicate that much of Day County and indeed, a significant part of eastern South Dakota were glaciated at least three times.

The first two advances, I and II from bottom up, are designated as pre-late Wisconsin in age and it is unclear as to which glacial stage they belong. Pelecypod shells were found in a perched lake deposit of Advance III in SW 1/4 SW 1/4 section 5, Township 124 North, Range 56 West. Radiocarbon dating of the shells by the United States Geological Survey revealed an age of 10,800 plus or minus 320 years which is definitely late Wisconsin. The distribution of deposits of all three advances indicates that Advances I and II came from the east while Advance III came from the northwest. These relationships are discussed fully under the subtitle "Pleistocene History." Figures 10 and 11 show the recognized extent of Advances I and II.

Pre-late Wisconsin Deposits

ADVANCE I

Basal Outwash

Resting immediately on top of the Pierre Shale is a very widespread sheet of outwash which covers almost the entire County (figs. 12 and 13). This basal material was first described by Rothrock (1935) as the "Contact Sand," i.e., it formed the contact between the shale bedrock and the overlying glacial drift. The thickness of this material varies considerably from place to place and seldom exceeds 30 feet although occasionally it may exceed 80 feet in thickness. The lithology is normally a mixture of clay, silt, sand, shale pebbles, and gravel. In a few places, notably in the vicinity of Lynn Lake, the material is quite clean and possesses good aquifer potential. Usually, however, the material is characterized as a very clay-rich outwash with numerous silty and clay-rich layers separating more sandy and gravelly layers.

The basal outwash is believed by the author to be of proglacial origin, i.e., deposited by meltwater flowing from the fronts of advancing glaciers. There are no other known sources of this sand and gravel and no other known processes which could deposit it. Considering the fact that the glaciers which advanced over Day County were probably temperate with seasonal melting, it is very probable that the basal outwash was deposited in this manner.

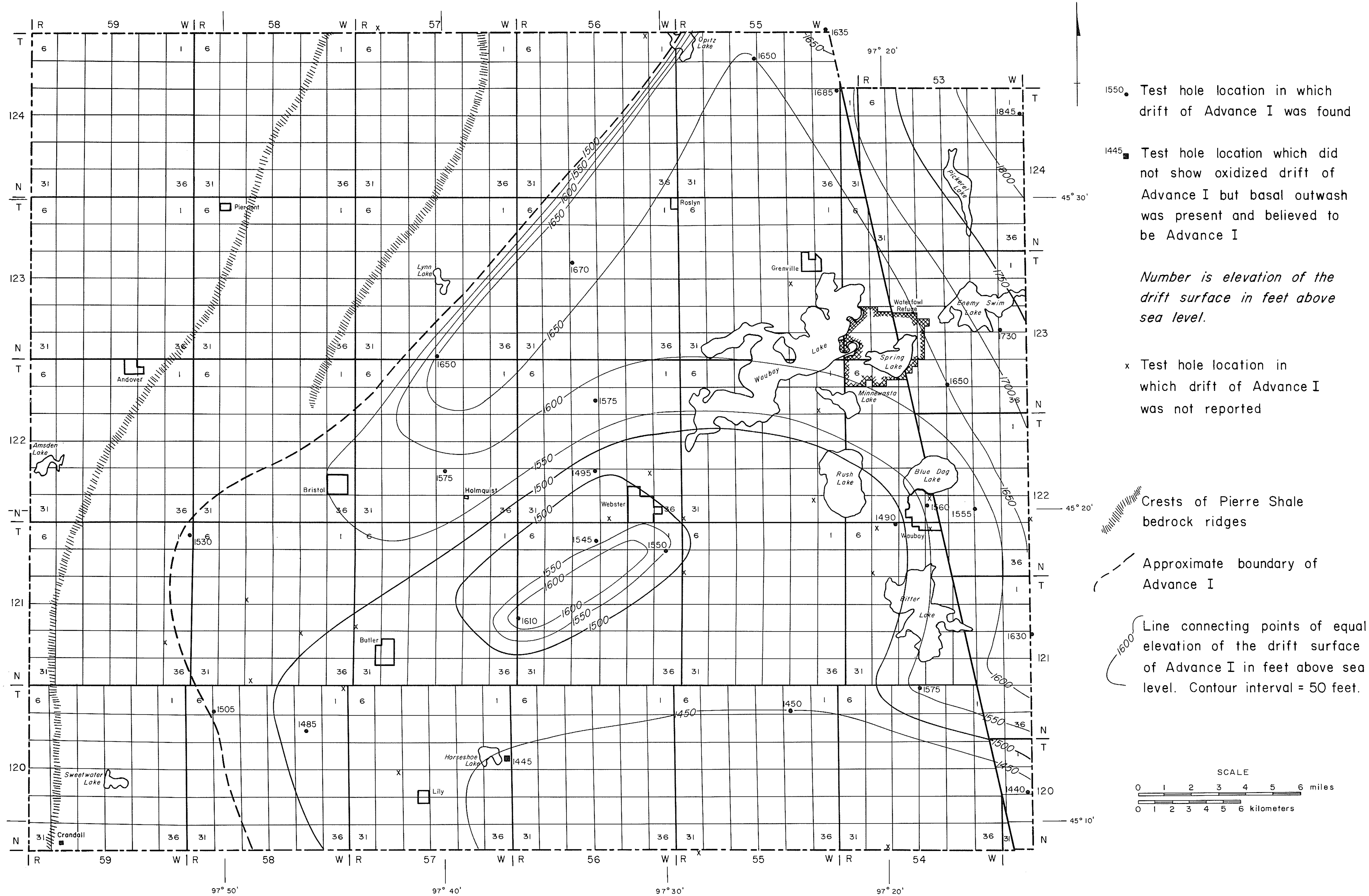


Figure 10. Map showing extent of drift of glacial Advance I in Day County, South Dakota.

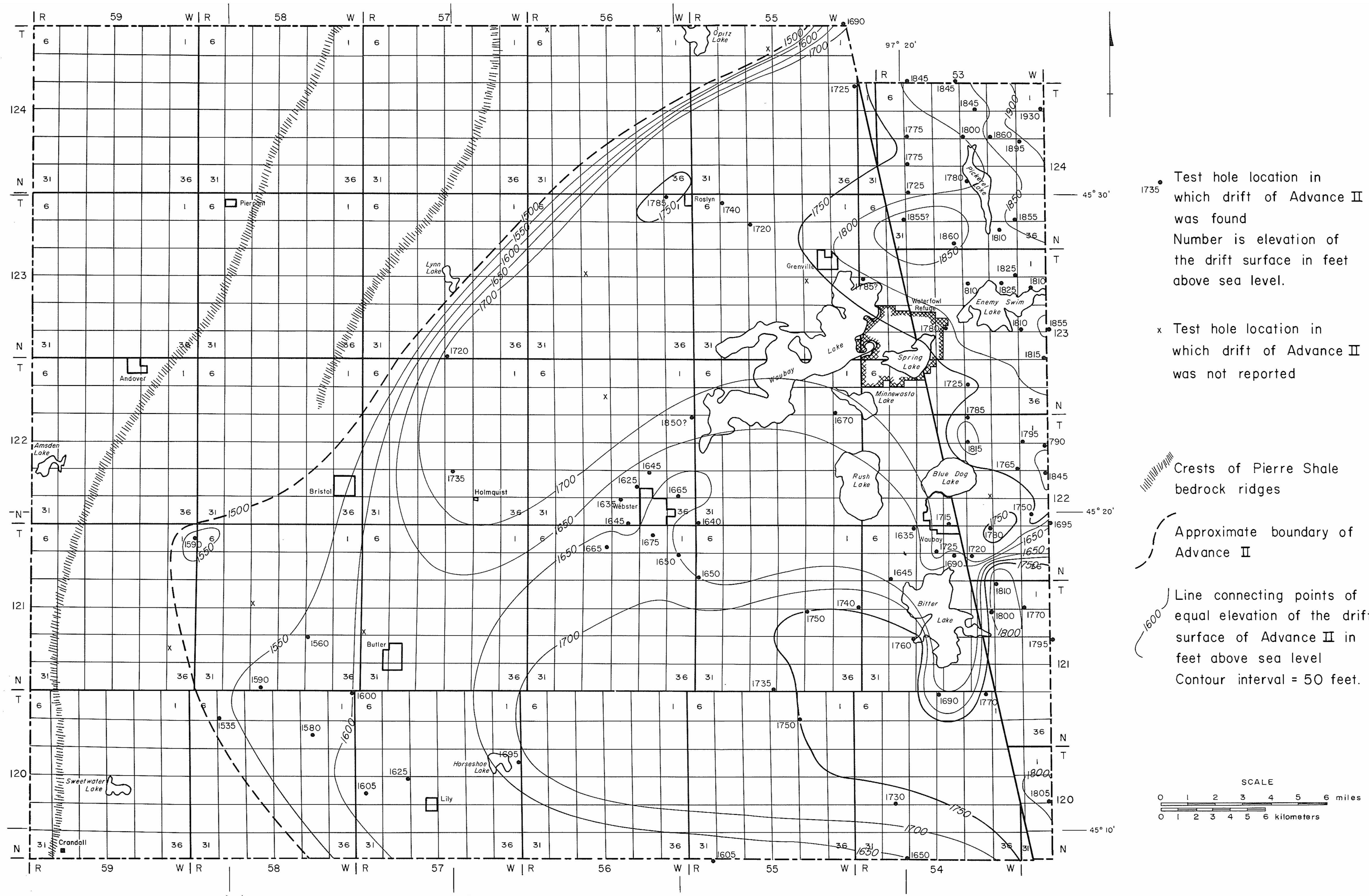


Figure 11. Map showing extent of drift of glacial Advance II in Day County, South Dakota.

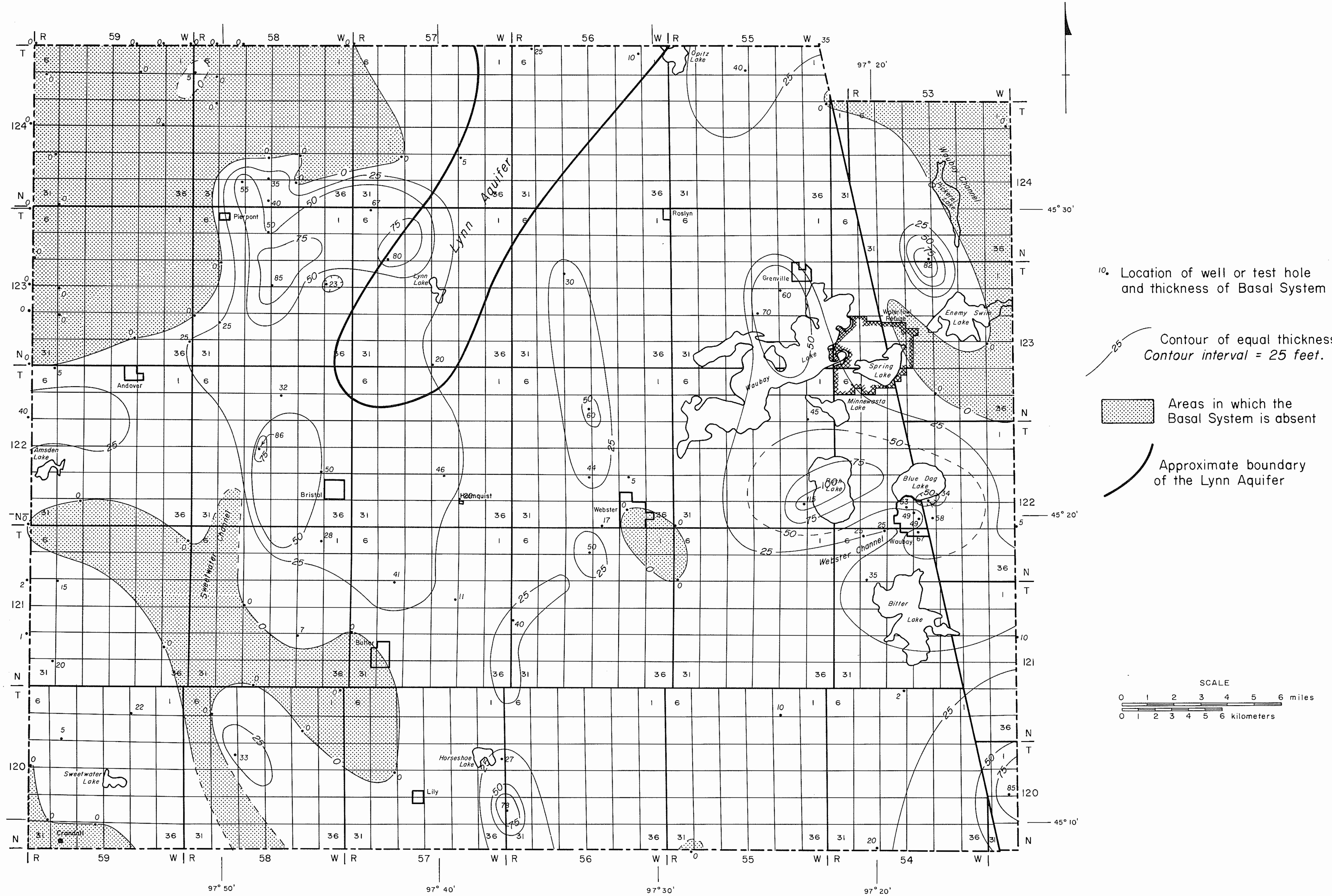


Figure 12. Isopach map of the Basal System (basal outwash) in Day County, South Dakota.

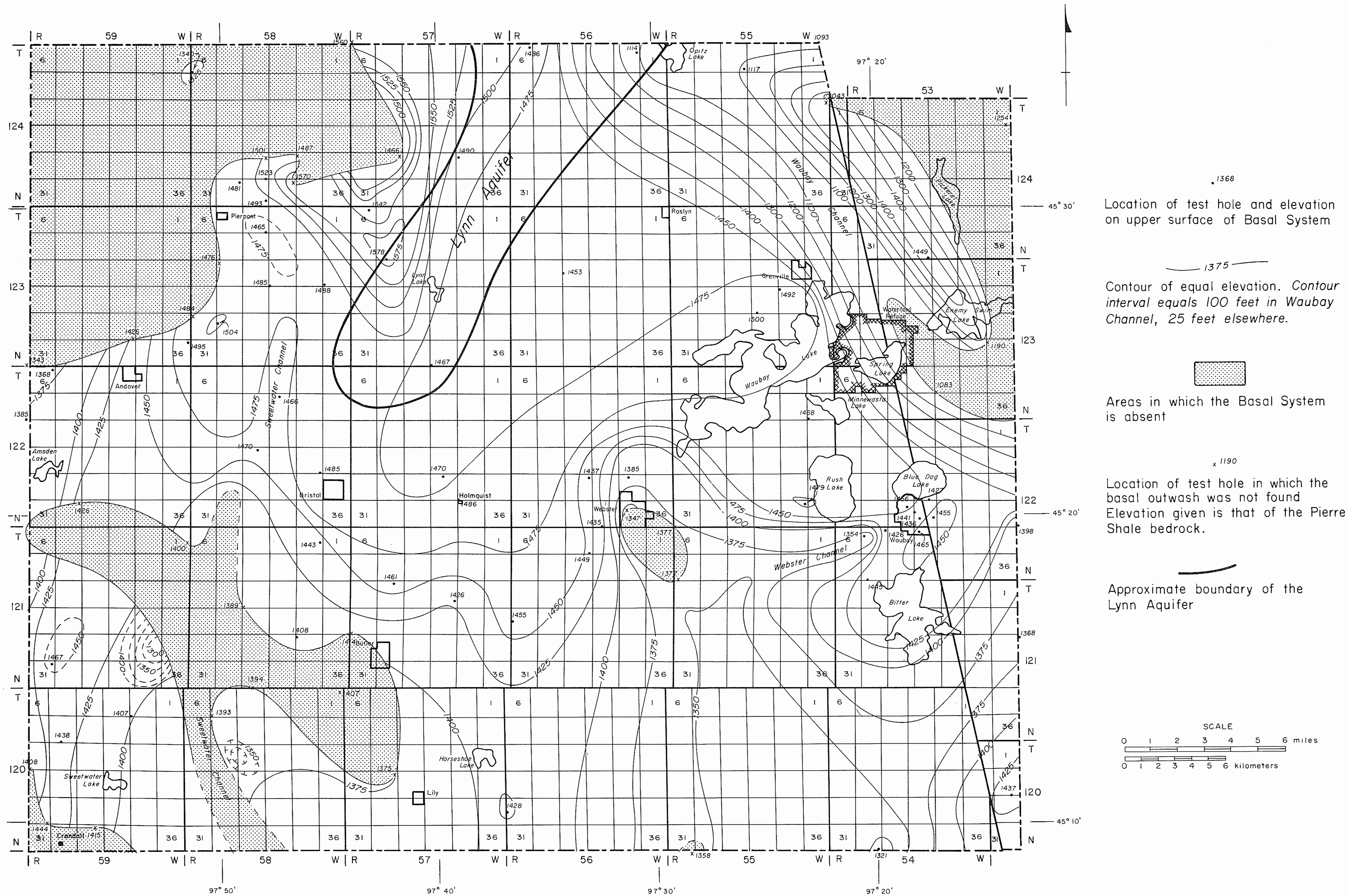


Figure 13. Contour map of the surface of the Basal System (basal outwash) in Day County, South Dakota.

There are actually two basal outwashes. The one discussed in this section was deposited by ice of Advance I. The other was deposited by Advance III or late Wisconsin ice and is discussed under the subtitle, "Late Wisconsin Deposits."

The basal outwash of Advance I covers that part of the County from its eastern border to approximately the western terminus of Advance I (fig. 10). This basal outwash was deposited in front of the ice of Advance I and subsequently overridden by the ice as it moved westward. The glacier moved mainly upslope as it advanced over Day County. Consequently, there was little or no outlet for meltwater to escape with enough velocity to winnow out the fine material as the outwash was being deposited. Therefore, the sediments were laid down as a heterogeneous, poorly-sorted deposit.

The basal outwash of Advance I joins that of Advance III or the late Wisconsin at about the western terminus of Advance I (fig. 10) and extends westward from this line to the western boundary of the County.

Probably a basal outwash underlies most of the northern part of the Coteau des Prairies. In 1970, a test hole in the City of Clark, 40 miles south of Webster, revealed a basal sand and gravel. It has also been found in Marshall County (N.C. Koch, personal communication).

<u>Sweetwater Channel Valley Fill</u>

The Sweetwater Channel was originally incised in the Pierre Shale to a depth of 125 feet. The ice of Advance I and II overrode the southern part of the Sweetwater Channel in the vicinity of the Day County-Clark County line (figs. 8, 10, and 11). As a result, the southerly flow of water in the channel was ponded. Thus the lithology of the channel fill reflects a ponded-water environment of deposition. The material deposited in the bottom of the channel, and especially, in the southern part of the channel, is characterized by a mixture of sand, silt, clay, gravel, shale pebbles, and considerable marl indicating a ponded-water environment. This material is believed to be genetically related to the basal outwash previously described because of similar lithologies and was probably deposited at about the same time as the basal material. Thickness of the fill varies from a few inches to 10 feet and is not considered good aquifer material because of the large amount of silt and clay. This fill is not considered to be a part of the basal outwash.

<u>Webster Channel Valley Fill</u>

The material in the Webster Channel was deposited entirely during Advance I and is believed to be genetically related to the basal outwash because of similar lithologies although it is not considered to be part of the basal outwash. It shows much the same lithology as the Sweetwater Channel fill only with a higher percentage of marl. The Webster Channel is 150 feet deep at its eastern end and connects down gradient with the Waubay Channel to the east. It was also ponded by the westerly moving ice (figs. 8 and 10). The lithology of the fill is similar to that of the Sweetwater Channel and again shows evidence of ponding with the presence of poorly sorted and marly deposits. There are a few lenses of fairly clean materials within the Webster Channel fill which probably reflect very local flushing action of meltwater; however, the deposits in the channel as a whole would not be considered as a good aquifer. In the Webster Channel the fill varies from a few inches to 50 feet in thickness.

Waubay Channel Valley Fill

The Waubay Channel is 300 feet deep and appears to have been the major drainageway for Day and Marshall Counties before the advance of the first ice sheet (fig. 8). This channel, like the aforementioned ones, was dammed by the ice of Advance I (figs. 8 and 10). The channel runs northwest through Marshall County and into North Dakota but its eastward and southward extension has not yet been determined. Drainage of this channel was probably northward and it is reasonable to expect that any ice damming of its upstream parts would not hinder the winnowing and sorting action of meltwater drained into it downstream from the dam; yet, the fill is mostly composed of the same type of material as in the Sweetwater and Webster Channels with occasional pockets of clean gravels and sand, but again is not considered part of the basal outwash. Evidence is not yet sufficient to determine the precise direction from which Advance I entered Day County, and although it did dam the channel east of Waubay, it may also have dammed it downstream in Marshall County which would have resulted in ponding in Day County. With a general northwest-southeast direction the channel may have been marginal to the ice of Advance I for an undetermined period of time and allowed water to flow unobstructed, sorting out fine material in the fill. This might account for the fact that the fill is good aquifer material in Marshall County (Koch, personal communication) and only poor to marginal in Day County. In Marshall County it is known as the James Aquifer (Koch, 1972) but in Day County the high percentage of clay, silt, and marl precludes its use as a good source of water supply. Thickness of material in the Waubay Channel in Day County may run from a few inches to 50 feet.

Upper Drift

Thickness and Distribution

The upper drift of Advance I is simply defined as that drift (mostly till and interbedded outwash deposits) between the basal outwash of Advance I and the drift of Advance II. Although two successive buried oxidized zones can be found throughout the drift in the eastern two-thirds of Day County, such data from Advance I are scarce in comparison to that from Advance II. Nevertheless, drilling data are sufficient to suggest that the earliest advance did not reach the westernmost vertical strip of townships in the County (fig. 10).

Previous petrologic studies have proven fruitless in distinguishing early drifts from each other and therefore were not attempted in this study (Clayton, 1962, p. 55). Visual examination of the drill cuttings from the upper drift of Advance I showed no significant differences from cuttings from Advance II, but both of the lower drifts are somewhat more lightly colored than that of Advance III. Thickness of the upper drift varies from a few inches to 595 feet and averages approximately 300 feet.

Relation of Terminus to Bedrock

Hedges (1968) reports the presence of three glacial drifts in Beadle County southwest of Day County and at the extreme southern end of Ancient Lake Dakota. Hedges assumes that all three advances came down the James Basin from North Dakota, but extensive drilling in Brown County to the north has failed to show the presence of buried drifts in that area (Leap, 1986). Therefore, it is probable that the bedrock ridge along the west side of Day County served as a topographic barrier to stop the westward movement of Advance I. This bedrock high caused the ice to be diverted south of the ridge into a topographic low where the resistance was less, i.e., through Clark and Spink Counties into the James Basin. This could account for the drift's presence in Beadle County and areas further south of Day County.

ADVANCE II

Thickness and Distribution

In most places in the County, the drift of Advance II is not nearly as thick as that of Advance I, and generally ranges from a few inches to 200 feet with an average thickness of approximately 100 feet. Whether this is due to greater erosion of the surface of drift II or lesser initial deposition is not known. Outcrops of Advance II drift are missing in the County due to complete burial by drift deposited during Advance III. Drift of Advance II is exposed at the surface over a large part of Grant County east of the Waubay End Moraine. All evidence concerning the drift in Day County comes from drill-hole data. Between Webster and Waubay, the surface of the drift of Advance II rises rapidly in elevation from 1,650 to 1,715 feet. In the vicinity of the large eastern lakes Advance II drift may be as little as 40 feet below the ground surface, indicating the relative thinness of drift of Advance III in this area (fig. 11).

Buried Bedrock Erratics

A few large slabs or erratics of Pierre Shale in drift of Advance II were found by drilling in sec. 13, T. 121 North, R. 55 W., and in sec. 34, T. 122 N., R. 54 W. These probably were incorporated into the glacial ice as it moved up over the eastern edge of the Coteau des Prairies. Just west of Bitter Lake in sec. 13, T. 121 N., R. 55 W., drillers for the South Dakota Geological Survey drilled into a block of shale at a depth of 90 feet from the surface and found it to be 20 feet thick. In the vicinity of Waubay, Beffort and Hedges (1967) found buried shale erratics as much as 100 feet thick.

Relation of Terminus to Bedrock

As in the case of Advance I, the terminus of Advance II appears to be located east of the bedrock ridge and in the same general area as that of Advance I. It appears that the bedrock ridge and the deposits of Advance I acted to resist the westerly movement of Advance II ice and it probably also went into the James Basin through Spink and Clark Counties to the south and spread south into Beadle County (Hedges, 1968) and Sanborn County (Steece and Howells, 1965).

Late Wisconsin Deposits

THICKNESS AND DISTRIBUTION

The drift of Advance III, the late Wisconsin, covers all of Day County (pl. 1) and is thinnest along its western border where in places it is not more than 10 to 15 feet thick. Eastward it thickens to over 200 feet locally in the interior of the County and thins again further east in the vicinity of Waubay where in places it may not be more than 40 feet in thickness. Figures 14 through 17 show cross sections through the drift of Day County and the relations of the various drifts to each other, to the bedrock and to the land surface.

LITHOLOGY

Glacial Till

The predominant lithology of the late Wisconsin deposits (Advance III) is a clay-rich till. Generally, the till is a medium to dark-gray material where unweathered and contains considerable shale, chalk, and igneous and metamorphic rocks. The enrichment of the till by shale and chalk reflects the nature of the lithology of the bedrock terrane over which the late Wisconsin ice moved in advancing south from its source in western Canada, i.e., the ice passed over several hundred miles of Cretacous shales and and chalk beds.

Although the tills of the late Wisconsin glaciation in Brown and Day Counties were derived from the same bedrock source area and were deposited from the same ice advance there is in general a striking difference in their gross lithologies. Both are rich in clay, but the till of Day County possesses a far greater amount of pebbles and boulders compared with tills of the same age in Brown County. Also there are several large bodies of outwash sand and gravel on its surface reflecting differences in the history of glacial retreat. The till of Brown County is richer in clay and the outwash deposits are not nearly as extensive. The explanation of these contrasts is found in the difference in depositional environments of the two localities. In Brown County the ice was actively moving most of the time and because of its weight (perhaps 1,500 feet in thickness) the ice produced large-scale shears or thrusts within the glacier which rode out onto the highlands of Day County to the east and the Counties of Edmunds, McPherson, and Faulk to the west. The shearing took place in several successive episodes and in many cases overrode previous shears. This process of stacking of debris-laden ice along with melting of the stagnating masses of ice caused the till to be enriched in gravel-size and cobble-size material as the finer material was washed away by the meltwater. The accumulation of vast areas of outwash is also due to this process. As melting proceeded, much of the silt and clay was washed out and deposited as lake sediments as on the Coteau des Prairies and in the bed of Ancient Lake Dakota.

Similar processes took place on the Coteau du Missouri during late Wisconsin time where the depositional environment was essentially a "mirror image" of that in Day County.

Basal Outwash

It was mentioned previously that the basal outwash resting on the Pierre Shale covers most of Day County and is composed of both Advance I and late Wisconsin material. The late Wisconsin component of the basal outwash begins just west of the western terminus of the Advance I drift and continues west and rises over the bedrock ridge and drops down into Brown County (figs. 10, 12, and 13). Along the line where the two basal beds join, the late Wisconsin probably lies on top of the outwash of Advance I. This area of overlapping is in a broad channel between the drifts of Advances I and II on the east and the bedrock ridge to the west. It probably was subject to the sorting action of late Wisconsin meltwater which left deposits in this particular area cleaner and more suitable as aquifer material when compared with basal outwash to the east or west. The material in this trough constitutes the center of the Lynn Aquifer which is described more fully later in this report. In general the basal outwash of late Wisconsin age is thinner than that of Advance I and ranges from a few inches to 50 feet in thickness.

A few outcrops of the late Wisconsin basal outwash can be seen in the sides of stream valleys cut into the edge of the Coteau des Prairies just northeast of Pierpont (sec. 32, T. 124 N., R. 58 W. and sec. 29, T. 124 N., R. 58 W.). The lithology of this outwash, as determined from outcrops and drilling information, is a mixture of sand, small gravel and a high percentage of water-worn shale pebbles with some clay.

The origin of the late Wisconsin basal outwash is believed by the author to be pro-glacial, i.e., it was laid down in front of the advancing James Lobe ice by meltwater derived from the glacier. No other source of basal outwash sediment or process of deposition can be ascertained. The glacier was probably temperate and produced copious amounts of meltwater to carry sediment off its snout. The stratigraphic relationship of the basal outwash is shown on figures 14 through 17.

Surface Outwash

One of the most striking features of the late Wisconsin surface in Day County is the enormous amount of outwash sand and gravel present (pl. 1). The various types of outwash features are described genetically under the subtitle "Pleistocene Geomorphology." The surface outwash deposits in Day County vary in size from a few acres to a few square miles in area. In the western and central parts of the County, the deposits may reach a thickness of 20 feet, and in the eastern part, around the large lakes, thicknesses of 50 feet are common (figs. 14 through 17). A maximum thickness of 125 feet was mapped between Blue Dog and Bitter Lakes. The outwash varies widely in grain size and is composed mainly of igneous and metamorphic rocks, limestone and dolomite, and a large percentage of shale pebbles. Many lenses of silt and clay are interspersed within the outwash deposits.

Loess

Late Wisconsin loess is found in two small areas east of the Waubay End Moraine (secs. 25 and 36, T. 122 N., R. 53 N. and secs. 12 and 13, T. 121 N., R. 53 W.). The material overlies late Wisconsin outwash (pl. 1) and both areas lie to the east of a large valley train system around Bitter Lake. The loess was probably deposited by the prevailing westerly winds which picked up the material out of the valley train deposits. The maximum thicknesses of the two deposits are not known but they probably do not exceed 8 feet. Most soil auger holes drilled in the material revealed outwash sand and gravel at 3 to 4 feet.

Thorp and others (1952) mapped approximately four-fifths of the land surface of Day County as loess deposits of late Wisconsin age and older but, what they called loess has since been interpreted to be lacustrine silts of late Wisconsin age.

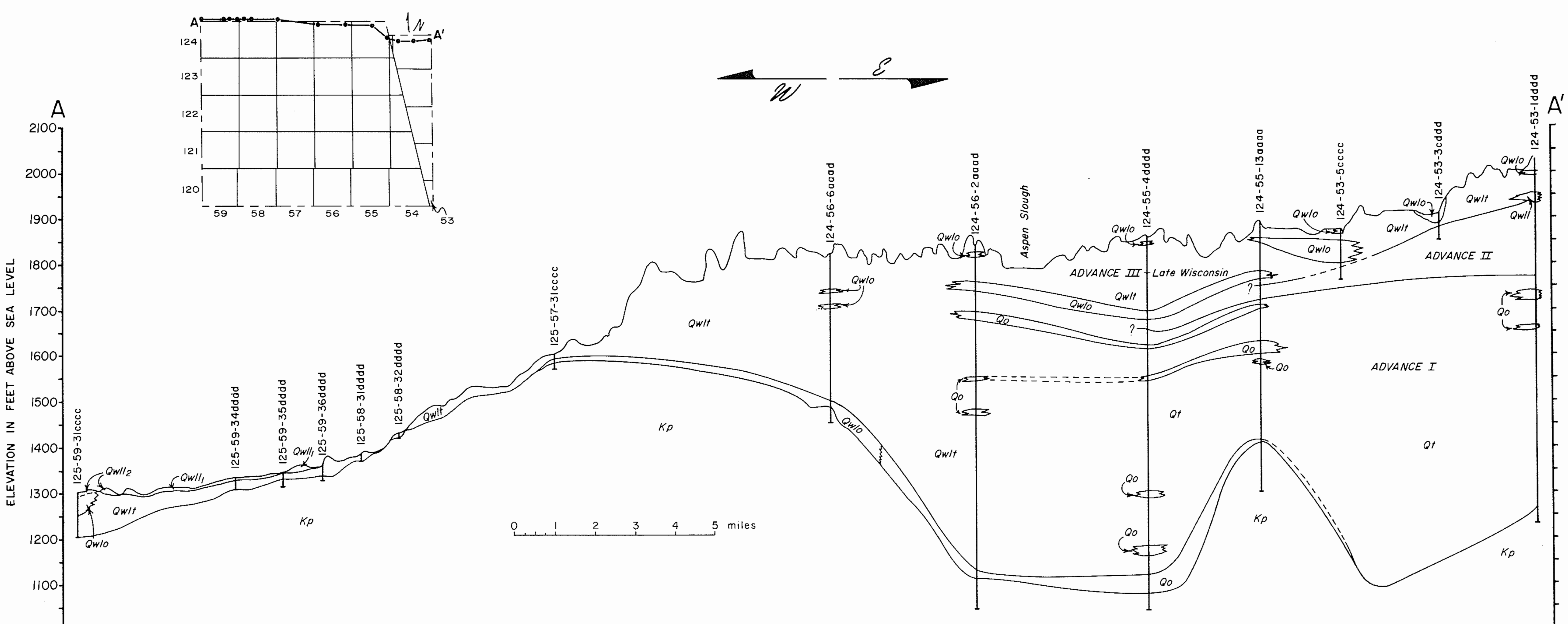


Figure 14. Diagrammatic cross section of the geology of Day County, South Dakota (A-A′).

Quaternary System

Late Wisconsin
- *Qwll-Lacustrine deposits (on Coteau des Prairies)*
- *Qwll₁-Lacustrine deposits (behind recessional moraines)*
- *Qwll₂-Lacustrine deposits of Lake Dakota*
- *Qwlo-outwash*
- *Qwlt-glacial till*

Pre-Late Wisconsin
- *Qo-outwash*
- *Qt-glacial till*

Cretaceous System
- *Kp-Pierre shale*

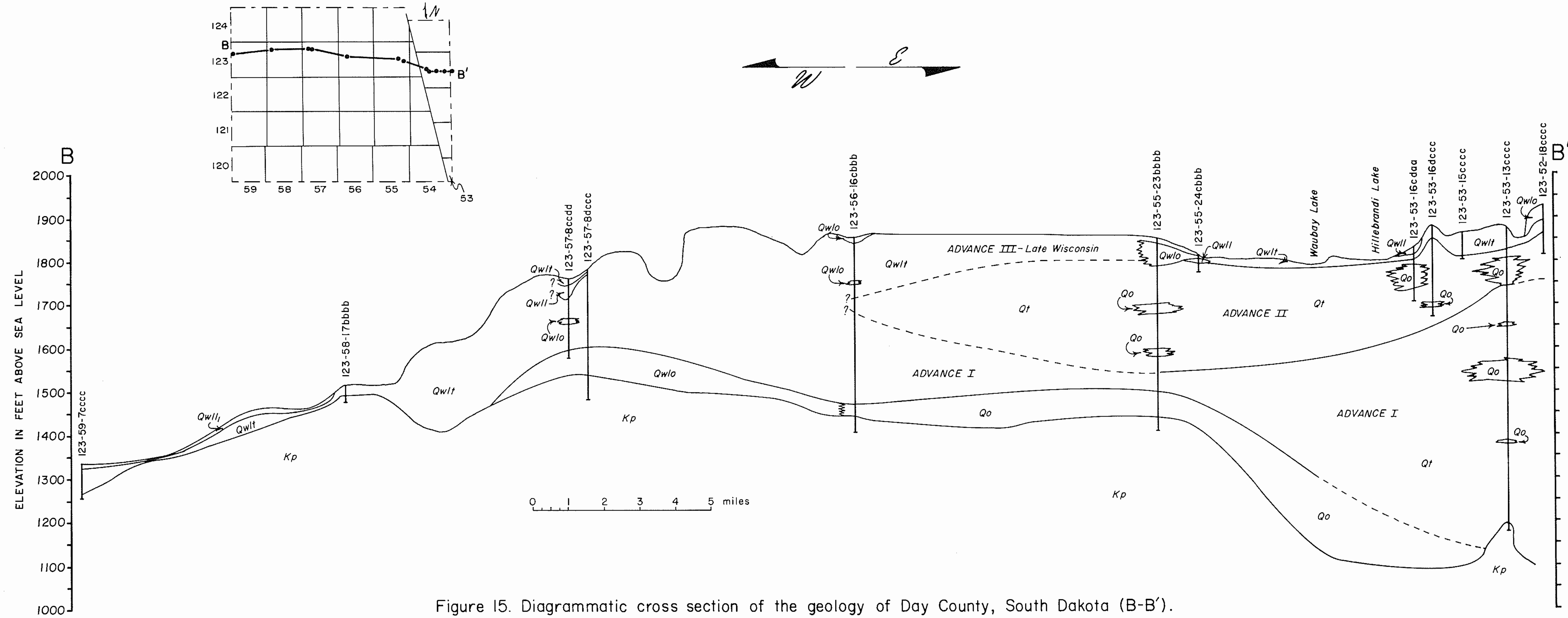


Figure 15. Diagrammatic cross section of the geology of Day County, South Dakota (B-B′).

	Quaternary System			Cretaceous System
Late Wisconsin	Qwll-Lacustrine deposits (on Coteau des Prairies)	Pre-Late Wisconsin	Qo-outwash	Kp-Pierre shale
	Qwll₁- Lacustrine deposits (behind recessional moraines)		Qt-glacial till	
	Qwlo-outwash			
	Qwlt-glacial till			

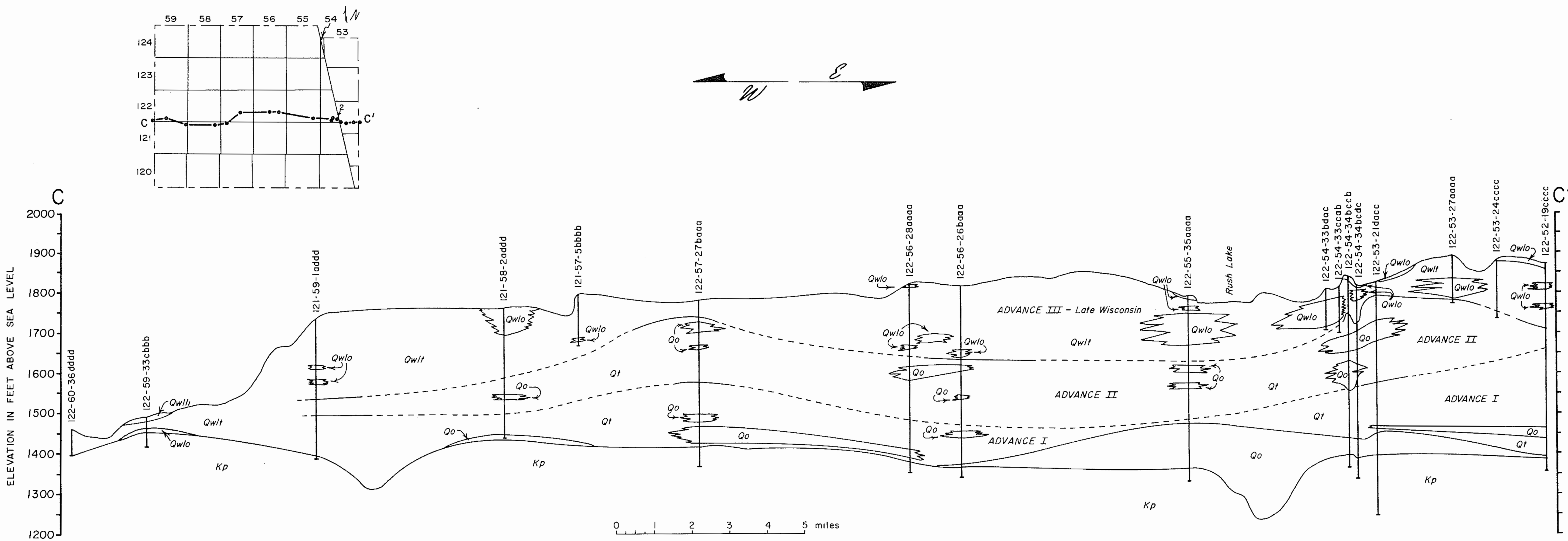


Figure 16. Diagrammatic cross section of the geology of Day County, South Dakota (C-C′).

Quaternary System				Cretaceous System
Late Wisconsin	$Qwll_l$ - Lacustrine deposits (behind recessional moraines)	Pre-Late Wisconsin	Qo - outwash	Kp - Pierre shale
	Qwlo - outwash		Qt - glacial till	
	Qwlt - glacial till			

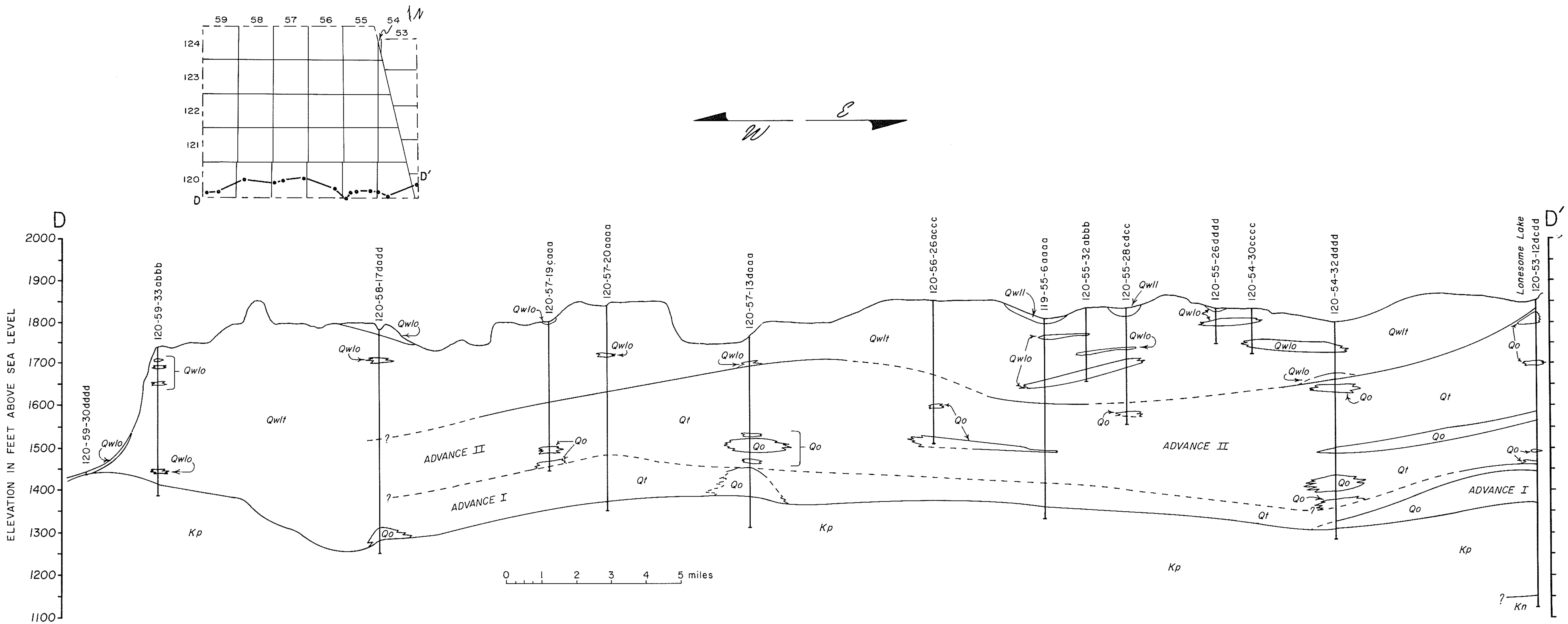


Figure 17. Diagrammatic cross section of the geology of Day County, South Dakota (D-D′).

	Quaternary System			Cretaceous System
Late Wisconsin	Qwll-Lacustrine deposits (on Coteau des Prairies)	Pre-Late Wisconsin	Qo-outwash	Kp-Pierre shale
	Qwlo-outwash		Qt-glacial till	Kn-Niobrara marl
	Qwlt-glacial till			

Lacustrine Deposits

Lacustrine deposits (Qwll on pl. 1) cover large areas of Day County and are mostly of ice contact origin (discussed under "Pleistocene Geomorphology"). Most of the deposits show strong evidence of having been deposited on top of the ice and then being let down during deglaciation. In addition there are large areas containing silts deposited in more stable, ice-free environments. A superglacial origin for many of the deposits is indicated because of the widespread collaspe features and hummocky nature of the surfaces of the deposits.

Around the large lakes of the eastern part of Day County most Pleistocene lacustrine deposits are found at elevations far above that of present-day lake levels, indicating that at one time toward the end of the Pleistocene Epoch the lakes held considerably more water.

In most cases the Pleistocene lake silts on the Coteau do not exceed 25 feet in thickness but a few deposits have been found through drilling to be as much as 100 feet thick. Along the western border of the County in the James Basin the silts formed behind receding ice. Here they seldom exceed 5 to 10 feet in thickness.

Recent Deposits

ALLUVIUM

In Day County alluvium is found mostly in the stream valleys along the west edge of the Coteau des Prairies. Generally it is a medium to dark-gray mixture of sand, silt, clay and pebbles with silt being the predominant grain size. In most cases observed, the alluvium in these valley lies directly on the Pierre Shale bedrock and ranges in thickness from 2 to 6 feet (pl. 1).

Two deposits of alluvium on the Coteau upland occur in short stream beds connecting two or three small lakes (secs. 23, 25, and 36, T. 121 N., R. 59 W. and secs. 6 and 11, T. 120 N., R. 58 W.) (pl. 1). These valleys probably contained flowing water during the latter part of the ice retreat while stagnant ice was still melting, but it is not certain if the alluvium is late Wisconsin or Recent in age.

LACUSTRINE DEPOSITS

Lacustrine silts of the Recent Epoch can be found in the numerous swamps and sloughs scattered throughout the County. Around larger lakes, Recent deposits are most difficult to distinguish from those of Pleistocent age and usually the two overlap because of changes in lake level since the Pleistocene. Because of these difficulties and because most of the Recent deposits are under water, they have not been mapped as such. The lithology of the Recent materials is a mixture of silt and clay with a large amount of organic material which gives them a very dark gray to black color.

GEOMORPHOLOGY

Pre-Pleistocene Geomorphology

Bedrock Geomorphology

The bedrock surface as shown in figure 8 may or may not be completely pre-Pleistocene in origin. It is impossible to determine if all the bedrock channels were eroded before the ice advanced into the County or if they in fact may have formed in part as ice marginal, proglacial and interglacial channels. Nevertheless, the regional slope of the bedrock surface indicates that before the advance of the first glacier the bedrock possessed a surface of rather gentle relief, much like the Pierre Shale landforms of the present day in the western part of the State. The bedrock map (fig. 8) shows the Pierre Shale surface rising gradually out of the James Basin to crest along a northeast-trending ridge at an altitude of 1,518 feet above sea level. East of this ridge the regional slope is generally southeast and is broken by a few deep channels. The bedrock ridge acted as a drainage divide with its eastern slope draining into the Waubay Channel (fig. 8) and its western part into the ancient Grand-Moreau-Cheyenne River system in Brown County. The ridge runs northeast into Marshall County for a short distance before it flattens out (Koch, personal communication). Its southward extension, west of the Sweetwater Channel has not yet been traced south of Day County.

Flint (1955, pl. 7) shows three major channel systems trending southwesterly through Day County, but drilling for this project failed to verify his interpretation and in fact yielded altogether different information.

SWEETWATER CHANNEL

The Sweetwater Channel begins in the vicinity of sec. 5, T. 124 N., R. 57 W. and trends slightly southwestward, splitting the bedrock ridge at a point 8 miles west of Butler. Here it turns and runs southeastward into Day County. At this point the channel is slightly over 100 feet deep at its deepest point; south of the turning point it widens until it is 4 to 5 miles wide at the Clark County line. The ultimate drainage of this channel is uncertain at the present time, but its southeastward trend and its position east of the bedrock drainage divide strongly suggest that it emptied into a channel to the southeast of Day County -- very possibly the Waubay Channel.

WEBSTER CHANNEL

The Webster Channel is a minor channel which begins at Webster and runs southeast for about 5 miles and then turns northeast to meet the Waubay Channel immediately northwest of Waubay. At its deepest point the channel is inferred to be about 150 feet deep and at its junction with the Waubay Channel it is about 4 miles wide (fig. 8).

WAUBAY CHANNEL

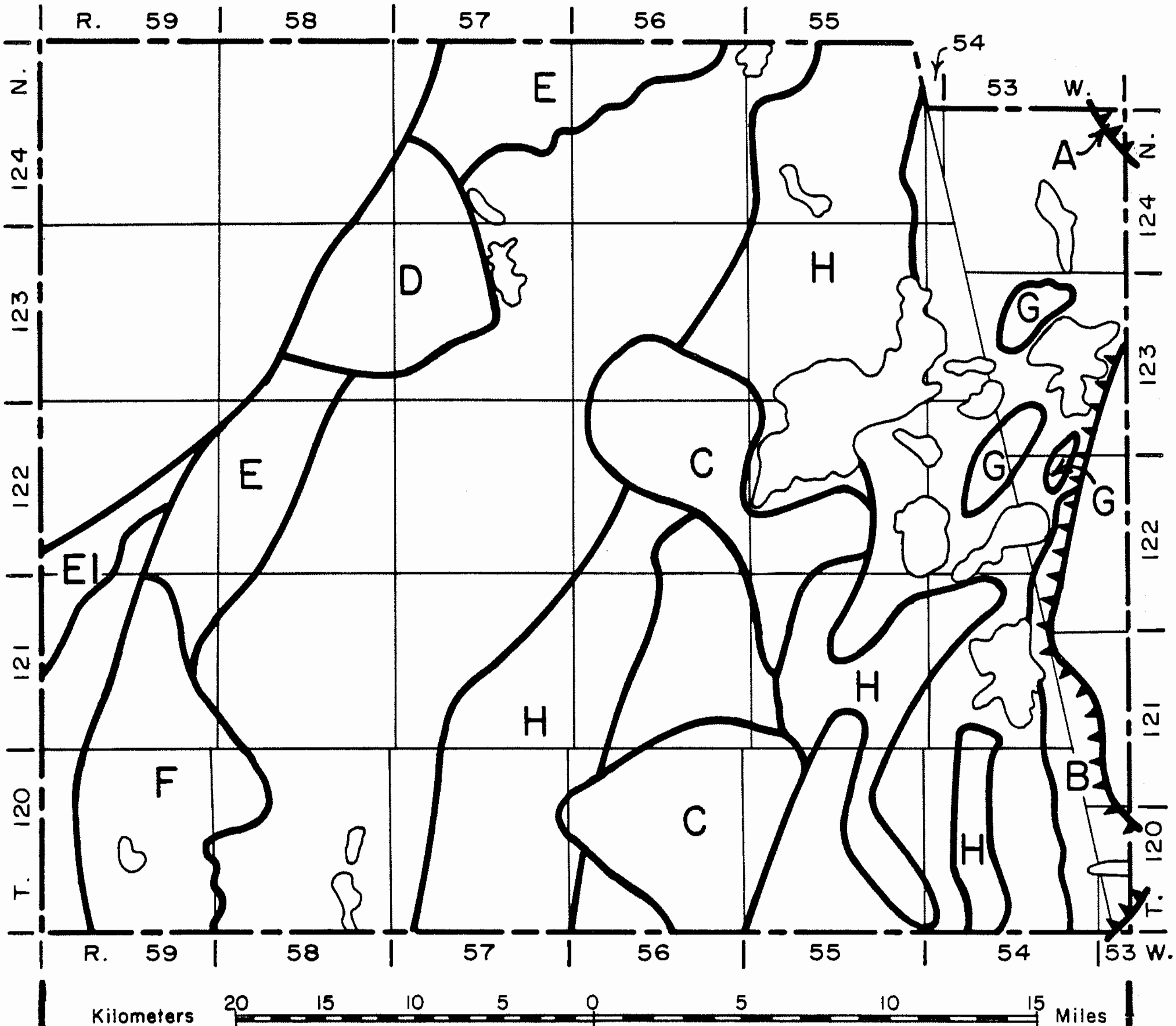
The Waubay Channel appears to have been the major drainage for Day and Marshall Counties before the Pleistocene, and may have been the major drainage for the northern part of what is now the area underlying the Coteau des Prairies. Bedrock data between the Channel and the eastern side of the Coteau are quite scarce and thus information concerning the channel in this area is minimal. The channel runs northwest through the northeastern part of Day County and into Marshall County where it turns to follow a more northerly direction into North Dakota (Koch, personal communication). The Waubay Channel in Day County is incised from 350 to 400 feet at its deepest part and on the Day-Marshall County line it appears to split into two smaller channels which join again in Marshall County. The southeastward extension of the channel into Roberts County is not known and bedrock information in that county is too sparse to allow extrapolation

Pleistocene Geomorphology

End Moraines

Flint (1971, p. 200) defines an end moraine as ". . . a ridgelike accumulation of drift built along any part of the margin of an active glacier. Its topography is primarily constructional." End moraine, for the purpose of this report, denotes a constructional, ridgelike accumulation of drift which marks the absolute limit of an ice advance. Figure 18 shows moraines in Day County and names assigned to them by various authors.

The major end moraine in Day County was called the Waubay Moraine (Rothrock, 1935, p. 6) due to its close proximity to the town of Waubay. Rothrock believed that it marked the easternmost extent of the Dakota Lobe of Wisconsin age (now called the James Lobe) which moved southward down the James Basin and overrode the Coteau des Prairies from the west. Although he did not assign a specific Wisconsin age to it, he indicated that it was younger than the Iowan drift to the east of it. Rothrock's work was published before glacial deposits assigned to the Iowan were considered to be part of the Wisconsin advance. Flint (1955) stated that it marked the easternmost terminus of the Cary substage of the James Lobe. Subsequently, Steece, Tipton, and Agnew (1960)



A — Rothrock (1935), Pickerel Moraine – Wisconsin end moraine. Flint (1955), Altamont Moraine – Wisconsin Mankato substage end moraine. This study, Altamont Moraine – late Wisconsin – Des Moines Lobe end Moraine.

B — Rothrock (1935), Waubay Moraine – Wisconsin end moraine. Flint (1955), and Tipton (1958a and b), Altamont moraine – Wisconsin Cary substage end moraine. This study, Waubay, (Altamont) moraine – late Wisconsin end moraine of James Lobe.

C — Rothrock (1935), Webster Moraine - Wisconsin end moraine. Flint (1955), End moraine of Wisconsin Cary substage. This study, high-level stagnation moraine, late Wisconsin.

D — Todd (1909), Antelope Moraine - recessional moraine of Fourth Antelope Stage. Rothrock (1935), Bristol Moraine - Wisconsin end moraine. Flint (1955), End moraine of Wisconsin Mankato substage. This study, recessional moraine of minor lobe from late Wisconsin James Lobe.

E — Todd (1909), Antelope Moraine - recessional moraine of Fourth Antelope Stage. Rothrock (1935), Bristol Moraine - Wisconsin end moraine. Flint (1955), End moraine of Wisconsin Mankato substage. This study, recessional moraines of late Wisconsin James Lobe.

EI — Todd (1909), Antelope Moraine - recessional moraine of Fourth Antelope Stage. Flint (1955), end moraine of Wisconsin Mankato substage. This study, recessional moraine of late Wisconsin James Lobe.

F — Todd (1909) Antelope Moraine - recessional moraine of Fourth Antelope Stage. Rothrock (1935), Bristol Moraine - Wisconsin end moraine. Flint (1955), end moraine of Wisconsin Mankato substage. This study, Crandall Shear Moraine - late Wisconsin.

G — Rothrock (1935), Pickerel Moraine - Wisconsin end moraine. Flint (1955), end moraine of Wisconsin Cary substage. This study, stagnation drift - late Wisconsin.

H — Rothrock (1935), Webster Moraine - Wisconsin end moraine. Flint (1955), end moraine of Wisconsin Cary substage. This study, stagnation drift.

Figure 18. Map showing major moraine nomenclature by various authors for Day County.

stated that this moraine was equivalent to the Altamont Moraine of the Des Moines Lobe.

The crest of the Waubay End Moraine can be traced continuously from the southeast corner of Day County north to a point just east of Enemy Swim Lake where it disappears (pl. 2). At this point the moraine makes a sharp turn to the northeast and runs into Roberts County where it is buried by a thick blanket of late Wisconsin outwash. Just a few miles further east it coalesces with the end moraine-stagnation moraine complex at the head of the Coteau des Prairies.

There can be little question that the Waubay End Moraine is the eastern end moraine of the James Lobe because just east of its location only two drift sheets can be found, whereas three distinct sheets can be located to its west in several drill holes.

In the extreme northeastern corner of Day County, in sec. 1, T. 124 N., R. 53 W., can be found a small area covered by moraine called the Pickerel Moraine by Rothrock (1935) and later called the Altamont by Flint (1955). This author believes the feature represents the only advance into Day County of the Des Moines Lobe and thus can be considered part of the western end moraine of that lobe. Geographic and topographic arguments are reinforced by the presence of three buried oxidized zones found in a hole drilled through the moraine in the location SE 1/4 SE 1/4 SE 1/4 SE 1/4 sec. 1, T. 124 N., R. 53 W. Drilling to the immediate west of the moraine has revealed only two buried oxidized zones indicating the presence of two buried drifts and one surface sheet. In the author's opinion, the three buried zones beneath the moraine are weathered surfaces of Advance I, Advance II, and Advance III (James Lobe). Thus, it appears that in this small area of the County, the Des Moines Lobe actually overrode the penecontemporaneous James Lobe.

Shear Moraine

Plate 2 shows a feature named the Crandall Shear Moraine which makes up the southwest edge of the Coteau des Prairies in Day County. It is a very prominent feature, standing as a high broad ridge along the edge of the Coteau with its western side composing the actual escarpment. At the Clark County line it rises 250 feet in 1 mile and northward retains a high slope angle to about Amsden Lake.

Previous investigations have interpreted this feature, and indeed the whole west side of the Coteau des Prairies, as a recessional moraine of various glacial episodes. Todd (1909) described it as a recessional moraine of the Fourth Antelope Stage which moved down the James Basin and thus gave it the name, Antelope Moraine. Todd did not assign an age to the feature other than Pleistocene. Rothrock (1935) named this moraine the Bristol moraine and described it as marking the last stand of Wisconsin ice of the James Lobe as it was retreating to the north. Flint (1955) did not give a name to the moraine but described it as the end moraine of the Mankato substage which would imply that it is an end moraine rather than a recessional feature as interpreted by Todd and Rothrock. Extensive drilling in Brown and Day Counties has failed to yield information that would suggest that more than one glacier advanced down the James Basin. Stratigraphic correlation indicates that the entire drift surface from the eastern edge of Day County to the western edges of Edmunds, McPherson, and Faulk Counties is the same age, i.e., late Wisconsin. In the absence of any other data it is concluded that the moraine in question is not of terminal character and, therefore, is indeed not an end moraine.

The possibility that the moraine is of recessional origin is difficult to ignore. It is in direct contact with known recessional moraines north of Amsden Lake and to the west in Brown County (pl. 2). The high relief and the steep sides are rather unusual for known recessional moraines in this part of the country, and it seems more logical from this idea and from the inferred dynamics of the glacial ice as explained under the sections, "Stagnation Drift," and "Pleistocene History," to term the feature a shear moraine; shear moraines as used here have been described as imbricate marginal thrusts by Parizek (1961 and 1967) and Clayton (1967). As such, the Crandall Shear Moraine would comprise a transitional area between the truly active ice of the James Lobe to the west and the stagnant ice on the Coteau des Prairies to the east. North of Amsden Lake the rather gentle relief of the Coteau edge probably reflects some change in glacial regimen which allowed the shear planes to move out onto the Coteau at relatively shallow angles.

Recessional Moraines

Thornbury (1969, p. 366) states, "the term recessional moraine has been used in the past to designate end moraines back of the outermost one, the implication being that a series of end moraines marks successive pauses in the position of a retreating ice front. Actually, some may be retreatal moraines, and others may mark readvances." Recessional moraines in the context of this report imply ridgelike constructional features built along the edge of an ice sheet during temporary halts in recession from its maximum position.

The only recessional moraines in Day County are found along the western edge of the Coteau des Prairies and have been classified into three types (pl. 2). Most of the moraines are grouped as RM1 and are covered by a thin layer of lake silt through which the linear features of the underlying moraines are visible. RM2 comprises small patches of recessional moraine in the southwest part of the County west of the Coteau and are part of the recessional moraines which rise above the surrounding lake silts. An area of about 25 square miles due east of Pierpont has been mapped as RM3. This feature is located in the four-corner area of T. 123 N., R. 58 W., T. 123 N., R. 57 W., and T. 124 N., R. 57 W. The area possesses distinct lobate features with curvilinear and parallel to sub-parallel ridges, and was built by a minor tongue or sublobe of the James Lobe which spread out onto the Coteau from the west. The topography of RM3 is much more rugged with much larger ridges than the previous two types. Ridges of RM3 are composed of till and average 40 feet high. All three types are part of the same system of recessional moraines and represent the recession of the east side of the James Lobe ice. It is possible that RM2 wraps around to the southwest beneath the deep silts of Ancient Lake Dakota to join a similar moraine in Brown County west of Lake Dakota, but tracing it beneath the lake silts is impossible. Together, the features of all three types comprise the Antelope moraine of Todd (1909). See figure 18 for an illustration of this concept.

Absence of Ground Moraine

Flint (1971, p. 199) defines ground moraine as ". . .moraine having low relief devoid of transverse linear elements." In addition to this definition, ground moraine has long been thought to have been deposited by a retreating glacier which retreated at a rather even rate and did not pause long enough to build a ridge-like feature. Classical ground moraine is absent in Day County although large areas of ground moraine were previously mapped by Rothrock (1935) and Flint (1955). The two investigators mapped the County before the concept of large-scale stagnation was generally accepted by glacial geologists and before it was known that stagnation was the predominant ice-retreat process on the Coteau des Prairies. Ground moraine is absent because the entire surface from the end moraine along the eastern edge of the County to the western escarpment of the Coteau is all composed of stagnation drift, and west of the escarpment, the remainder of the County is covered with recessional moraines and lake silts.

Lake Beds in the James Basin

ICE-CONTACT LAKE BEDS

The geologic map (pl. 1) shows lacustrine sediments classified as QwllI. These silts were deposited in a trough formed between the Coteau escarpment and the eastern edge of the main mass of the James Lobe ice as it receded away from the Coteau. The silts are generally very fine grained and of a creamy yellow color when oxidized. The surface of these lake silts slopes westward from an elevation of approximately 1,550 feet at their eastern edge to an elevation of about 1,305 feet at the edge of the Ancient Lake Dakota bed. In places the lake bed is crossed by stream valleys which run west from the west side of the Coteau des Prairies to the James Basin, and in several places patches of stream-laid outwash can be seen in contact with the silts. The silts are generally thin enough that they do not mask lineations of the buried recessional moraines and are quite distinct on aerial photographs.

ANCIENT LAKE DAKOTA BED

The bed of Ancient Lake Dakota only covers about 4 square miles of Day County in the extreme northwest corner of the County (pl. 2). Silts of the Lake Dakota bed are identical in lithology of those of the ice-contact lakes mentioned above and there is no beach, wave-cut cliff, or other distinct feature separating the two deposits in the County. Therefore, the approximate boundary between the two lake beds was taken as the same elevation contour as known beaches in Brown County (Leap, 1986). In the southern half of Brown County the highest known beaches on both sides of the Lake Dakota bed can be definitely traced along the 1,305-contour for some distance. About 8 miles northeast of Ferney the beach on the east side becomes indistinguishable. Extrapolating the remaining eastern boundary into Day County seems reasonable because at the North Dakota boundary the western boundary of the lake bed in only 5 feet higher than at the south end of Brown County. There is the possibility that wave and wind action as well as slope wash could have altered any definite beach line that once existed.

Stagnation Drift

DESCRIPTION AND ORIGIN

Stagnation or dead-ice drift has been recognized on the Coteau du Missouri in North Dakota and Canada for over 20 years by, among others, Townsend and Jenke (1951), Christiansen (1956), Colton and Lemke (1957), Bayrock (1958), Gravenor and Kupsch (1959), Clayton (1962), Winters (1963), Clayton and Freers (1967), and Parizek (1961 and 1967). In South Dakota it has been studied by F. V. Steece of the South Dakota Geological Survey on the Coteau des Prairies, but his results are unpublished. Hedges (1972) described stagnation on the Coteau du Missouri in Campbell County as does C. M. Christensen (1977) in Edmunds, McPherson, and Faulk Counties. A report by N. C. Koch (1975) describes stagnation in Marshall County.

Stagnation drift as used in this report implies large scale geomorphic features distributed over many square miles. Certainly even in predominantly active glaciers there is always a limited amount of stagnation, especially at the margin of the ice, but the stagnation on the Coteau des Prairies is of a much broader nature. Stagnation of the magnitude seen on the northern part of the Coteau des Prairies resulted after great thrust sheets of ice from the main ice masses came out onto the Coteau and began to break up and melt.

The thrust sheets came from the bases of the James Lobe and the Des Moines Lobe and as they moved out of the main masses of the glaciers they dragged great masses of till and added it to the top of the ice on the Coteau. Such shearing or thrusting was of a more or less continuing nature. After each shear was thrust out and eventually came to rest it was no longer part of the active ice of the main lobe and did not react to changes in the dynamics of the main mass but remained in place as the main body of the ice moved down gradient in the lowlands. In this situation, the ice behaved almost "organically," i.e., being separated from nourishment and forward movement of the main lobes, it "died" or stagnated and began to fall apart in an irregular manner along what were probably great structural features such as large scale crevasses and joints. Clayton (1967) believes that the stagnant ice on the Coteau du Missouri in North Dakota did not stagnate enmasse but rather along the forward margin of each thrust sheet. As superglacial drift accumulated on top of the stagnant ice, it insulated the ice against the warm summer air and sunlight and thus it persisted, melting slowly, for a few thousand years. The insulation certainly did not prevent melting of the buried ice, but caused it to melt unevenly and more slowly over a long period of time, during which the surface and superglacial drift was constantly changing shape, distribution and character. As the buried ice melted, collapse of parts of the surface took place along with constant slumping and sliding of wet, clay-rich materials as well as sand and gravel into the hollows to produce topographic inversion which finally, after all the ice had melted, resulted in the characteristic hummocky surface of today with its thousands of closed depressions. Such topography is the most obvious and characteristic feature of stagnant ice areas throughout the High Plains of North America.

DISTRIBUTION

The entire surface of Day County from the Waubay End Moraine on the east to the recessional moraines and lake beds on the west side is covered by stagnation drift (pl. 2).

Landforms Produced by Glacial Stagnation

LAKES AND SLOUGHS

Thousands of closed depressions pockmark the surface of Day County and range in size from an acre to lakes a few miles in diameter. All the depressions formed when blocks or masses of ice melted away leaving the hollows. The largest of the ice-formed lakes are found in the eastern part of the County and probably were formed by the breakup of the first thrust sheet to reach the eastern side of the County, which was also probably the only sheet to reach that far east. There are two arguments for this hypothesis. The first is based upon the fact that around the very large lakes in the eastern part of the County the late Wisconsin drift is no more than 40 feet thick in places, which is less than the distance from the lake bottoms to the tops of the hills immediately surrounding them. This would indicate that the breakup of only one sheet produced the depressions. If more than one ice sheet rode into the depression at different times, one would expect filling of the depressions left by the previous sheet. The second argument bears upon an opposite relationship between drift thickness and lake size in the area west of the large eastern lakes. In this area the lakes and depressions are noticeably smaller and the late Wisconsin drift may be as much as 200 feet thick. The greater thickness of drift probably implies that it was deposited by the ablation of several sheets of ice stacked on top of each other which would also prevent very large lakes from forming because after one sheet broke up into large blocks, later sheets would override it and fill up any depressions created by the former.

Scattered among all the lakes and depressions are hollows of varying size which formed as the result of breakup of the ice into blocks of varying size and the resulting slumping and flowing of water-saturated drift to produce a hummocky topography.

The origin of the large lakes in the eastern part of the County deserves special consideration. The contoured surface of the drift of Advance II shows deep depressions in the areas now occupied by Bitter Lake and Pickerel Lake (fig. 11). It is apparent that the ice accumulated in these depressions during the first advance that reached this area. When the ice of the late Wisconsin advance moved into this region large blocks filled up the depressions and later melting produced the lakes of today. Not quite as striking, but more than coincidental, is the relation between the other large lakes and the broader and more shallow depressions in the drift of Advance II. Waubay and Rush Lakes were evidently formed when large ice blocks settled in the wide low between Webster and Waubay. Although Enemy Swim and Blue Dog Lakes are large in area, they are not very deep and their relation to the buried surface topography is not as direct as that of the other major lakes.

DISINTEGRATION RIDGES

Disintegration ridges are very prominent features in areas resulting from glacial stagnation and occur in many different forms. They are formed in at least three major ways (fig. 19). Most of the ridges form when sand, gravel and/or water-saturated till washes and slumps into channels and crevasses in the ice and subseqently the ice melts away leaving a constructional feature whose shape in the horizontal plane resembles the shape of the original depression filling in the ice. Such masses of material which accumulate in channels and crevasses will form ridges of a sinuous to linear shape, while those that form in holes or closed depressions in the ice will be circular or near circular in form. The second process of formation involves accumulation of material

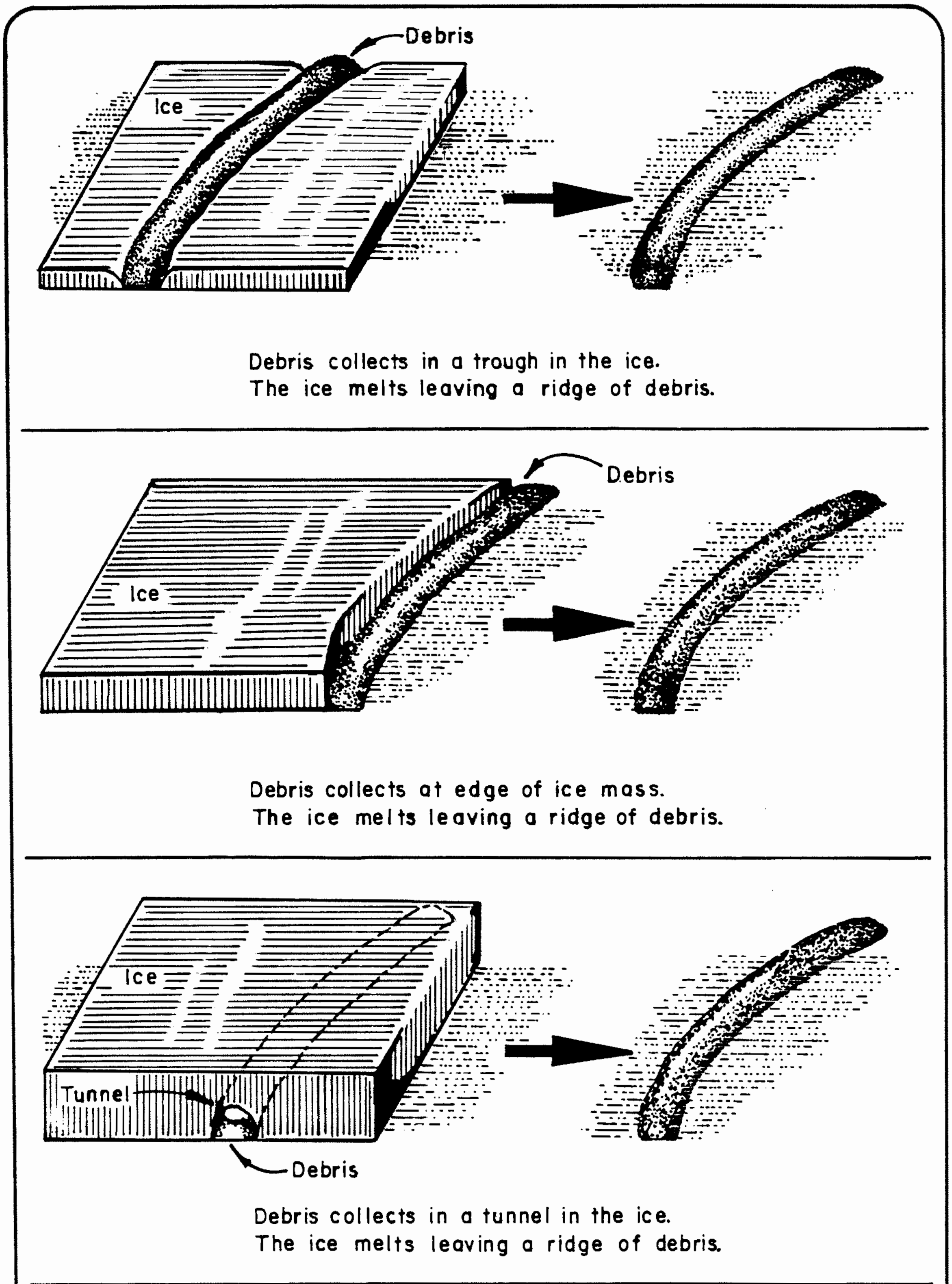


Figure 19. Processes of formation of disintegration ridges.

at the edge of an ice sheet or block. When the ice melts back from the mass, a positive feature is left which outlines the edge of the ice. The third method involves the deposition of sand and gravel by meltwater inside tunnels in the ice. When the ice melts away the material is again left as a ridge or series of connecting ridges resembling the plan view of the pre-existing tunnels. Such features have long been known in the literature as eskers.

Rothrock (1935, p. 41) described several eskers in eastern Day County in T. 120 N., R. 55 W. and in T. 123 N., R. 53 W. It is impossible to determine if these features are truly eskers or disintegration ridges formed on the surface of the ice, but for the purpose of this report they are termed disintegration ridges.

There are many modifications of the above methods of formation and in addition, the features are often connected to forms of different genesis. Detailed treatises concerning the origin of the ridges can be found in Clayton and Freers (1967, pp. 31, 32), Bik (1967, pp. 83-94), Gravenor and Kupsch (1959, pp. 52-54), and Parizek (1967, pp. 49-102).

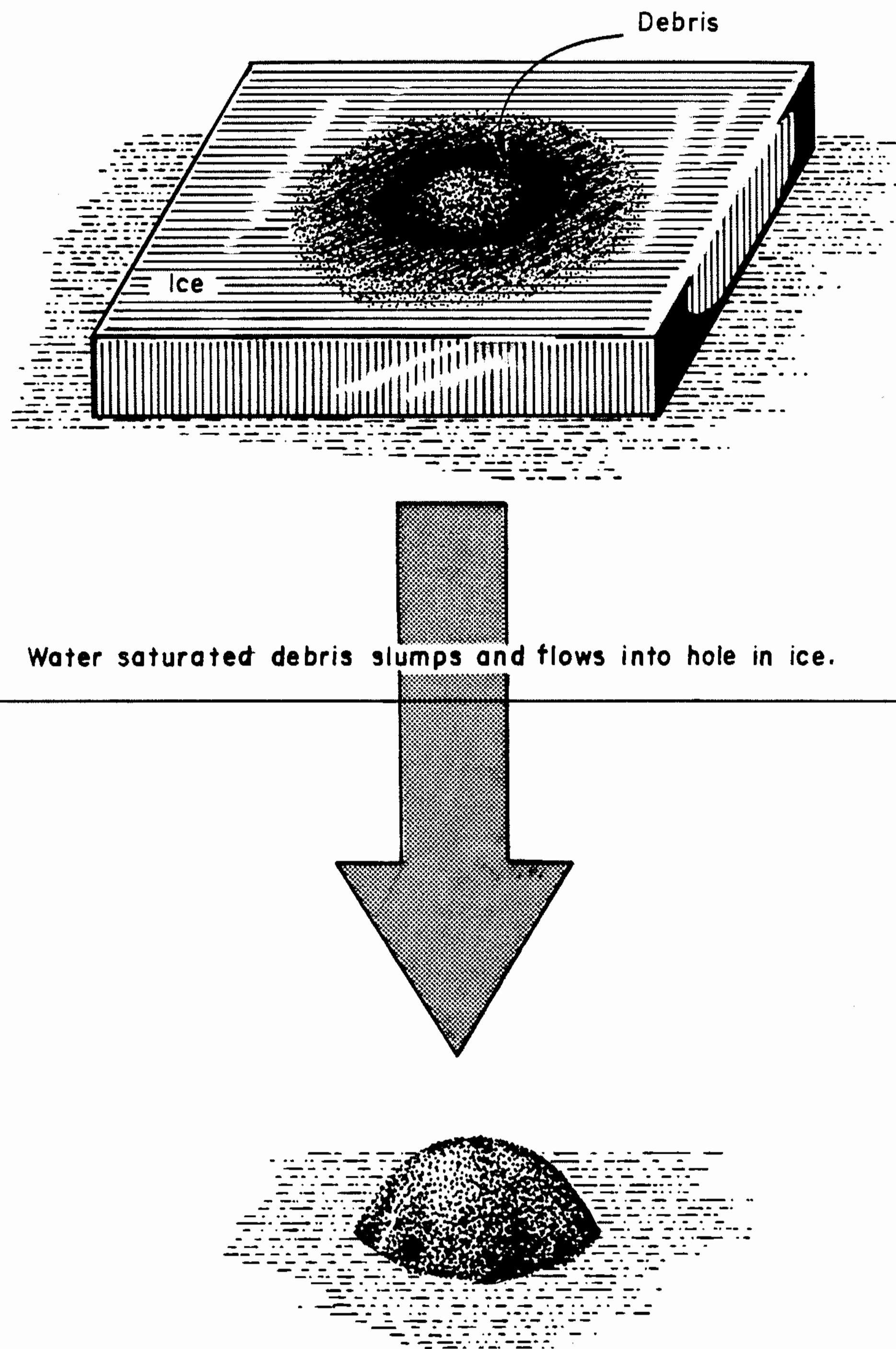
Plate 2 shows the location of disintegration ridges of diverse origin in Day County. Generally the larger ridges are good sources of sand and gravel. These deposits may be well developed only locally but they are widely distributed throughout the Coteau and vary widely in grain-size.

KAMES

A kame is a mound of material, usually sand, gravel and silt, which was formed by slumping and flowing of water-saturated drift into a hole in the ice with subsequent melting away of the ice (fig. 20). Often kames provide a significant amount of sand and gravel, but frequently they contain large amounts of clay and silt, the presence of which results from the fact that the material, being deposited in a closed depression was not subject to the winnowing action of running water. In Day County kames can be found in all parts of the stagnation drift area. They have not been mapped because of their great number and small size.

KAME TERRACES

Kame terraces are geomorphic features composed of outwash which was deposited between a mass of ice and a hill or valley side. They are genetically closely related to kames (fig. 21). After the ice melts, the material on the ice-ward side assumes a slope near the angle of repose while the material close to the upland remains fairly flat, thus giving rise to the terrace-like shape. Like kames, kame terraces are usually good sources of sand and gravel which are often of good quality owing to the flushing action of the meltwater. Plate 2 shows kame terraces in



Ice melts away leaving mound of debris (kame).

Figure 20. Process of formation of kames.

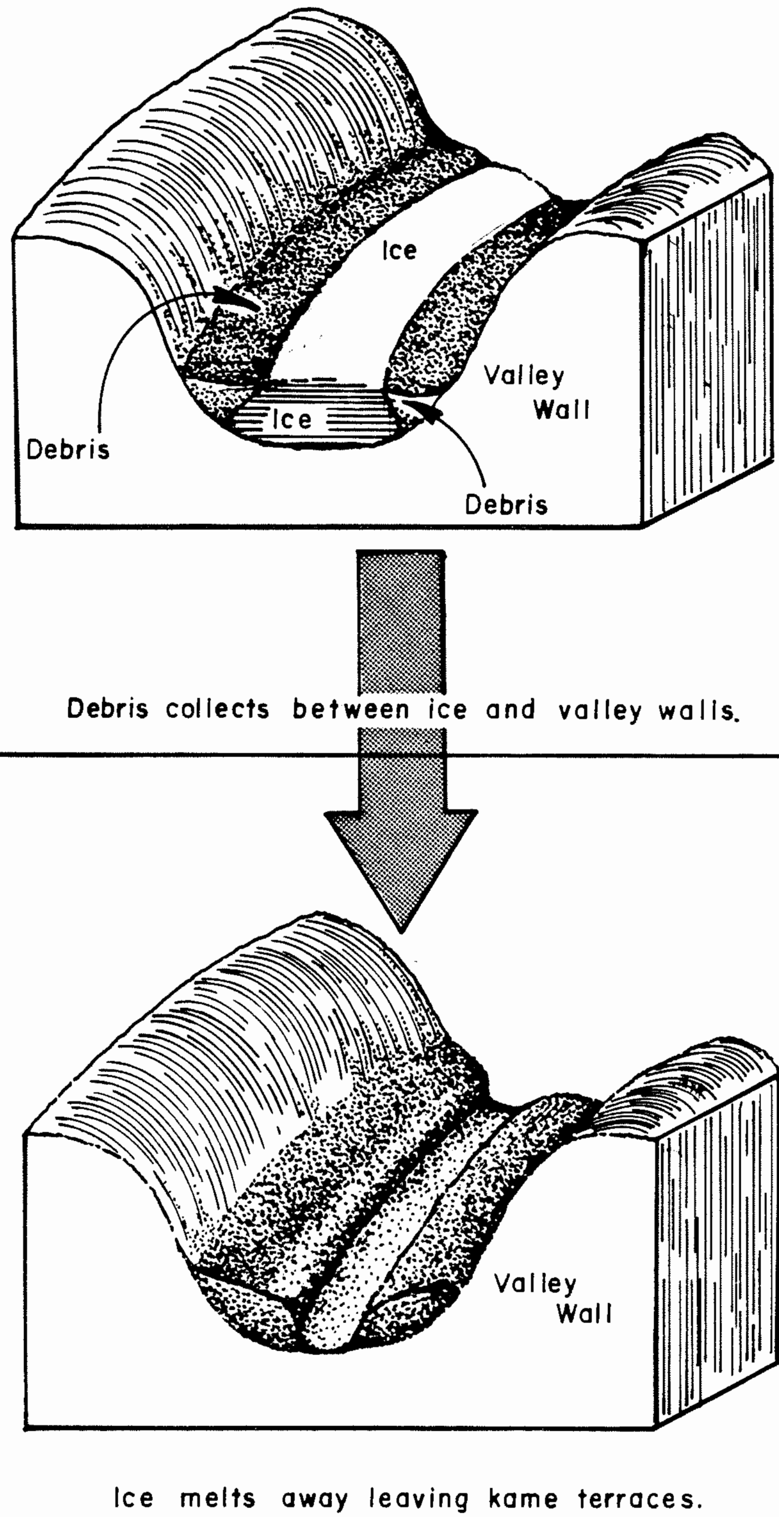


Figure 21. Process of formation of kame terraces.

the area around Sweetwater Lake and north of Crandall in secs. 10, 14, and 15, T. 120 N., R. 59 W.

PRAIRIE MOUNDS

Prairie mounds are much like kames in their mode of origin in hollows or depressions in the ice. They differ from kames in that they are usually composed of material richer in clay than kames and also possess a different geomorphic form than kames (fig. 22). Prairie mounds are known by various names such as rimmed kettles, closed disintegration ridges, doughnuts, humpies and others; Parizek (1961 and 1967) gives a good review of the literature concerning the form and proposed manner of formation of these features.

The general geomorphic form of a prairie mound is a mound with a depression in the top. They form through the following three steps (fig. 22).

1. Superglacial drift slumps and flows into closed depressions on the surface of a stagnant glacier and insulates the ice directly below the drift mass.

2. The surrounding ice around the mass melts away leaving the ice-cored mound.

3. Eventually the ice core melts causing the top of the mound to collapse leaving a depression in the top.

Depending upon the shape of the initial depression, the final form when viewed from the top may resemble two concentric circles, a barley grain, a ridge with a furrow in the top, and other variations upon these forms. Often these features are 5 to 15 feet high at the top with a central depression 5 to 15 feet deep.

In Day County, a field of prairie mounds exists northeast of Blue Dog Lake in secs. 1 and 2, T. 122 N., R. 53 W.

HIGH-LEVEL STAGNATION MORAINE

Rothrock (1935) described two systems of Wisconsin terminal moraine running generally northeast-southwest through Day County which he named the Bristol Moraine and the Webster Moraine (fig. 18). In addition, Tipton (1958a) described much of the southeast part of Rothrock's Webster Moraine as the Cary End Moraine. Evidence today does not support this interpretation although the areas described by these investigators are indeed high topographically in comparison to the area around them.

Close inspection of the surface and subsurface geology of the high and low area showed that land forms in the two areas are essentially identical. Indeed, lithologies and geomorphic

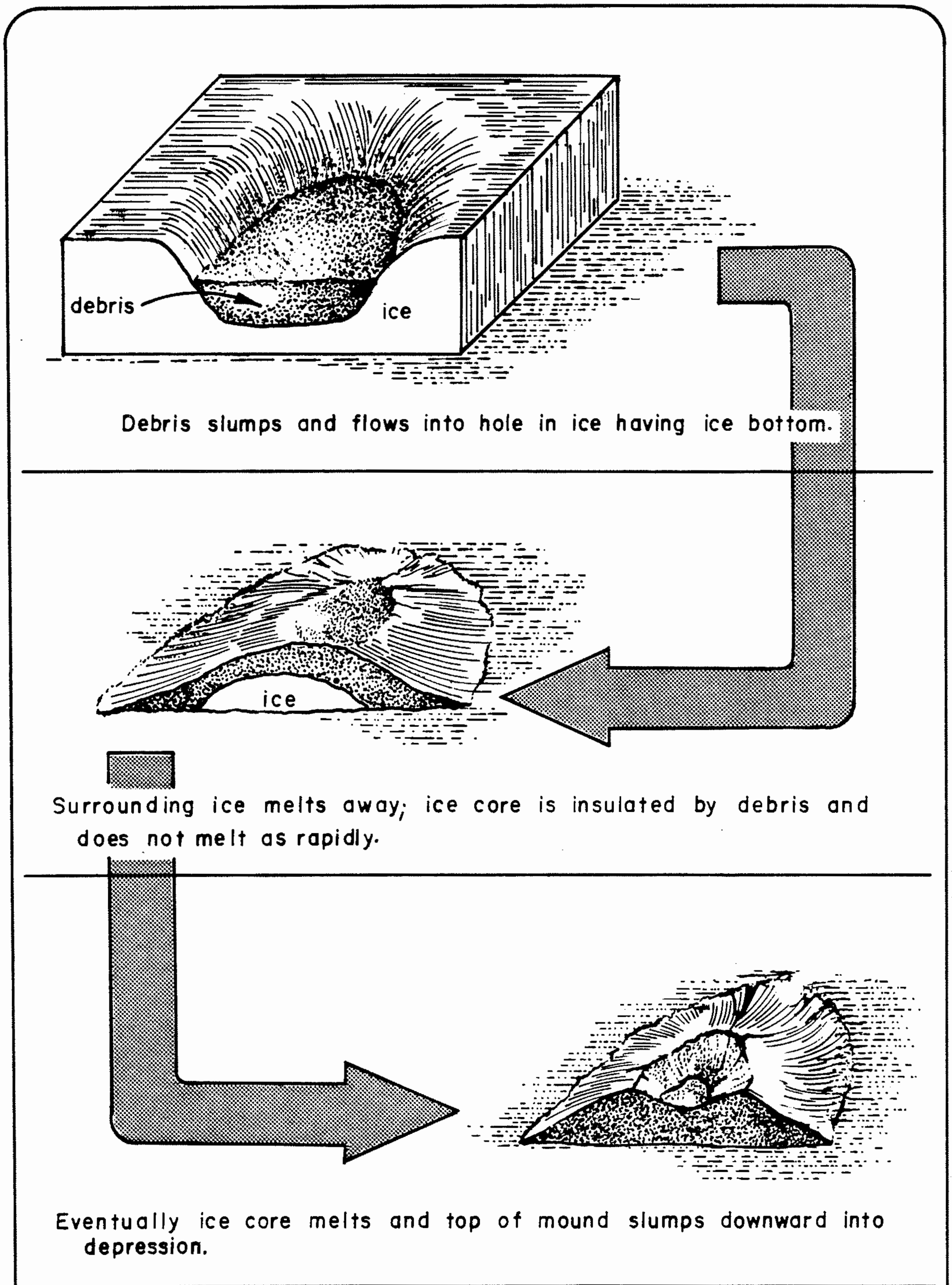


Figure 22. Process of formation of prairie mounds.

features on the high areas drape over the sides of the high places and continue across the surrounding low areas. Throughout their entire extent the areas show evidence of extreme ice stagnation (abundant disintegration ridges, prairie mounds, lake silts, etc.). Because these areas are so geologically similar to the surrounding lower regions they are referred to as high-level stagnation moraines.

The origin of these high-level stagnation moraines is not completely understood but they may result from the ablation of stacked drift-laden ice sheets or imbrications of greater thickness than in the surrounding lower areas where ice was cleaner. From subsurface data showing the bedrock topography and topography of earlier drift sheets, it is not very likely that they reflect buried topography. Plate 2 shows the high level moraines running generally north-south through the County.

MORAINE PLATEAUS

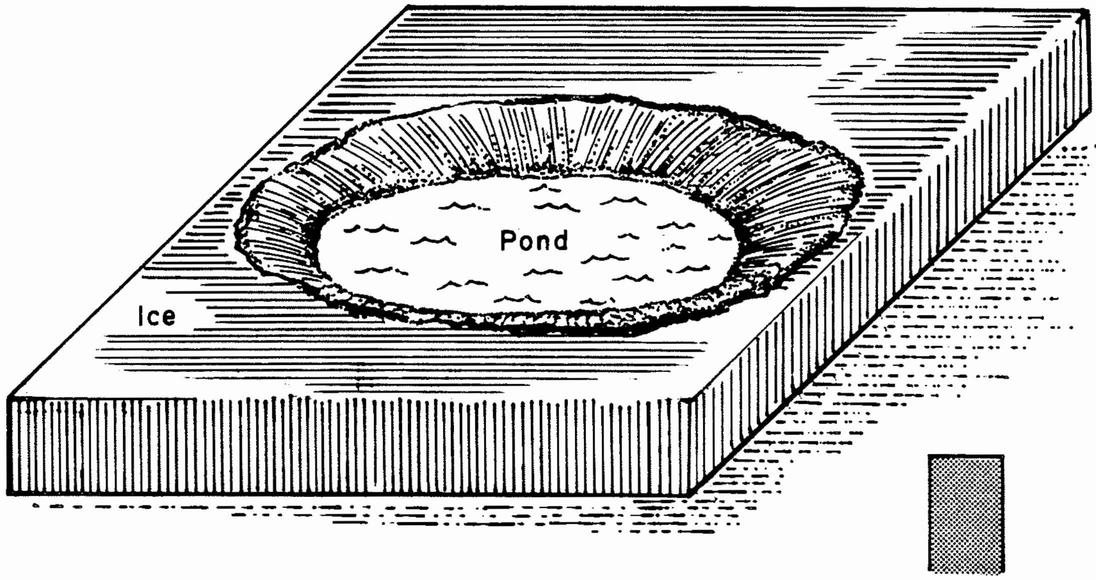
Moraine plateaus are mesa or butte-shaped features with flat to nearly flat tops and steeply sloping sides. They are very common in areas of glacial stagnation and similar features have been described in detail by various authors (Hoppe, 1952, 1957, 1959, 1963; Parizek, 1961 and 1967; Clayton, 1967; Clayton and Cherry, 1967; Stalker, 1960; Winters, 1963; Kume and Hansen, 1965; and Hansen, 1967).

Moraine plateaus range in diameter from a few hundred feet to a few miles and from 30 to 75 feet high. They are generally very prominent features of the landscape. Flint (1955) interpreted features similar to moraine plateaus in eastern South Dakota as bedrock-controlled features similar to the bedrock mesas and buttes of the western part of the State. In the last few years drilling information has refuted this interpretation and has shown that bedrock generally lies a few hundred feet below the plateau surface and that the plateaus themselves are actually composed of glacial drift.

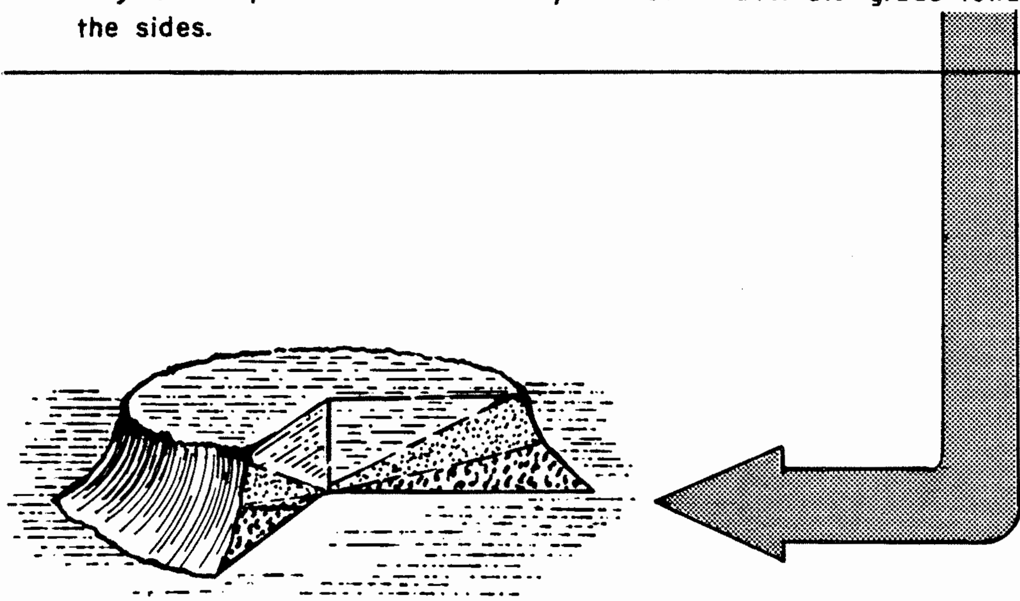
In Day County, three general types of moraine plateaus have been found--moraine mudflow plateaus, moraine lake plateaus, and moraine outwash plateaus. In many cases, all three types may be found in one plateau complex. The main difference depends upon the type of sediment and velocity of water during deposition (fig. 23).

MUDFLOW PLATEAUS

During ablation in areas of stagnant ice most of the supraglacial drift is saturated with water and will slump and flow as the ice beneath and around it melts. In such cases, water-saturated till will often flow into a hollow or closed depression in the ice. With such a high water content, the material will settle and



Outwash is carried by flowing water into large hole in ice; silt and clay are deposited in the center, coarser materials grade toward the sides.



Ice melts and sides of deposit slump to angle of repose. (Cut-away view showing ideal grain size sorting which may vary depending on material available and velocity of transporting water.)

Figure 23. Process of formation of moraine plateaus.

flow until it assumes a level to near-level surface. Eventually, the ice around the mass melts away and the sides of the mass flows and slumps until the angle of repose is attained, leaving a mesa-shaped feature.

A very large moraine mudflow plateau can be found in secs. 24 and 25, T. 123 N., R. 57 W. Drilling to a depth of 150 feet below the surface of this feature revealed that the entire mass was composed of a material looking like till that has slumped and flowed into water.

MORAINE LAKE PLATEAUS

Moraine lake plateaus form when silt and clay are washed into superglacial lakes and settle to the bottom and the surrounding ice melts away as in mudflow type plateaus. In Day County most such features often possess sand and gravel sides which grades into lacustrine silt and clay near the center.

MORAINE OUTWASH PLATEAUS

Similar in formation to the above two types, the outwash plateaus are composed of sand and gravel and form under conditions of faster flowing meltwater than the other types. In Day County, outwash plateaus comprise very good sources for sand and gravel and can be found in a large area of the County (pls. 1 and 2).

Most of the moraine plateaus in Day County are composites of outwash and lacustrine sediments. Typically the bulk of the feature is composed of sand and gravel with lake sediment on the top. The grain size of the material usually decreases from the sides to the interior and indicates a changing depositional environment--sand and gravel were deposited close to the edge of the superglacial lake where meltwater was derived from the enclosing mass of stagnant ice and silts and clays toward the interior where meltwater was ponded. As the meltwater decreased in velocity and load capacity over a period of time silt and clay became the major lithology and thus were laid down over the sand and gravel producing the common stratigraphic sequence, form and structure seen today.

COLLAPSED FEATURES

The great thickness of late Wisconsin glacial drift on the Coteau des Prairies is believed to be due to successive thrusting of great sheets of drift-laden ice onto the Coteau from the James and Des Moines Lobes and the subsequent melting of this drift-laden ice. Several sheets were piled on top of each other and with each successive thrust more drift from the base of the main lobes was added to the superglacial drift on the Coteau.

As the ice beneath the drift melted over a long period of time the geomorphic features developed in the superglacial drift collapsed and slumped until topographic inversion was the rule. Deposits and landforms were shaped and reshaped as they shifted from the surface of the stagnant glacier to their final positions. Day County contains widespread evidence of such collapse features.

Collapsed Lake Plains

The large areas of lake silt in Day County between the recessional and shear moraines in the western part of the County and the end moraine along the eastern edge attest to the fact that there were numerous hollows and depressions in the stagnant ice. Plates 1 and 2 show most of this area covered by lake silts. Close inspection showed that most of the material had collapsed after deposition as evidenced by the rugged nature of the surface and contortions and folds in the bedded sand, and gravel and lake sediments revealed in road cuts.

Collapsed Outwash Plains

Low areas in the stagnant ice which were subject to high-velocity streams of meltwater collected vast amounts of outwash sand and gravel. As in the case of collapsed lake sediments the ice beneath the outwash melted away and caused the outwash to collapse and slump into new topographic forms and positions. Gravel pits throughout the County show evidence of collapse in the form of slumps, folds, and faults running through the material.

Collapsed outwash plains differ from collapsed valley trains in that the plains are of a much broader nature and were deposited over a flatter and broader area of the ice. Plate 2 Shows collasped outwash plains in the areas south and west of Bitter Lake (T. 121 N., Rs. 54 and 55 W.).

Collapsed Valley Trains

Superglacial streams were often subject to large torrents of outwash-laden meltwater. Stream valleys floored and walled by ice were often depositional sites for valley-train outwash deposits which later collapsed when the ice floor and walls melted away. Plate 2 shows collapsed valley train outwash around Sweetwater Lake and in the area around the large eastern lakes (T. 120 N., R. 59 W.).

BEDROCK STRUCTURE

The structure of the bedrock underlying Day County and indeed most of northeast South Dakota reflects the general structure of the granitic Precambrian Canadian Shield which dips gently to the south and west at about 5 feet per mile. The Dakota Formation directly overlying the basement generally thickens and dips to the west (Schoon, 1971, fig. 1). The surface of the Greenhorn Limestone is essentially flat in this area (Schoon, 1971, fig. 14). The overlying Pierre Shale has a more rugged surface as shown in figure 8. Generally the subsurface data concerning the Cretaceous formations are too sparse to allow very specific inferences about the bedrock structures.

In recent years since the advent of high-altitude imagery obtained from satellites, investigators in various parts of the United States have discovered lineaments which were previously unknown and have attributed them to propagation of fractures upward from the basement to the surface. Infrared images of the Coteau des Prairies region have revealed two distinct lines running through the area which could be reflections of basement conditions although no proof of this is at hand. The lines were found on ERTS infrared image 16484, Band 7. One line trends from the north side of Spring Lake northeasterly past the northwest end of Pickerel Lake and into Marshall County. A second line trends from near Claremont in Brown County, southeasterly for approximately 50 miles into western Day County.

GEOLOGIC HISTORY

Pre-Pleistocene History

Precambrian History

The Precambrian basement of eastern South Dakota is part of the southern extension of the Canadian Shield which crops out in northern Minnesota and southern Canada. Sometime before the beginning of the Paleozoic Era a large structural downwarp began to form in the tri-state area of Montana, North Dakota, and South Dakota and formed the Williston Basin which is elongated generally north to south. Day County sits east of the east edge of this basin.

Paleozoic History

During Paleozoic time the Williston Basin continued to deepen as the seas encroached and marine sediments were deposited within it. No Paleozoic sediments have been found in Day County and the nearest deposits are probably located in western Brown County. It is likely that during Paleozoic time the eastern limb of the basin beneath Day County was elevated above sea level and was undergoing erosion with sediments being carried into the interior of the basin from the region of Day County.

Mesozoic History

By the time of the Mesozoic Era the sediments in the interior of the basin had reached sufficient thickness to cause deposition to take place on the eastern slope of the basin; however, no Triassic or Jurrasic rocks are present in the County which indicates that either they were never deposited, or were deposited and later eroded away.

The earliest Mesozoic rocks resting directly on Precambrian aged rocks are those of the Dakota Formation of Cretaceous age. Although the Dakota is characterized by both terrestrial and marine sediments it is not known for certain of which type the Dakota in Day County is representative. There is some inference in Schoon (1971) that they may be terrestrial in origin. If this is indeed the case, it would seem likely that the source of the sediments was the higher part of the Precambrian to the east.

From the top of the Dakota to the top of the Pierre Shale the rocks reveal a marine environment of deposition as the Cretaceous seas persisted in the midcontinent region.

Cenozoic History

After deposition of the Pierre Shale and regional uplift at the end of the Mesozoic Era, subaerial erosion began to change the surface of the Pierre and probably continued throughout all of the Tertiary Period, although the western part of South Dakota at this time was still undergoing deposition.

During the Tertiary period or perhaps early Pleistocene, the major drainage way of eastern South Dakota formed on the Cretaceous rocks. In the northeastern part of the State the major north-south channel was that of the ancient Grand-Moreau-Cheyenne River system which ran northwest through Brown County probably to the Arctic Ocean (Flint, 1955, pl. 7; Leap, 1986). Within what is now Day County three important channels formed during the Tertiary or early Pleistocene--the Sweetwater, the Webster, and the Waubay Channels (fig. 24). The Sweetwater drained south to an unknown outlet. The Webster Channel drained eastward to the Waubay Channel which in turn probably drained north to an undetermined outlet. A note of caution should be observed in interpreting the history of the bedrock channels, for it is not known if they were formed before the first ice advance into Day County or during the advance.

<u>Pleistocene History</u>

Figure 10 shows the extent of the earliest ice sheet in Day County, Advance I. No glacial deposits older than late Wisconsin have been found in Brown County. Hedges (1968, pl. 3) shows a "pre-Wisconsin" till extending west of the James River for a

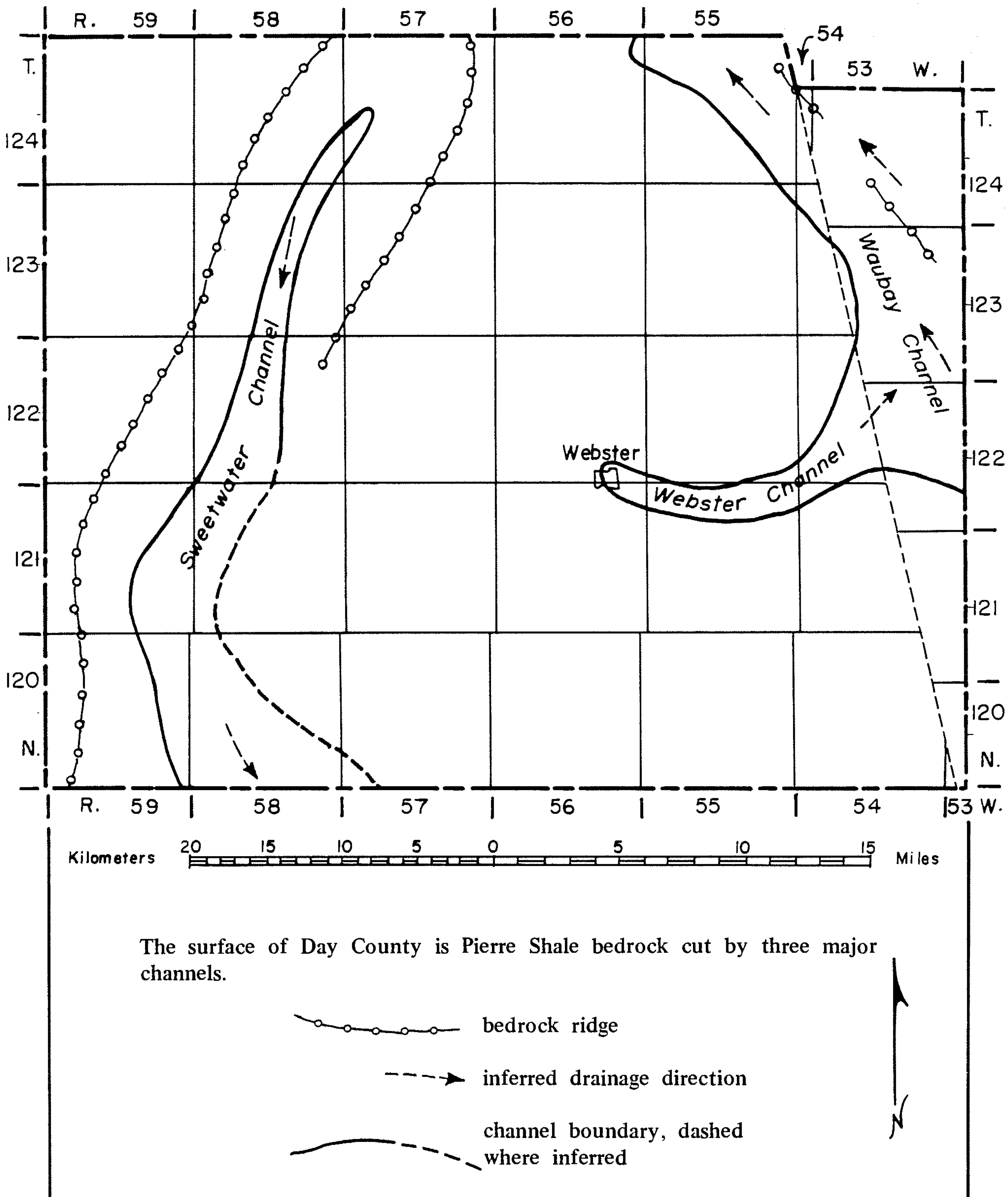


Figure 24. Map showing major features of Day County before Advance I.

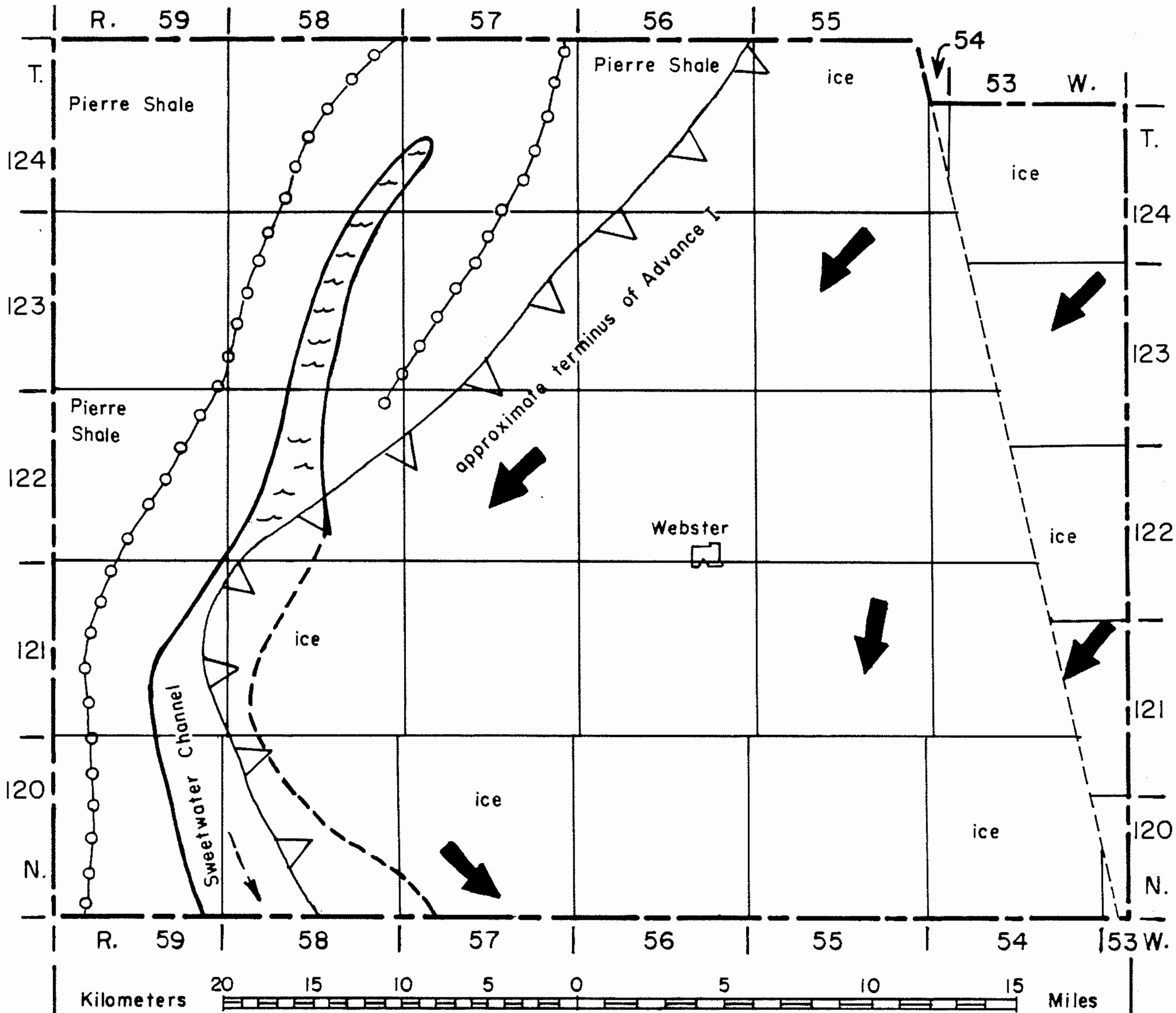
short distance in Beadle County. It is quite possible that this drift sheet is correlative with the deposits of Advance I as described in this report and it may extend southward and westerly through Clark County and into Spink County. Advance I probably came from the east or northeast and was stopped by the bedrock ridge on the west side of Day County and forced to turn south (fig. 25). Subsurface data concerning the drift of Advance I are less complete than for the drift deposited during the two later advances. As Advance I moved across the County it probably melted somewhat during warm periods and the meltwaters deposited the basal outwash and valley fills which the glacier later overrode as it continued to move across the County from the east.

Advance II also came from the east but did not move into Brown County (fig. 26). Figure 11 shows that its terminus is almost the same position as that of Advance I. As the ice of Advance II passed over the eastern edge of the Coteau des Prairies it sheared off large slabs of Pierre Shale and carried them to the vicinity of Waubay. Why this advance stopped at about the same position as Advance I is a good question. Probably the bedrock ridges also stopped it as they did in the first advance. Also, the presence of an end moraine of Advance I may have provided resistance to further movement, but no such moraine has been detected in drilling.

The late Wisconsin ice, Advance III, came from the northwestern and central parts of Canada. When it reached the nose of the Coteau des Prairies just inside the North Dakota-South Dakota line it split into two lobes--the James and the Des Moines. As both lobes spread to the south and laterally, shears developed from their bases and many large sheets of ice were thrust out onto the Coteau.

Probably the first ice mass which came out of the James Lobe moved as far as the eastern border of Day County and built the Waubay End Moraine (fig. 27). It is not completely clear when the ice stopped at this particular position, but the answer may rest with the relatively high surface topography that was formed as a result of Advance II and the restricted nature of the lobes. Figure 11 shows that between Webster and Waubay the surface begins to steepen toward the east and this increase in slope and higher surface elevations may have provided enough resistance to stop the ice mass at that locality.

During or after the time the mass had melted along its eastern edge and was building the Waubay End Moraine, the rest of the ice mass was stagnating and slowly breaking up en masse into large blocks several miles across which in time melted away to leave the closed depressions that now contain the large lakes in the eastern part of the County (fig. 27). The final ice blocks were at least 100 to 150 feet thick when they first broke up, judging from the distance from the bottoms of the present day lakes to the tops of the hills surrounding them. Prior to this the ice

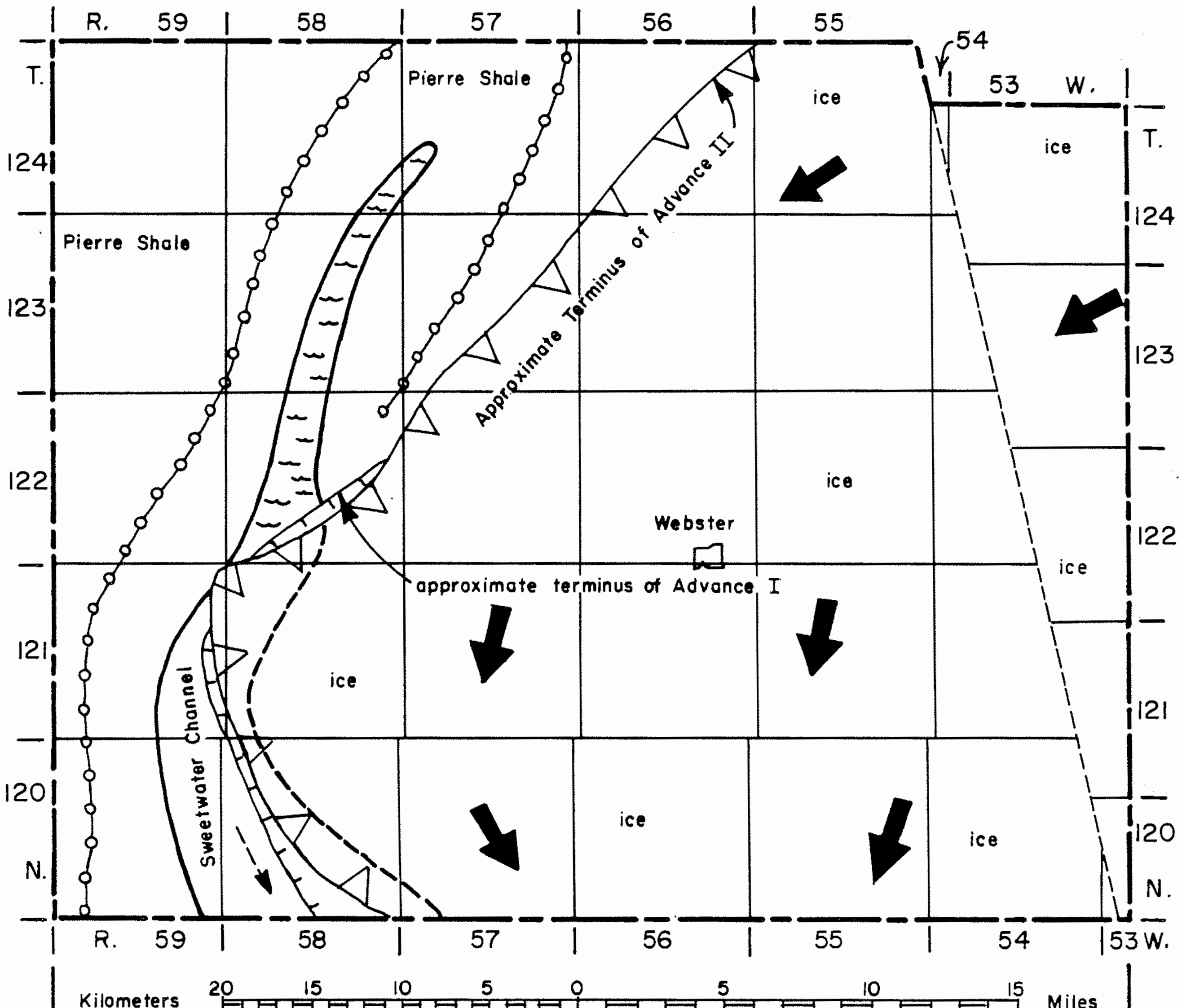


Advance I ice covers most of the county and terminates along western bedrock ridges. Northern part of Sweetwater Channel is ponded.

- bedrock ridge
- water
- approximate terminus of Advance I
- inferred direction of ice movement
- inferred drainage direction
- boundary of Sweetwater Channel, dashed where inferred

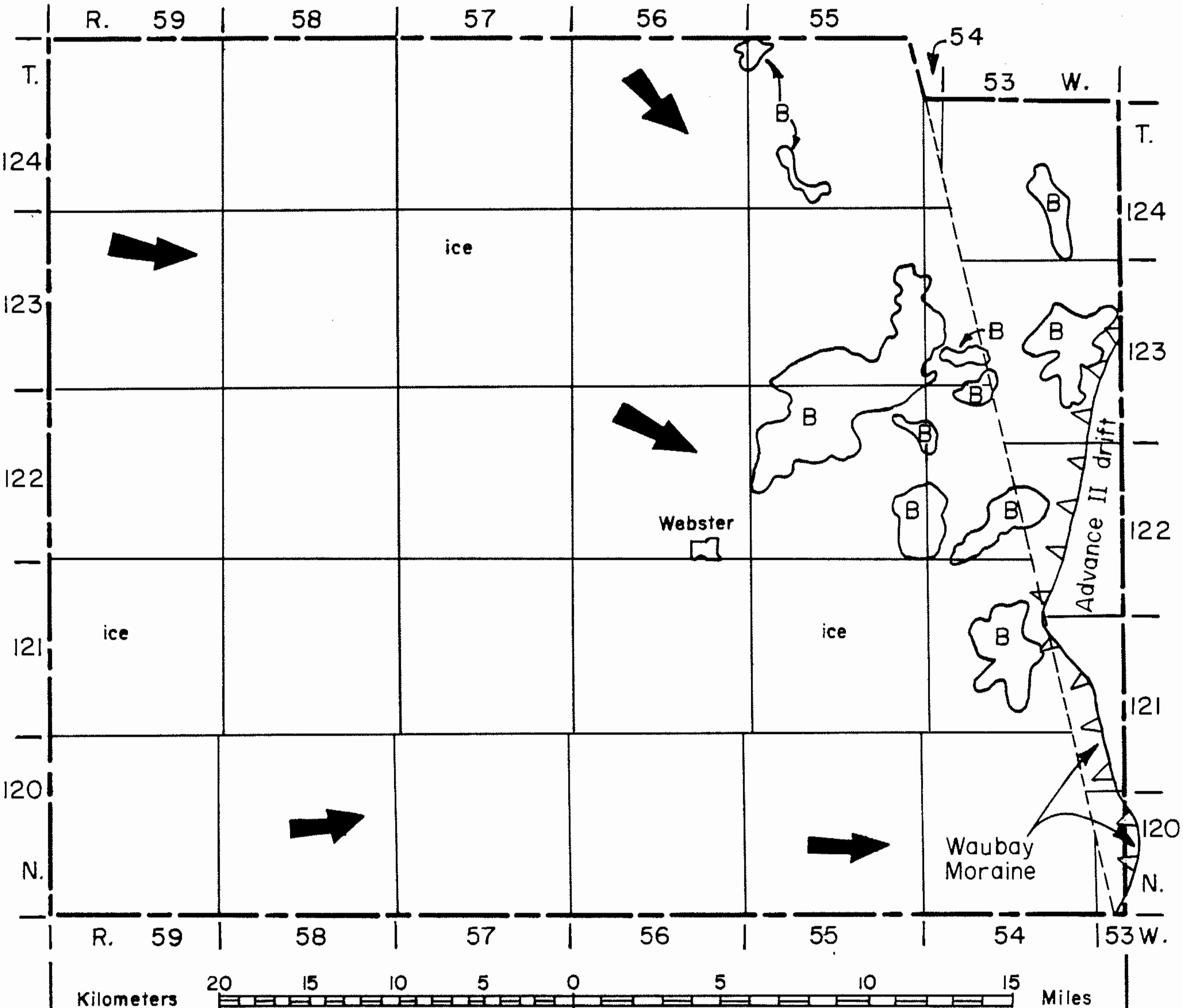
N

Figure 25. Map showing Day County after glacial Advance I.



Advance II ice covers most of the county, buries most of Advance I, terminus, and terminates along western bedrock ridges.

Figure 26. Map showing Day County after glacial Advance II.



Advance III (late Wisconsin) ice comes out of the James Basin and moves eastward across the county and terminates along the eastern border building the Waubay Moraine. West of the terminus the ice mass begins to stagnate and break up into large blocks.

B ice block

terminus of late Wisconsin James Lobe

inferred direction of ice movement

N

Figure 27. Map showing Day County after glacial Advance III (late Wisconsin).

must have been several hundred feet thicker when the edge of the glacier first began to stagnate.

The great thicknesses of the stagnant ice blocks in the eastern part of the County probably provided added resistance to the mobile glacier which helped form later debris-enriched thrust sheets near the ice front coming from the west out of the James Lobe and may have caused them to pile up to form the high-level stagnation moraine described earlier in this report (fig. 28). After each thrust sheet formed it stagnated and broke up into hundreds of blocks whose geological legacy can be found in the form of the many lakes and sloughs in the County.

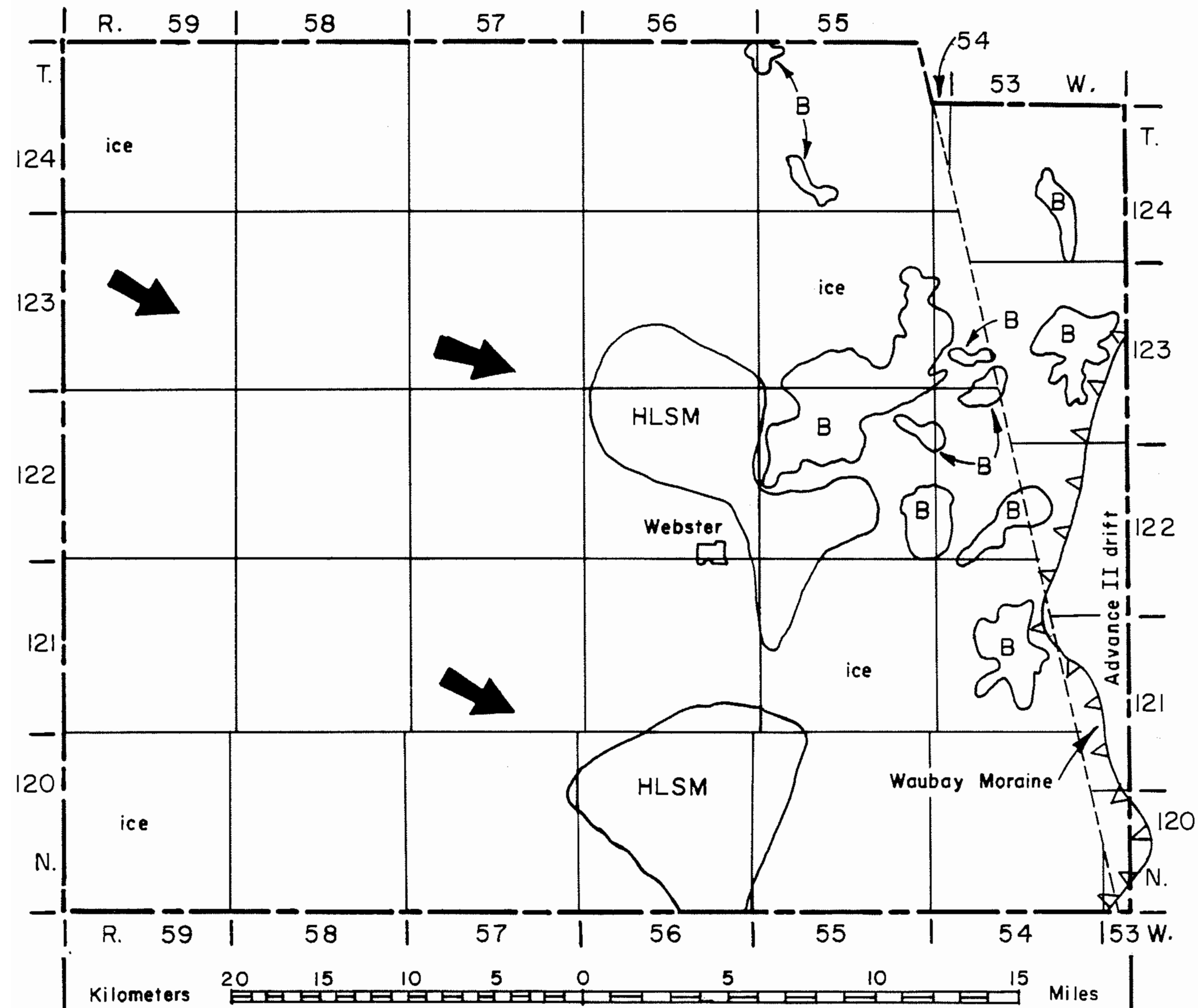
It appears that each successive major thrust sheet stopped somewhat west of the preceding thrust sheet. Each preceding sheet probably added new resistance for the one succeeding it. Finally, after the Coteau was covered by a few hundred feet of stagnant ice, the resistance became so great that the large sheets could not be moved any great distance and therefore thrusting took place at steeper angles producing the large Crandall Shear Moraine (fig. 29 and pl. 2).

At some period in time, probably toward the end of the major thrusting episodes, a small lobe of glacial ice came out of the James Basin in the vicinity of Pierpont and pushed eastward for a few miles northeast of Pierpont (fig. 29). As it receded it left the arcuate recessional moraine described as RM3 (pl. 2).

The late Wisconsin glacier was evidently a temperate mass of ice and during the summers there must have been extensive melting as evidenced by the basal outwash that underlies late Wisconsin till. As the ice moved eastward up the bedrock slope on the western side of the Coteau des Prairies, it deposited a blanket of outwash which draped over the top of the bedrock ridge in the northwest part of the County and joined and overlapped the already existing basal outwash deposited during Advance I.

Sometime after the Waubay End Moraine was built, a thrust sheet from the Des Moines lobe reached Day County in sec. 1, T. 124 N., R. 53 W. On its way across the Coteau it overrode and buried the Waubay End Moraine just northeast of Enemy Swim Lake in Roberts County (fig. 30). Thus south of Enemy Swin Lake the area between the Waubay End Moraine and the end moraine of the Des Moines Lobe (the Altamont Moraine) in Roberts County to the east became an interlobate area which was to receive vast amounts of outwash from the melting ice around it.

The large area between the high-level stagnation moraine near Webster and the Waubay End Moraine containing the comparatively cleaner large ice blocks from the stagnation of the first thrust sheet acted as a regional low. As the ice surface was lowered by melting faster here than near Waubay and the Waubay End Moraine it eventually contained two large superglacial sluiceways for



Presence of ice blocks in the eastern part of the county provides the resistance to ice thrusting from the west causing thrusts to pile up into high level stagnation moraines.

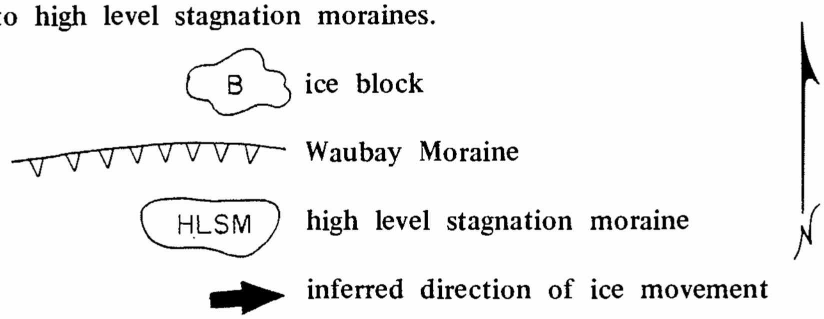
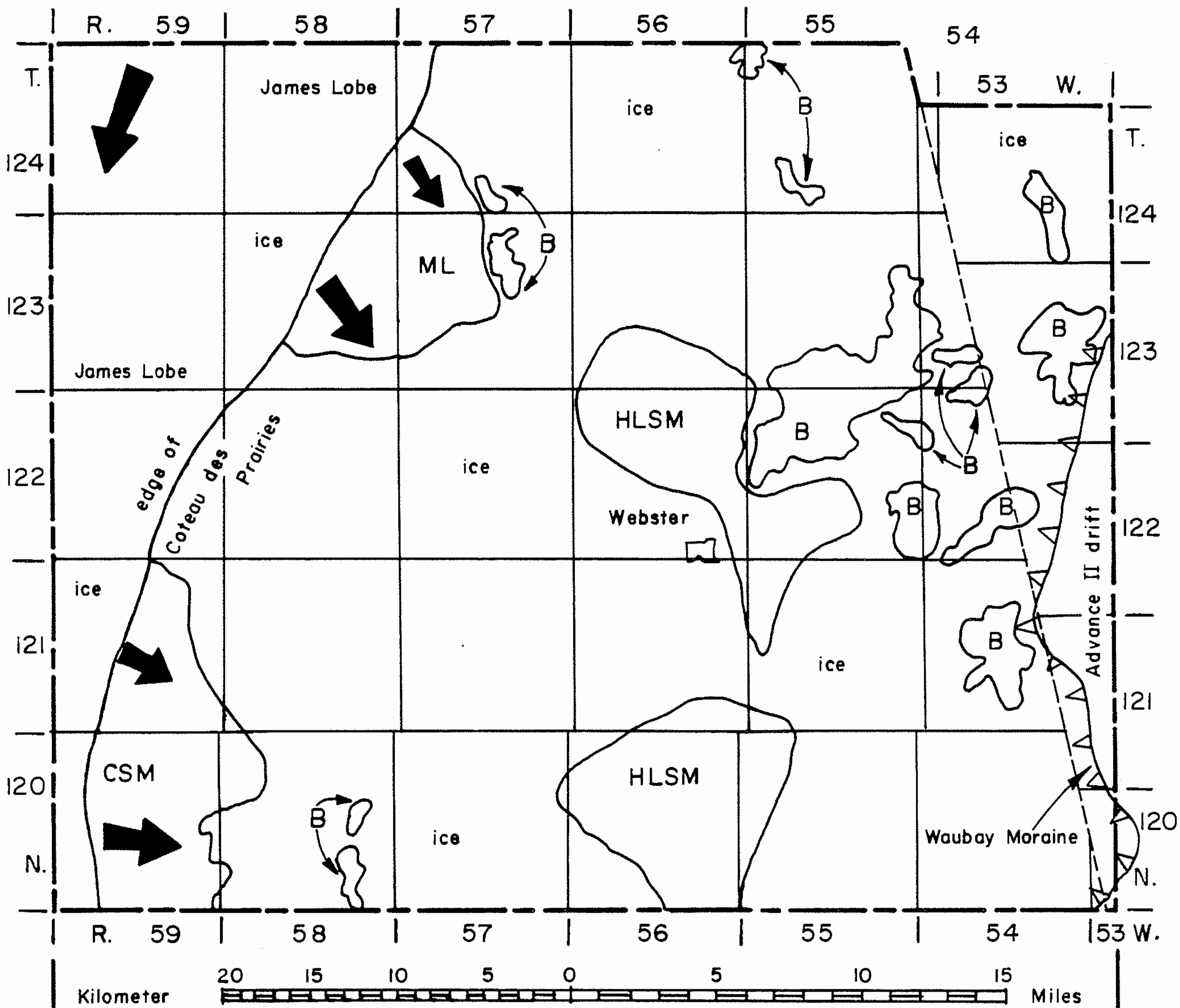


Figure 28. Map showing Day County during formation of high level stagnation moraines.



Continued stacking of ice sheets provide further resistance to eastward movement of ice from the James Lobe. Consequently, shear moraines form along the western border of the county. Later, a minor lobe (ML), comes out of the James Lobe.

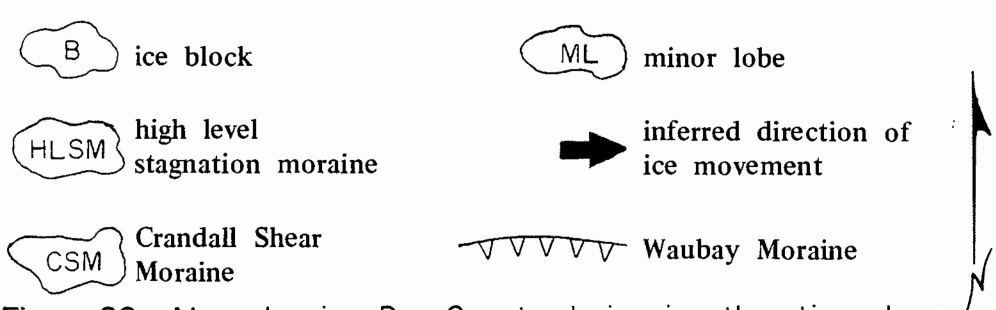
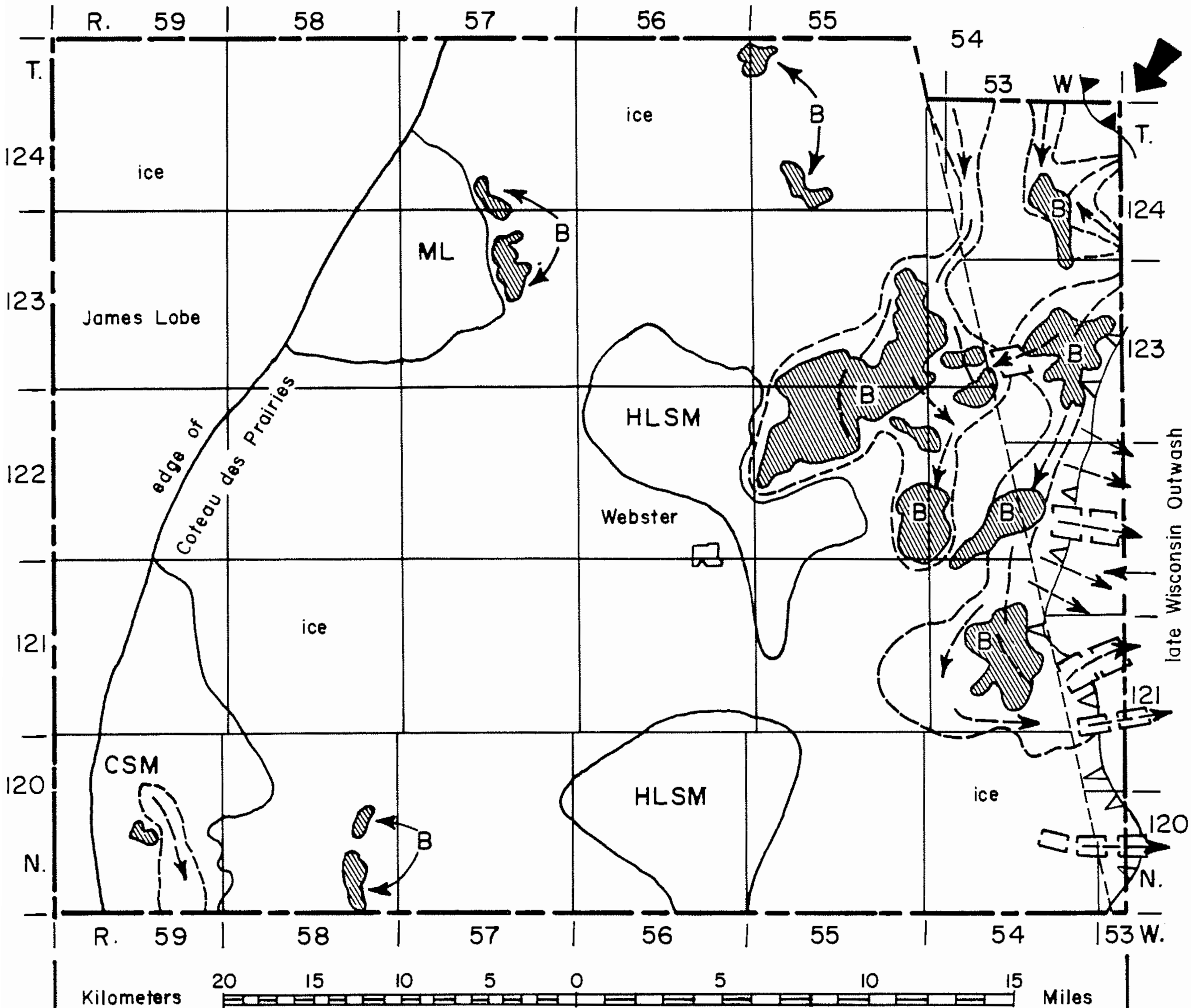


Figure 29. Map showing Day County during ice thrusting along the west edge of the Coteau des Prairies.



Des Moines Lobe reaches the northeast corner of Day County and forms the Altamont Moraine which buries the Waubay Moraine. Superglacial spillways form on the ice blocks and intervening areas. Meltwater and outwash from both Des Moines Lobe and stagnant James Lobe ice flows southerly in the spillways and flows over the Waubay Moraine both en masse and through high level spillways. A small superglacial spillway forms in the Crandall Shear Moraine and discharges south.

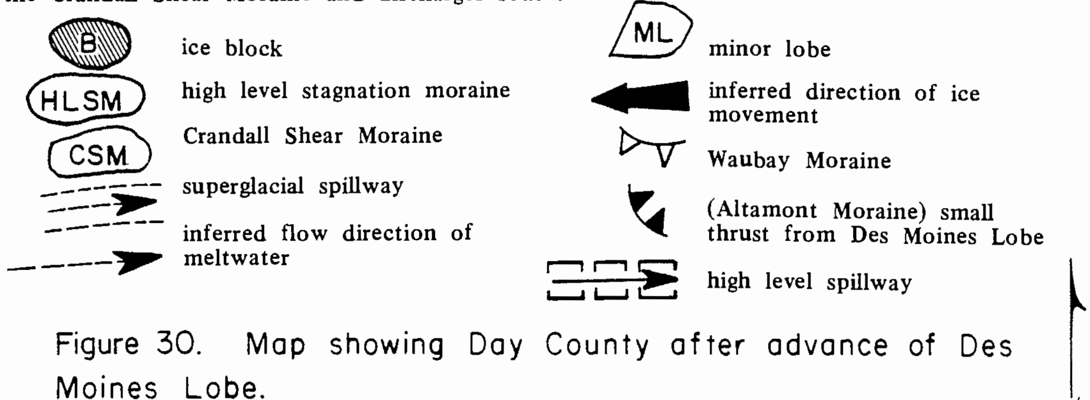


Figure 30. Map showing Day County after advance of Des Moines Lobe.

meltwater from the ice in Marshall, Roberts, and Day Counties (fig. 30).

The westernmost of the sluiceways ran south from Marshall County through the Waubay and Spring Lakes areas and joined the eastern one at Waubay. The eastern sluiceway ran from Pickerel Lake south to Enemy Swim, Blue Dog and Bitter Lakes. At times it released some of its water and outwash to the western sluiceway through a low area between the western end of Enemy Swim Lake and the northeast corner of Spring Lake. It must be remembered that the sluiceways were developed largely on the surface of the stagnant ice which was considerably higher in elevation than the present-day land surface in the same area. Due to the high elevation and the extreme amount of outwash being carried much of it at times flowed over the Waubay End Moraine to produce a thick blanket of outwash on its eastern flank. In fact, between Enemy Swim Lake and the end moraine of the Des Moines Lobe in Roberts County, the Waubay End Moraine is completely buried by sand and gravel. From Blue Dog Lake to south of Bitter Lake much of the outwash was carried across the Waubay End Moraine through high-level spillways and dumped on the surface of the drift of Advance II to the east of the moraine in Grant County. It is in this area of Grant County that the meltwaters carried through the spillways carved out the meltwater channels that now serve as the headwaters of the Big Sioux River.

In time the meltwater from the north and west diminished in volume and velocity. Broad and thin belts of outwash sand and gravels were left on the surface of the ice in the vicinity of all the major lakes. As the large ice blocks and intervening minor blocks melted, the outwash sheets were let down onto the till surface to surround the present-day lakes. As a result, most of the large lakes are connected by bodies of outwash today which shows extensive hummocky areas.

The Advance II drift surface beneath Bitter Lake is noticeably lower in elevation than under the other major lakes (fig. 11). As a result the bottom of the ice block which first protected and later formed the depression for Bitter Lake rested at a lower elevation and when it melted away, the depression assumed the lowest elevation of all the big lakes. Consequently, Bitter Lake today has no surface outlet for its waters--the lake level is maintained by a balance between ground-water and surface-water inflow and evaporation from its surface. Bitter Lake serves as a trap for dissolved mineral matter and prolonged evaporation accounts for its high total dissolved solids.

Sometime when meltwater occupied the big sluiceways, probably toward the end of their period of activity, prevailing westerly winds sweeping across the wide expanse of exposed outwash in the Bitter Lake depression picked up silt and rock flour and deposited it just east of the crest of the Waubay End Moraine in the form of two small areas of thin loess (pl. 1).

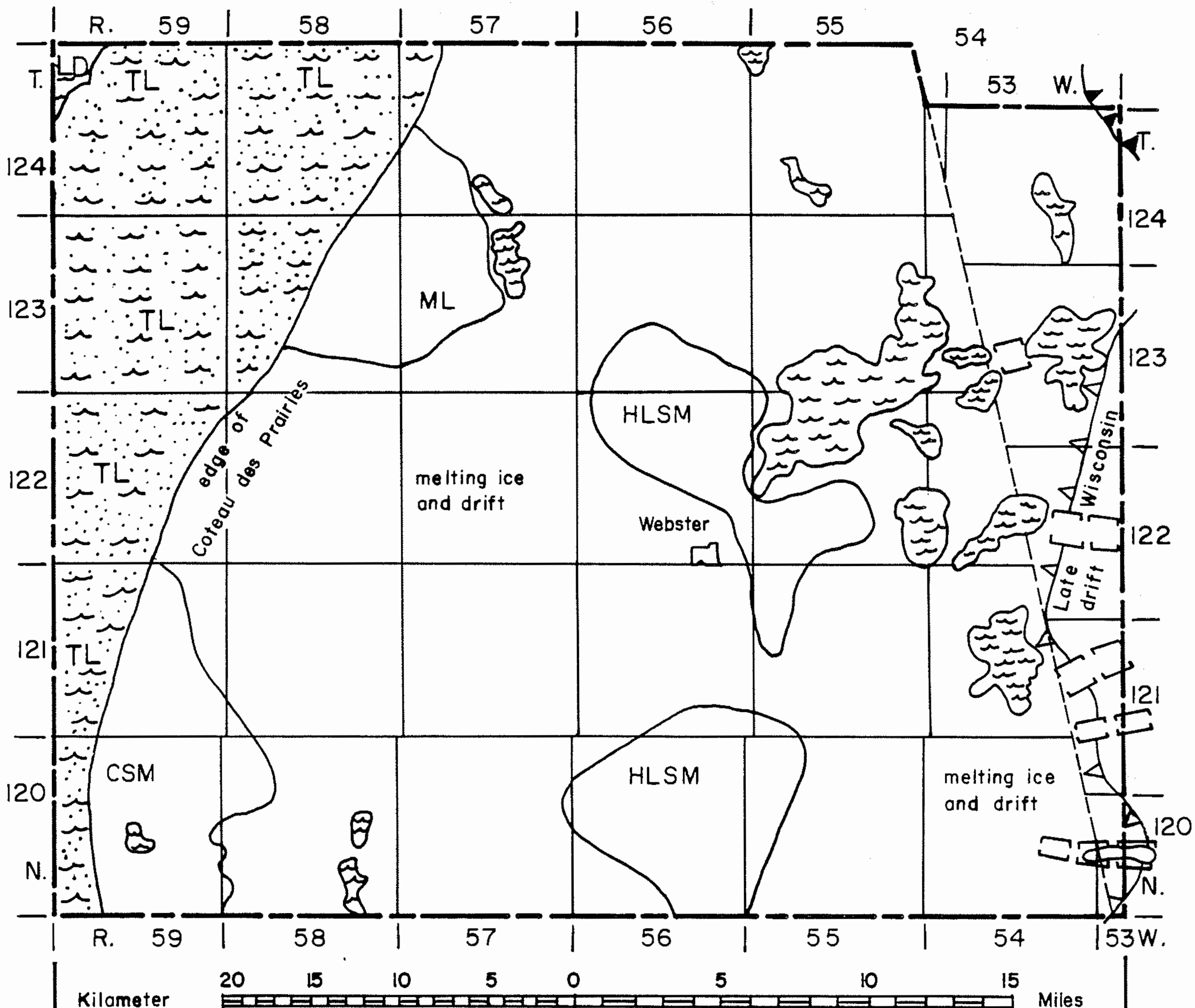
Elsewhere in the County, a smaller superglacial sluiceway was formed in the vicinity of Sweetwater Lake whose general outline is shown by the southeasterly-trending deposit of outwash in that area (fig. 30). This feature drained meltwater into Clark County a few miles south of the Day County line. As in the case of the eastern sluiceways, the ice floor finally melted away leaving collapsed valley train deposits and hummocky terrane where previously a rather gently sloping valley train had been formed.

Other large deposits of outwash were being formed in Day County as the ice continued to melt on the Coteau des Prairies. Of these, the major ones were a large deposit just south of Webster (actually a large, complex moraine outwash plateau), and two large deposits in the vicinity of Butler.

After the James Lobe reached the Missouri River near Yankton, it began to melt back up the James Basin leaving behind a large number of essentially concentric arcuate ridges or recessional moraines. When the ice melted back to the vicinity of the Beadle-Spink County line it built a rather large and broad complex of recessional moraines. As the ice continued to retreat northward from this complex, meltwater became ponded between it and the ice front and thus began Ancient Lake Dakota (fig. 31). Flint (1955, p. 127) suggests the possibility of two ancient Lake Dakotas, but no evidence has turned up subsequently to verify this idea.

As the James Lobe continued to retreat and the lake continued to grow in size streams flowing from the stagnant ice of the Coteau des Prairies and the Coteau du Missouri poured vast amounts of sediment into the lake, depositing sand and gravels near the lake edge and silts and clays farther out away from the shore. During its growth, the lake was also draining to the south through the morainal dam by way of the ancestral James River. In order for the lake to persist, melting of the ice around it had to produce as much water flowing into the lake as was being drained away by the James River. The large present-day valleys, remnants of meltwater channels, on the west side of the Coteau des Prairies are reminders of the large amounts of water that was carried into the lake (pl. 2).

During retreat the ice persisted for a time between Amsden Lake and Crandall and perhaps south along the edge of the Coteau. While holding in this area it was retreating away from the Coteau north of Amsden Lake and perhaps retreating up the valley on the west side of the lake in Brown County. As a result, water was being ponded north of Amsden Lake between the ice and the edge of the Coteau. Evidence for this ponding can be found today in the form of high-level lake silts covering recessional moraines and rising to over 100 feet higher than the west shore of Lake Dakota (pl. 1). After the ice south of Amsden Lake began to retreat back from the Coteau, water was also ponded between it and the Coteau edge in which lake silts were deposited. Figure 32 is a cross-sectional time-space diagram summarizing the Pleistocene history of this point.



After the James Lobe ice retreats northward lakes form between the ice front and the Coteau des Prairies. Temporary lakes form near the Coteau edge. Farther west Lake Dakota eventually comes into existance. Large eastern lakes begin to form as ice blocks melt. Throughout the remainder of the Coteau ice is melting and providing water for the James Basin lakes.

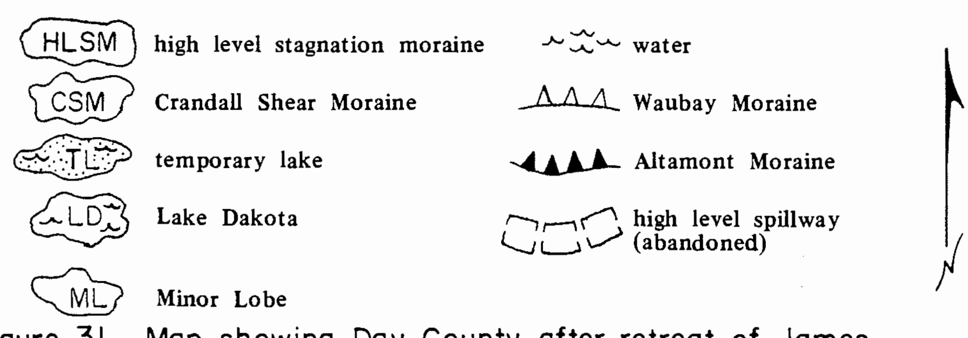
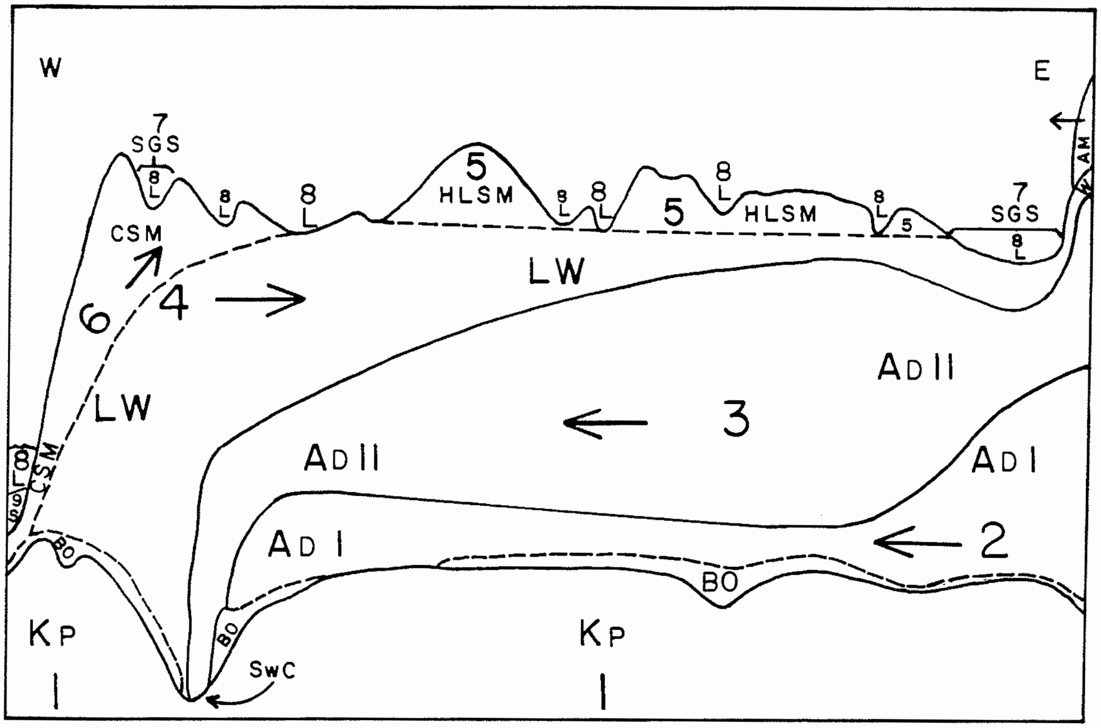


Figure 31. Map showing Day County after retreat of James Lobe.



1. Pierre Shale bedrock (Kp) exists before Pleistocene Epoch and is cut by channels such as the Sweetwater Channel (SwC).

2. Pre-late Wisconsin Advance I ice (AD I) advances from the east and deposits a basal outwash (BO).

3. Pre-late Wisconsin Advance II ice (AD II) advances from the east and terminates at approximately the same position as Advance I.

4. Late Wisconsin Advance III ice (LW) advances from the west out of the James Basin and builds Waubay End Moraine (W) along the eastern edge of the county. It deposits basal outwash (BO) west of the Sweetwater Channel.

5. Further movement of James Lobe ice from the west causes high level stagnation (HLSM).

6. Ice in the interior of the Coteau provides added resistance to movement from James Lobe and produces Crandall Shear Moraine (CSM).

7. Ice from Des Moines Lobe (AM) reaches northeastern Day County and overrides the Waubay End Moraine. Super-glacial spillways form (SGS) and channel water and outwash to the south.

8. James Lobe retreats, and lakes form (L).

9. Lakes dry up and silts remain (S).

Figure 32. Cross-sectional time-space diagram summarizing Pleistocene history for Day County.

Eventually all the ice along the Coteau des Prairies melted away from the highlands and the entire James Lobe retreated north into North Dakota. For perhaps 3,000 years after the James Lobe ice had melted out of South Dakota the stagnant ice on the Coteau continued to melt. It persisted for at least this length of time because the superglacial drift acted as an insulating medium and slowed melting. During the melting process a vast number of shallow closed depressions formed in the ice. These depressions were basins into which large amounts of silt and clay were carried by meltwater to form the large areas of lake silt present throughout the County.

When all the ice had melted away on the Coteau des Prairies, Day County was left with essentially the surface features we see today, little changed over the past 9,000 to 10,000 years.

Recent History

Geological processes of weathering and erosion have little changed the surface of Day County since the close of the Pleistocene Epoch. The streams of the west side of the Coteau have lengthened themselves by headward erosion back into the interior of the Coteau, and in the process have deposited alluvium in the valleys. On the Coteau itself, integrated drainage has not developed extensively and streams are small and intermittent and usually run from one slough to another.

Many of the small sloughs and potholes have been filled with organic sediment until they are now only marshes supporting a wide variety of flora and fauna. Surface water quality also has deteriorated in Bitter Lake and certain other small lakes in response to prolonged evaporation.

ECONOMIC GEOLOGY

Water Resources

Day County has a copious amount of ground and surface water for domestic and light industrial use. The quality of water is a major problem in developing the resource for certain uses such as irrigation because the water is quite high in dissolved minerals. In the eastern part of the County, the shallow aquifers and a few of the large lakes possess more suitable quality water for irrigation. One of the reasons for studying the geology of Day County was to find the relation between geology and hydrology of the County. A more complete description of the hydrology is found in a later part of this report.

Sand and Gravel

Of solid mineral resources, sand and gravel are the most important in Day County. The land surface is covered by many square miles of sand and gravel and a complete description of the resource and its potential can be found in Leap (1972). Although sand and gravel are plentiful in supply, the presence of large amounts of shale limits its use for certain purposes such as concrete, but for an aggregate, most of the County is well supplied.

Oil and Gas

A few oil and gas tests have been made in northeastern South Dakota and a few in Day County. Thus far, no commercial quantities of oil and gas have been found in the County, and much more information about the Cretaceous strata will have to be obtained to give more definitive information about oil and gas potential. Records of oil and gas test wells are on file with the South Dakota Geological Survey.

Clay and Boulders

During the time the geological and hydrological investigations were being carried out in Day County an attempt was made to find supplies of clay suitable for brickmaking and other ceramic products. The surface of the Coteau des Prairies is quite young geologically (9,000 to 10,000 years) and leaching of carbonates from glacial deposits has not progressed far enough to yield carbonate-free clay. Thus, the clay is quite high in calcium and magnesium carbonate and probably is not suitable for making high-quality brick. The clay probably could be used for rough ceramic products such as field tile. In addition, the Pierre Shale which crops out along the western edge of the Coteau might also be examined for similar uses. In any case, further laboratory tests will have to be made on both the clay and shale to precisely determine its potential uses and limitations.

On the steep slopes along the western edge of the Coteau des Prairies and along the Waubay End Moraine there are scattered fields of boulders of igneous and metamorphic rock and of limestone which could be crushed for rip-rap and aggregate. In addition, numerous farm fields throughout the County have piles of boulders which have been gleaned from the fields and are suitable for the purposes listed above.

GEOLOGY AND ITS EFFECTS ON HYDROLOGY

The geology of Day County is the result of a complex sequence of events (of which a more detailed account can be found in the preceding pages of this report). Before the Pleistocene Epoch the surface of Day County was entirely Pierre Shale bedrock of

Cretaceous Age. The Pierre Shale is marine in origin and as such contains high concentrations of magnesium, iron, manganese, and sulfate.

The Cretaceous bedrock section in Day County includes from top to bottom (younger to older) the Pierre Shale, Niobrara Marl, Codell Sandstone, Carlile Shale, Greenhorn Limestone, Graneros Shale, and Dakota Formation.

The Dakota rests upon the Precambrian and thins eastwardly beneath Day County. Because its potentiometric gradient is from east to west the water in the Dakota also flows in this direction.

During the Pleistocene Epoch at least three glaciers passed over Day County depositing glacial drift in thicknesses exceeding 800 feet. The drift was derived from the grinding and crushing of the marine shales and limestones over which the glaciers passed on their way south with additional crystalline and sedimentary rock materials brought down from Canada. The reduction in size of the rock materials produced a greater surface area subject to chemical attack by circulating ground water in the derived drift. The chemical nature of the ground water contained in glacial deposits in Day County today reflects the chemistry of the parent rocks from which the drift was derived.

The physical structure and topography of the drift are also the result of glaciation. Generally the regional elevation decreases from a high of 2,000 feet above sea level in the northeast part of the County to a low of 1,300 feet in the northwest part. The surface is broken in places by deep lake basins and sloughs and near the western border of the County, by the steep edge of the Coteau des Prairies.

Beneath the drift the Pierre Shale bedrock acts as an almost-impermeable barrier to vertical percolation of ground water to the rocks below. There is no doubt that there is some recharge to the formations below the Pierre, but the contrast in the permeability of the Pierre with that of the overlying drift is quite large.

Thus, the combination of the westward regional slopes of the land and potentiometric surface, and the slightly permeable shale beneath more permeable drift defines the general direction of flow of ground water in the drift--that is from east to west.

CLIMATOLOGY

Temperature

Records of temperature at Webster, South Dakota, collected by the U.S. Weather Bureau during the years 1967-1972, are shown in table 2. For the 6-year period the lowest average monthly

TABLE 2. Temperature at Webster, South Dakota - 1967-1972
(in degrees Fahrenheit)

Year	Jan	Feb	Mar	April	May	June	July	Aug	Sept	Oct	Nov	Dec	Annual Average	
1967	15.6	10.8	32.2	43.5	51.4	63.6	69.0	67.8	60.3	45.9	29.8	17.5	42.3	
1968	12.0	14.3	37.8	44.6	52.4	66.0	69.3	70.1	59.6	47.0	30.7	12.3	43.0	
1969	3.6	17.4	18.8	46.5	58.0	59.9	69.4	72.1	62.7	40.9	32.4	18.8	41.7	
1970	3.5	16.8	22.8	41.4	57.2	69.0	73.2	71.4	59.7	46.9	27.4	13.1	41.9	
1971	3.2	14.0	28.9	46.0	53.8	68.6	67.0	69.9	57.8	48.2	29.9	13.3	41.7	
1972	5.9	8.2	26.3	41.2	58.5	65.4	68.6	70.1	57.7	42.8	28.4	9.3	40.2	
Monthly averages for 6-year period	7.3	13.6	27.8	43.9	55.2	65.4	69.4	70.2	59.6	45.3	29.8	14.0	41.8	Average for 6 years

temperature was 3.2 degrees Fahrenheit in January, 1971, and the highest average monthly temperature was 72.1 degrees Fahrenheit in August, 1969.

The average January temperature for 6 years was 7.3 degrees Fahrenheit and is the minimum average. The maximum average occurred in August and was 70.2 degrees Fahrenheit for the 6-year period.

The climate of Day County can be classified as sub-humid with extremes of summer heat and winter cold which has ranged from -40 degrees to over 100 degrees Fahrenheit. The County has a growing season of 120 to 130 days per year. The average date of the last spring freeze is May 15 to 20, and the average date of the first autumn freeze is September 20 to 25.

Precipitation

Precipitation data at Webster are shown in table 3. These data represent inches of water from both snow and rain; amounts of snow and rain are not separated. The average annual precipitation of the 6-year period was 21.5 inches or 1.79 feet. The table shows that the lowest amount of precipitation falls in January and for 6 years averaged 0.66 inches per month. The highest monthly precipitation falls in June and averaged 3.93 inches per month for the 6-year period.

During this period Day County received its maximum precipitation in 1972 which was 23.87 inches or 1.99 feet of water. The minimum for this period was 17.21 inches (1.43 feet) which fell in 1970.

The amount of precipitation falling on the County in terms of acre-feet can be calculated by multiplying the area of the County by the number of feet of water for any particular time. The total area of Day County is approximately 648,773 acres. Therefore, during the period 1967 to 1972, the maximum annual precipitation was 1,291,096 acre-feet in 1972 and minimum was 927,773 acre-feet in 1970. Assuming that the yearly average is 1.79 feet, Day County then receives an average of 1,161,338 acre-feet of water per year from precipitation.

Evapotranspiration

Evapotranspiration is defined as the sum of water loss by evaporation from open water surfaces and that lost by transpiration through the stomata of plants. Evapotranspiration is also called comsumptive use by some authors (Veihmeyer, 1964).

Evapotranspiration rates are directly proportional to the amount of moisture in the root zone. Using this relationship, Thornthwaite (1948) suggested the term "potential

TABLE 3. Precipitation at Webster, South Dakota - 1967-1972
(measured in inches)

Year	Jan	Feb	Mar	April	May	June	July	Aug	Sept	Oct	Nov	Dec	Annual (in)	total (ft)
1967	.97	1.60	.26	2.47	1.30	6.52	.75	2.78	.91	.76	.22	.93	19.47	1.62
1968	.45	.12	1.05	3.81	3.38	3.53	2.01	1.40	2.73	1.65	.89	1.90	22.92	1.91
1969	1.71	2.06	.48	1.20	3.10	1.83	6.48	1.26	.56	2.38	.34	.64	22.04	1.84
1970	.10	.05	1.05	1.79	2.28	3.25	2.57	.33	1.84	1.48	2.22	.25	17.21	1.43
1971	.31	.47	.10	1.34	1.83	7.36	2.42	3.71	.56	3.47	1.34	.58	23.49	1.96
1972	.41	.50	.52	.85	7.41	1.10	9.08	1.80	.09	.97	.47	.67	23.87	1.99
Monthly averages for 6 years	.66	.80	.58	1.91	3.22	3.93	3.88	1.88	1.12	1.78	.91	.83	21.5 Averages for 6 years	1.79

evapotranspiration" to define the evapotranspiration that would occur if the soil moisture supply were adequate at all times to meet maximum demands. The actual amount of evapotranspiration seldom equals potential evapotranspiration because soil moisture is normally not at field capacity except in water-logged areas or fields which have recently undergone heavy irrigation.

Pengra (1961) has developed a table of monthly potential evapotranspiration figures for South Dakota for the months of March through October for each degree of temperature from 32 to 102 degrees Fahrenheit. These data are reproduced for this report in table 4. Pengra's data were computed from basic data taken at Redfield, South Dakota, approximately 60 miles southwest of Webster, in Spink County. The climatic conditions at Redfield differ only slightly from those in Day County and the computed figures at Redfield should be applicable to Day County.

To use the figures of Pengra for calculating the potential evapotranspiration for any one day, take the daily mean temperature and find the column representing the month in which the day occurs. The figure at that point is the potential evapotranspiration in inches for that day.

Approximate values of average monthly potential evapotranspiration in Day County were calculated from the average monthly temperatures and are shown in table 5. The yearly potential evapotranspiration is slightly greater than the yearly precipitation. Fortunately, this amount of evapotranspiration never occurs because the top few inches of soil are seldom if ever fully saturated.

Actual evaporation measurements were made at Redfield during the period, 1967 to 1972, by the U.S. Weather Bureau. These measurements represent total evaporation from a U.S. Weather Bureau Class A pan and are presented in table 6 by the symbol Ep. In order to calculate actual evaporation from a large body of water such as a lake, the Ep values were multipled by the standard pan coefficient of 0.7. The resulting actual lake evaporation values are tabulated as EL. During the period 1967 to 1972, evaporation measurements were generally only made from May through September. Before and after this period the water surfaces are often frozen and evaporation is significantly less than during the warmer months. Kohler, Nordenson, and Baker (1959) state that in Day County the average May-to-October evaporation is 82 percent of the annual total. Therefore, the annual totals listed in table 6 have been calculated using this factor.

Table 6 shows that the greatest evaporation takes place during the month of July with the average lake evaporation for this month being 6.2 inches or 0.5 foot.

TABLE 4. Potential evapotranspiration figures for South Dakota (from Pengra, 1961)

Potential evapotranspiration figures (in hundredths of inches)

TEMPERATURE (1)	MARCH (2)	APRIL (3)	MAY (4)	JUNE (5)	JULY (6)	AUGUST (7)	SEPTEMBER (8)	OCTOBER (9)
32	00	00	--	--	--	--	--	--
33	00	00	--	--	--	--	--	00
34	00	01	01	--	--	--	--	00
35	01	01	01	--	--	--	--	01
36	01	02	02	--	--	01	01	01
37	01	02	02	--	--	01	01	01
38	02	02	02	02	02	02	02	02
39	02	02	02	02	02	02	02	02
40	02	02	03	03	03	03	02	02
41	03	03	03	03	03	03	02	02
42	03	03	03	03	03	03	03	02
43	03	04	03	04	03	03	03	03
44	04	04	04	04	04	04	03	03
45	04	04	04	04	04	04	03	04
46	04	04	05	05	05	04	04	04
47	05	05	05	05	05	05	04	04
48	05	05	06	06	06	05	05	04
49	05	06	06	06	06	06	05	05
50	06	06	06	06	06	06	05	05
51	06	06	07	07	07	07	06	06
52	06	07	07	07	07	07	06	06
53	06	07	08	08	08	08	07	06
54	07	08	08	09	09	08	07	06
55	07	08	09	09	09	09	07	07
56	08	09	09	10	09	09	08	07
57	08	09	10	10	10	09	08	07
58	08	09	10	11	10	10	09	08
59	09	10	11	11	11	10	09	08
60	09	10	11	12	12	11	10	09
61	10	11	12	12	12	11	10	09

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
62	10	11	12	13	13	12	10	09
63	10	12	13	13	13	12	11	10
64	11	12	13	14	14	13	11	10
65	11	13	14	14	14	13	12	10
66	12	13	14	15	15	13	12	11
67	12	13	15	15	15	14	12	11
68	12	14	15	16	16	14	13	12
69	13	14	16	16	16	15	13	12
70	13	15	16	17	17	15	14	12
71	14	15	17	18	17	16	14	13
72	14	16	17	18	18	16	15	13
73	15	16	18	19	18	17	15	14
74	15	17	19	19	19	18	16	14
75	16	18	19	20	20	18	16	14
76	16	18	20	20	20	19	17	15
77	16	19	20	21	21	19	17	15
78	17	19	21	22	21	20	18	16
79	17	20	21	22	22	20	18	16
80	18	20	22	23	23	21	19	16
81	--	--	22	23	23	21	19	17
82	--	--	23	24	24	22	20	17
83	--	--	24	24	24	23	20	18
84	--	--	24	25	25	24	21	19
85	--	--	25	25	26	24	21	20
86	--	--	25	26	27	25	22	--
87	--	--	26	27	27	25	22	--
88	--	--	27	28	28	26	23	--
89	--	--	28	29	28	26	23	--
90	--	--	29	29	29	26	24	--
91	--	--	--	30	29	27	25	--
92	--	--	--	30	30	27	26	--
93	--	--	--	31	30	28	27	--
94	--	--	--	31	31	28	28	--
95	--	--	--	32	32	29	--	--
96	--	--	--	33	33	--	--	--
97	--	--	--	--	33	--	--	--
98	--	--	--	--	34	--	--	--
99	--	--	--	--	35	--	--	--
100	--	--	--	--	36	--	--	--
101	--	--	--	--	36	--	--	--
102	--	--	--	--	37	--	--	--

TABLE 5. Average monthly potential evapotranspiration figures for South Dakota from March through October

(data computed from Pengra, 1961)
(monthly temperatures in degrees Farhrenheit are averages for 1967-1972)

Month	Average daily temperature (at Webster)	Average daily potential evapotranspiration (in inches)	Number of days in month	Average monthly potential evapotranspiration (in inches)
March	27.8	0	31	0
April	43.9	.04	30	1.20
May	55.2	.09	31	2.79
June	65.4	.14	30	4.20
July	69.4	.16	31	4.96
August	70.2	.15	31	4.65
September	59.6	.10	30	3.00
October	45.3	.04	31	1.24
Total potential evapotranspiration, March-October (in inches)				22.04
Total potential evapotranspiration, March-October (in feet)				1.84

TABLE 6. Evaporation data for Redfield, South Dakota 1967-1972
(measured in inches)

EP = measured evaporation in inches from Class A pan   EL= computed evaporation from lakes (EL = 0.7 EP)

Assuming evaporation from May to October equals 82 percent of annual total, the annual total equals 1.22 the May to October evaporation.

Year		Jan	Feb	Mar	April	May	June	July	Aug	Sept	Oct	Nov	Dec	Annual Total (in)	Annual Total (ft)
1967	EP	--	--	--	--	6.96	6.67	8.37	8.82	6.53	4.19	--	--	50.68	4.22
	EL	--	--	--	--	4.87	4.67	5.86	6.17	4.57	2.93	--	--	35.47	2.96
1968	EP	--	--	--	--	5.66	7.41	9.36	8.61	5.46	--	--	--	44.53	3.71
	EL	--	--	--	--	3.96	5.19	6.55	6.03	3.82	--	--	--	31.17	2.60
1969	EP	--	--	--	--	7.10	7.82	8.28	10.15	6.79	--	--	--	48.97	4.08
	EL	--	--	--	--	4.97	5.47	5.80	7.10	4.75	--	--	--	34.28	2.86
1970	EP	--	--	--	--	--	9.28	9.70	8.86	8.02	--	--	--	43.75	3.65
	EL	--	--	--	--	--	6.50	6.79	6.20	5.61	--	--	--	30.62	2.55
1971	EP	--	--	--	--	6.74	8.75	9.19	--	5.75	--	--	--	37.12	3.09
	EL	--	--	--	--	4.72	6.12	6.43	--	4.02	--	--	--	25.99	2.17
1972	EP	--	--	--	--	5.81	7.20	8.23	7.19	--	--	--	--	34.68	2.89
	EL	--	--	--	--	4.06	5.04	5.76	5.03	--	--	--	--	24.28	2.02
	EP					5.38*	7.85*	8.85*	7.27*	5.42*	.70*			43.28**	3.61*
	EL					3.76*	5.50*	6.20*	5.09*	3.80*	.49*			30.30**	2.53*

*Monthly averages for 6 years

** 6-year averages

Runoff

Runoff is equal to precipitation minus the water retained on the surface and that which infiltrates into the soil. Runoff values estimated by the U.S. Department of Agriculture Soil Conservation Service are mapped in U.S.D.A. (1966), and are reproduced in this report in figure 33. In this figure are shown four drainage areas. Area A comprises the gentle slopes and lake plain west of the foot of the Coteau des Prairies escarpment. Area B includes the steep slopes of the Coteau escarpment. Runoff from these two areas goes into tributaries of the James River. Area C is a region of internal drainage in which runoff drains into the many lakes and sloughs which dot the County. Area D is a small area of 6 square miles surrounding Lonesome Lake in the extreme southeastern corner of the County. It drains into Lonesome Lake and thence into the headwaters of the Big Sioux River during periods of high water. Normally the runoff in area D goes into Lonesome Lake and evaporates or adds to ground-water recharge.

By multiplying the acreage of each drainage area by its runoff in feet (fig. 33) the annual runoff of each area in acre-feet is calculated. Therefore, area A has a runoff between 1,840 and 3,690 acre-feet per year. Area B yields 5,240 to 6,980 acre-feet per year and the combined areas C and D drain 0 to 1,880 acre-feet yearly internally into closed basins. In addition, there is some interchange of runoff to and from area C from similar areas in Clark, Codington, and Marshall Counties through intermittent streams. The drainage density and stream gradients are about equal for streams flowing into and out of area C and any net gain or loss of water in area C through them is probably negligible. A small amount of runoff from Grant and Roberts Counties also enters Day County through intermittent streams along its eastern border. This runoff is also probably negligible due to the number of closed depressions in the westward sloping drainage areas of these counties which tend to collect and retain most of the water before it can reach the streams.

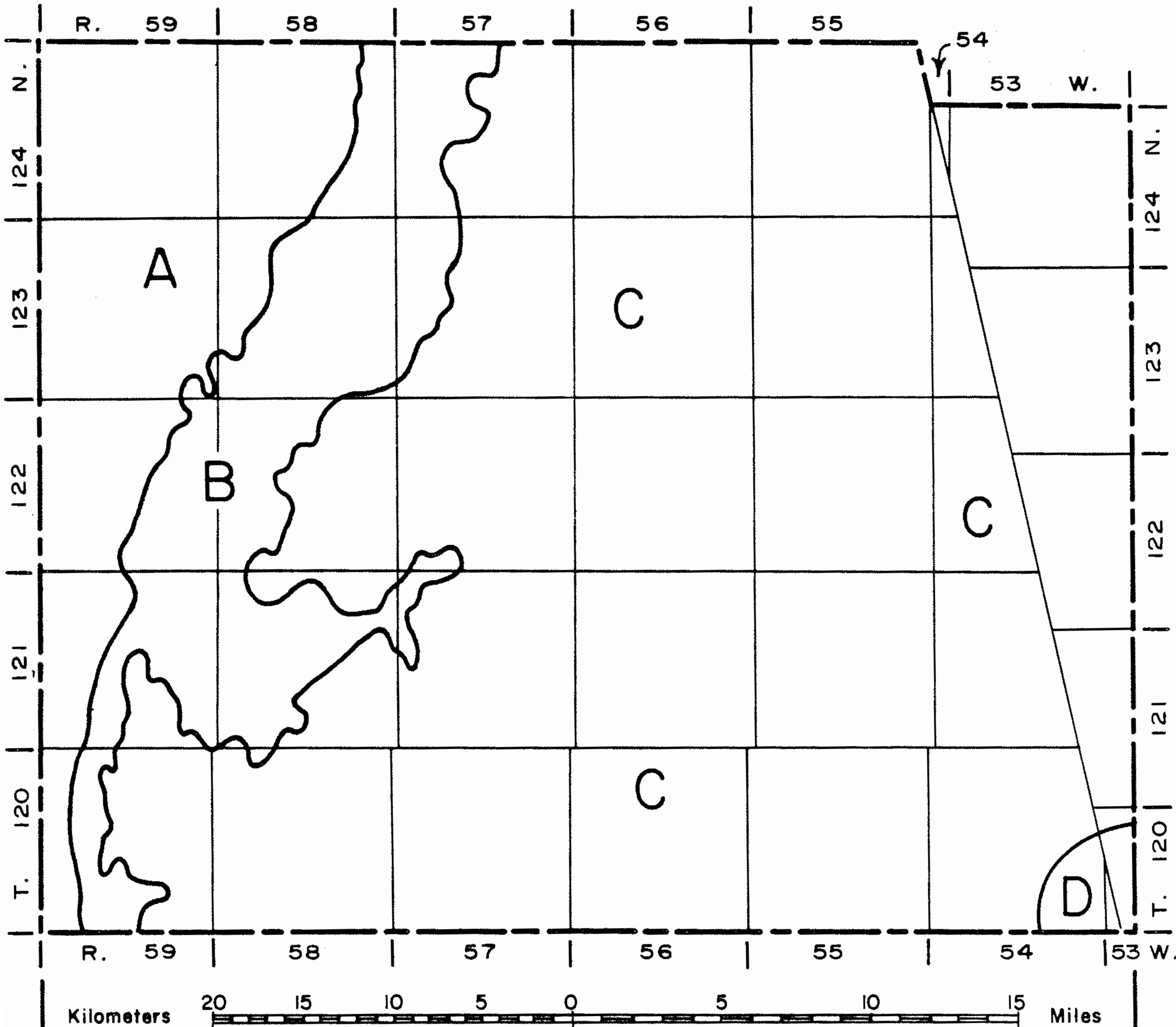
SURFACE-WATER HYDROLOGY

Streams

The major streams in Day County flow down the western slope of the Coteau des Prairies and drain into the James River. The most important streams are Antelope, Mud and Pickerel Creeks (fig. 5).

Smaller streams occur on the Coteau des Prairies and usually connect two or three potholes or lakes. All streams in the County are intermittent and have no persistent base flow because ground-water discharge is not sufficient to maintain it.

Streams in Day County contribute little to the available water supply in the County except where they are dammed or where dug-outs are constructed in their beds for stock-watering purposes.



AREA	RUNOFF (acre feet per year)
A	1,840–3,690
B	5,240–6,980
C	0–1,880
D	0–1,880

(Estimated by U.S. Department of Agriculture, Soil Conservation Service)

Figure 33. Map showing runoff amounts for four areas in Day County.

A few dugouts can be found in the major western streams and also in the small ones on the surface of the Coteau. Only two streams are dammed; Amsden Lake is an artificial reservoir in the valley of Pickerel Creek and Pierpont Lake is formed behind a dam in the Mud Creek valley. Other storage facilities could also be provided to retain flood waters accompanying occasional storms and snow melt.

Lakes

The surface of Day County is dotted with hundreds of depressions ranging from potholes a few scores of feet in diameter to lakes with a diameter of a few miles. Approximately 43,400 acres, or 6 percent of the surface area of the County, is covered by lakes. Of this area approximately 22,800 acres belong to intermittent or minor lakes and approximately 20,600 acres are distributed among the major lakes in the eastern part of the County.

Major Lakes

Major lakes whose combined water surface areas total 20,600 acres include Pickerel, Enemy Swim, NE Waubay Lake, SW Waubay Lake, Minnewasta, Spring, Rush, Blue Dog, and Bitter Lakes. Table 7 is a compendium of physical statistics of the major lakes gathered from the records of the United States Geological Survey in Huron, the South Dakota Geological Survey in Vermillion, and the South Dakota Department of Game, Fish, and Parks in Webster, South Dakota.

Total volume of water stored in the major lakes is approximately 165,000 acre-feet with the Waubay Lakes containing the maximum, nearly 82,900 acre-feet. Blue Dog Lake contains the smallest volume of water of all the major lakes holding in storage approximately 6,000 acre-feet.

The major lakes are at their highest water levels in May and lowest in November or December even though the greatest amount of precipitation occurs in June. The reason for this relationship is that evaporation and transpiration by shore-line vegetation is greatest in July and exceeds precipitation from May through September. During this period each of the large lakes lose approximately 2 feet of water to evapotranspiration or a combined total of 41,700 acre-feet. During this period they receive an average of 1.16 feet of precipitation directly on the lakes. Inflow to the lakes to make up the difference between evaporation and precipitation must come from direct precipitation on the surrounding drainage areas, and ground-water inflow. The yearly loss of water by evaporation is approximately 52,000 acre-feet from the major lakes. No attempts have been made to suppress evaporation from free water surfaces, but this could be adopted as a water management procedure during periods of extreme drought.

TABLE 7. Physical statistics of the major lakes in Day County, South Dakota

Lake	Elevation in 1970	Average depth in 1970	Surface area (acres)	Acre-foot volume vol. = 1/2 (average depth x area)	Average May-November drop in elevation (ft) 1966-1970
Pickerel	1,845	30	955	14,325	-.06
Enemy Swim	1,853	20	2,146	21,460	-1.3
Waubay SW	1,786	<20	≅2.304	<23,040	no information
Waubay NE	1,785	<20	≅5,984	<59,840	no information
Minnewasta	1,797	14	610	4,270	-.95
Spring	1,788	≅20	960	9,600	no information
Rush	1,799	≅ 6	1,997	5,990	no information
Blue Dog	1,801	8	1,502	6,000	-.30
Bitter	1,772	<10	≅4,110	20,550	no information
TOTALS			20,568	165,075	

The major lakes act as important sources and sinks for ground-water flow. The map showing the recharge and discharge areas for the Pierre and Basal aquifer System, hereafter referred to as the Basal System (fig. 34) shows that Pickerel and Enemy Swim Lakes are recharge areas and the remaining major lakes with the exception of the southwestern part of Waubay Lake act as discharge areas for the Basal System and Pierre aquifer and shallower aquifers in the vicinity of the lakes.

There is a ground- and surface-water circulation pattern between the major lakes. Interchange of water from one lake to another takes place through surface streams, surficial outwash and probably through underlying deeper tills. Figure 35 shows the circulation pattern that has been defined between the major lakes.

The southern extremity of Enemy Swim Lake, called Campbell's Slough, possesses the highest water level of all the major lakes, 1,854 feet above sea level (1970 measurement). This body of water drains northward through surface connections into the main body of Enemy Swim Lake. To the south, Campbell's Slough drains to Blue Dog Lake through both a surface stream and a surface deposit of sand and gravel.

The main body of Enemy Swim Lake drains westward into Spring Lake through seeps located in a low trough which connects the two lakes in secs. 16 and 20, T. 123 N., R. 53 W. Enemy Swim Lake also probably discharges through tills and deeply buried sand and gravel lenses into Pickerel Lake to the north.

Pickerel Lake has only one discharge stream which leaves its west side in sec. 22, T. 124 N., R. 53 W. This small stream runs west for about 3 1/2 miles and drains into a series of sloughs and swampy areas. The drainage from these sloughs and swamps is south to NE Waubay Lake through small intermittent streams. Thus, drainage from Pickerel Lake eventually reaches Waubay Lake minus a certain amount lost to evaporation, transpiration, and perhaps ground-water recharge to deeper aquifers that discharge their waters to Waubay Lake.

Blue Dog Lake drains southwesterly through lakes and surface outwash materials into Rush Lake which in turn drains northwesterly through two different paths. The western-most path is through an intermittent stream flowing only during high water and through surface outwash into SW Waubay Lake. The eastern path is through Minnewasta Lake and thence through swamps and outwash into NE Waubay Lake.

Spring Lake also discharges into NE Waubay Lake through swampy areas and surficial outwash.

Bitter Lake does not connect surficially to any of the major lakes although it does receive water through streams connecting several small lakes to the east. Blue Dog Lake probably

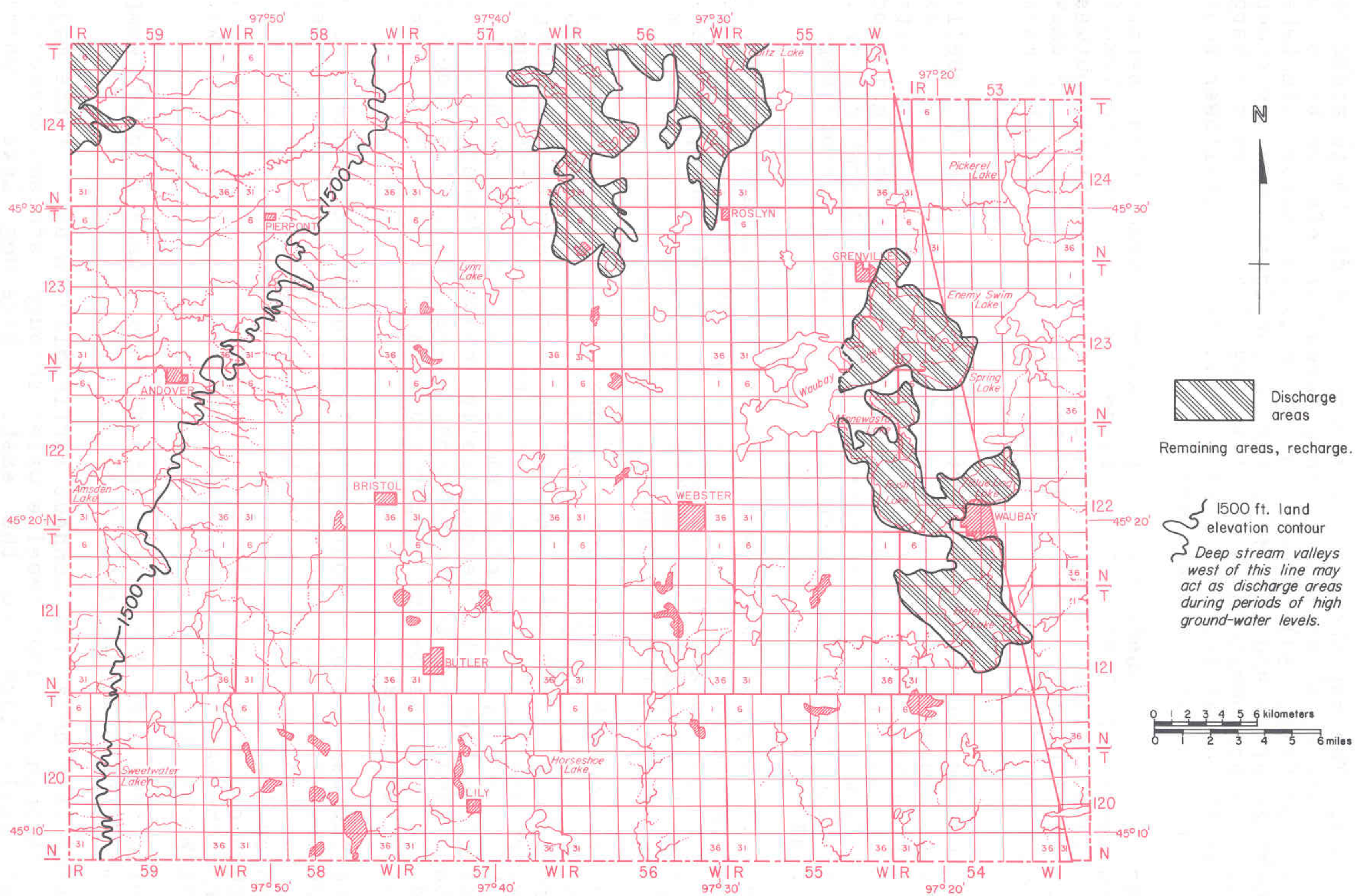
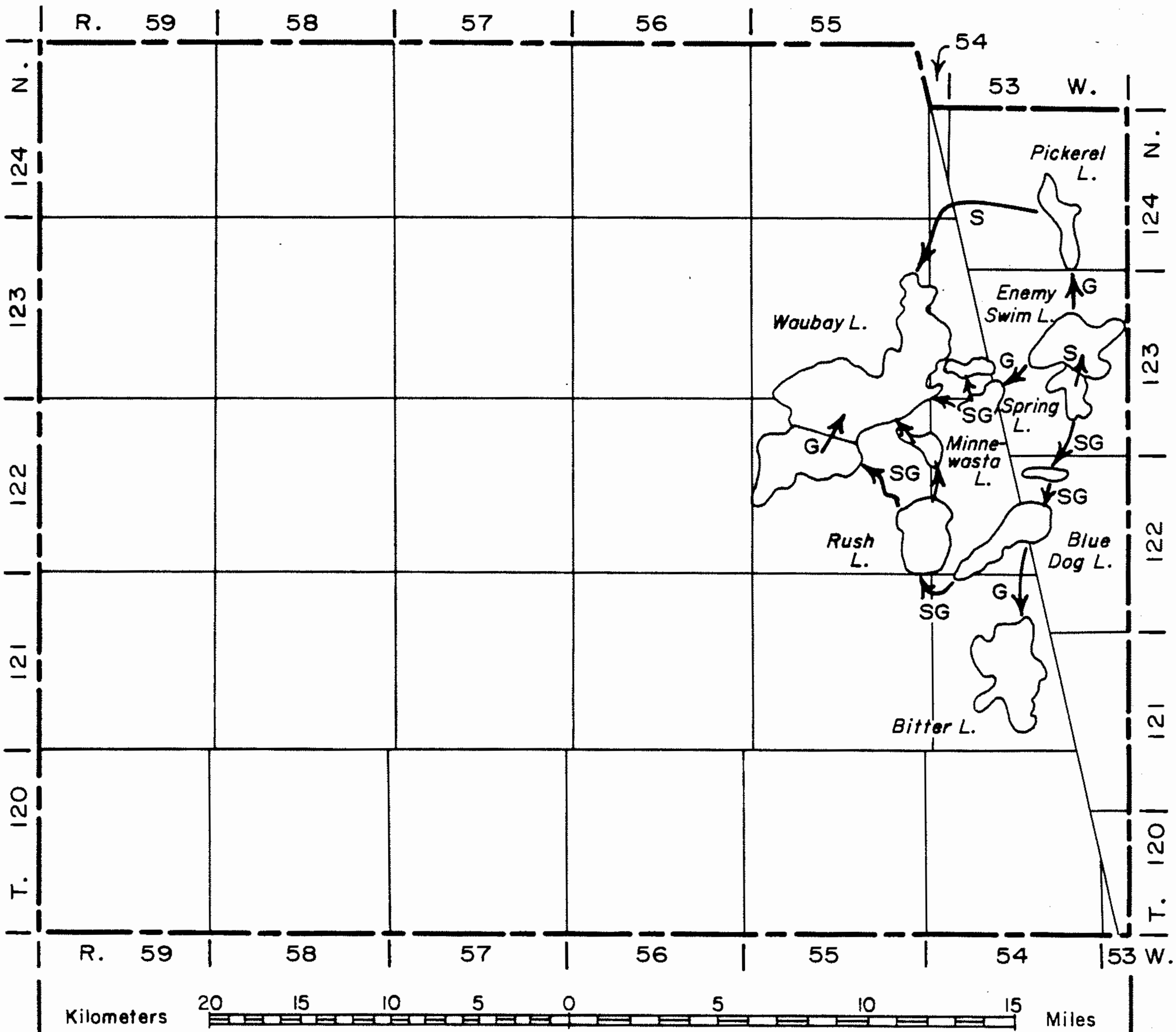


Figure 34. Map showing recharge and discharge areas for the combined Pierre and Basal System aquifers.



G Ground-water flow

S Surface-water flow

↙ Direction of flow

Figure 35. Map showing circulation pattern between major lakes in Day County.

discharges some water through the Waubay Aquifer into Bitter Lake.

Thus NE Waubay Lake is the ultimate surface- and ground-water sink for all the major lakes except Bitter Lake and as such shows a much higher amount of total dissolved solids than its feeders. Comparison of figures 35 and 36 shows that total dissolved solids in the major lakes increases in the direction of drainage in response to the progressive loss of water by evapotranspiration along the flow system.

Surface streams do not transfer water between lakes all year long. Streamflow occurs when precipitation is great enough to provide runoff into the streams, and/or lake levels are high enough to spill water over into the streams.

Minor Lakes

Little is known about the hydrography of the hundreds of minor lakes and ponds on the Coteau. Many of these are ephemeral features which dry up during hot weather. Their combined surface area of approximately 22,800 acres loses to evaporation yearly approximately 57,700 acre-feet of water. An additional unknown amount is lost by transpiration. Like the major lakes, the minor lakes are usually the highest in May and the lowest in November and serve as local sinks for both surface water and ground water.

Water Balance in the Lakes

The combined yearly loss to evaporation from all the lakes in the County averages approximately 109,700 acre-feet of water. Approximately this amount is regained yearly by the lakes in the form of direct precipitation, runoff from surrounding areas and ground-water inflow. An additional unknown amount is lost through transpiration from aquatic plants in the lakes.

Quality of Surface Water

The chemistry of lake water in South Dakota varies widely from almost 25,000 parts per million of dissolved solids to slightly less than 200 depending upon local conditions. Between 1969 and 1971 water samples from all the major lakes and all the more permanent minor lakes were chemically analyzed. Figure 36 shows total dissolved solids of all the lakes that were analyzed; table 8 shows the complete analyses. Figure 37 shows locations of lake water samples by sample number.

All the major lakes and most of the minor ones were analyzed between 1969 and 1971 in order to determine the suitability of the surface water for potential municipal, stock and domestic, and irrigation uses.

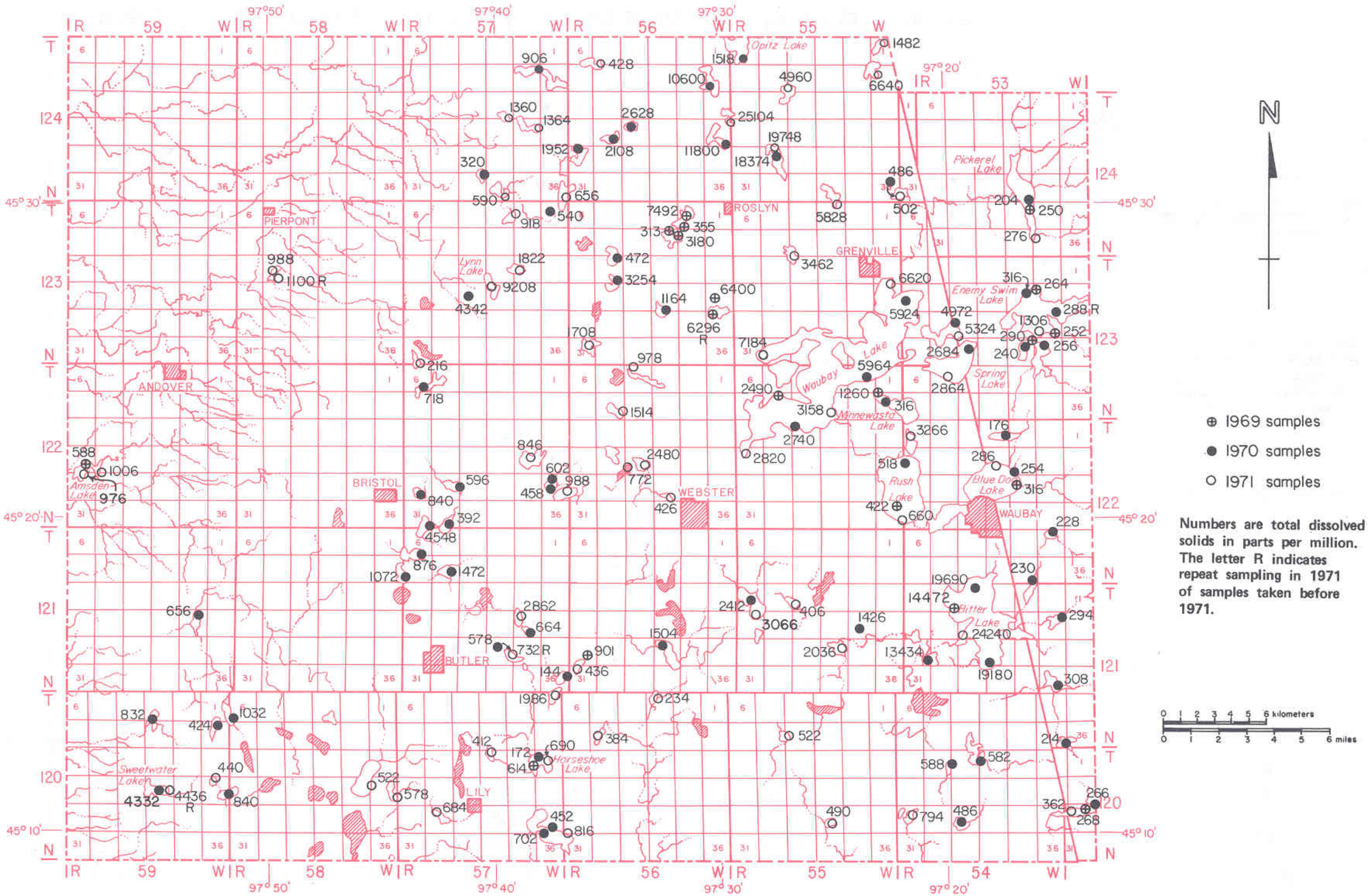


Figure 36. Map showing total dissolved solids of lake waters.

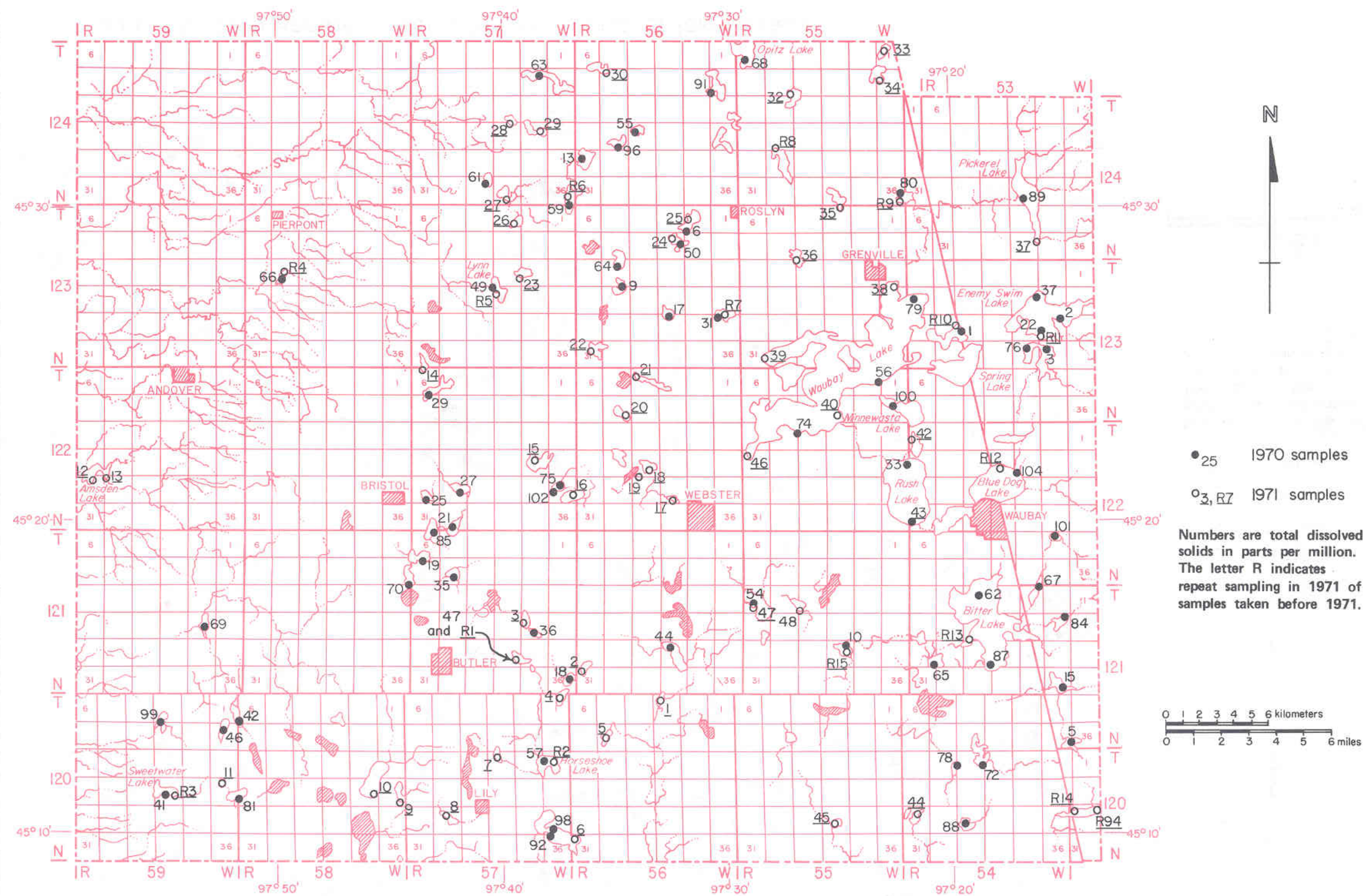


Figure 37. Map showing locations of lake water samples by sample number.

All the lakes were analyzed in mid-summer over a period of 3 years and show an important constancy of composition over the 3 years; most do not vary by more than 10 percent in total dissolved solids. Probably there is greater variation in chemical composition between seasons of the year rather than from year to year due to evaporation, precipitation, and water level changes in the lakes.

Bitter Lake and NE Waubay are sinks having no natural surface outlet. Prolonged evapotranspiration losses have concentrated the salts in Bitter Lake to almost 25,000 parts per million and in NE Waubay Lake, to around 7,000 parts per million during the few thousand years since the lake basins were formed. Why Bitter Lake is more saline than NE Waubay is not known precisely. Both lakes lie in ground-water discharge areas for the Basal Aquifer flow system and perhaps the dilution effect of fresher surface water inflow into NE Waubay Lake may help offset the salt contribution from the Basal System. Bitter Lake does not possess as great a surface inflow and therefore evaporation concentrates salt from water richer in total dissolved solids than that of NE Waubay Lake.

Perhaps the most common method of classifying water according to its suitability for irrigation is by plotting the sodium absorption ratio along the ordinate against specific conductance along the abscissa on semi-logarithmic paper. This type of plot is explained in Wilcox (1955). The sodium absorption ratio (SAR) is calcuated as

$$SAR = \frac{Na+}{\sqrt{\frac{Ca{+}{+} + Mg{+}{+}}{2}}} \qquad (1)$$

Where the concentration of sodium, calcium, and magnesium are given in milliequivalents per liter. Millieqivalents per liter may be calculated by dividing the constituents' molecular weight by the ionic charge or valence. Sodium, calcium, and magnesium concentrations in lake water were measured as well as specific conductance. Sodium absorption ratios were computed from data presented in appendix A and plotted against specific conductance and are shown in figure 38 and figure 39. These plots shows that Pickerel, Enemy Swin, SW Waubay, Minnewasta, Spring, Rush, and Blue Dog Lakes possess water suitable for irrigation, i.e., water which does not exceed 5,000 micromhos in specific conductance nor sodium absorption ratios exceeding 10.0. There is quite a large variation in surface-water quality throughout the County.

The widely scattered smaller lakes do not seem to display any relationship between relative elevation and their chemistry. No doubt many of them act as recharge areas and others as discharge areas for near-surface local ground-water systems. Recharge-discharge functions may change with the seasons. Attempts to relate relative relief of lakes with chemistry through cross-section

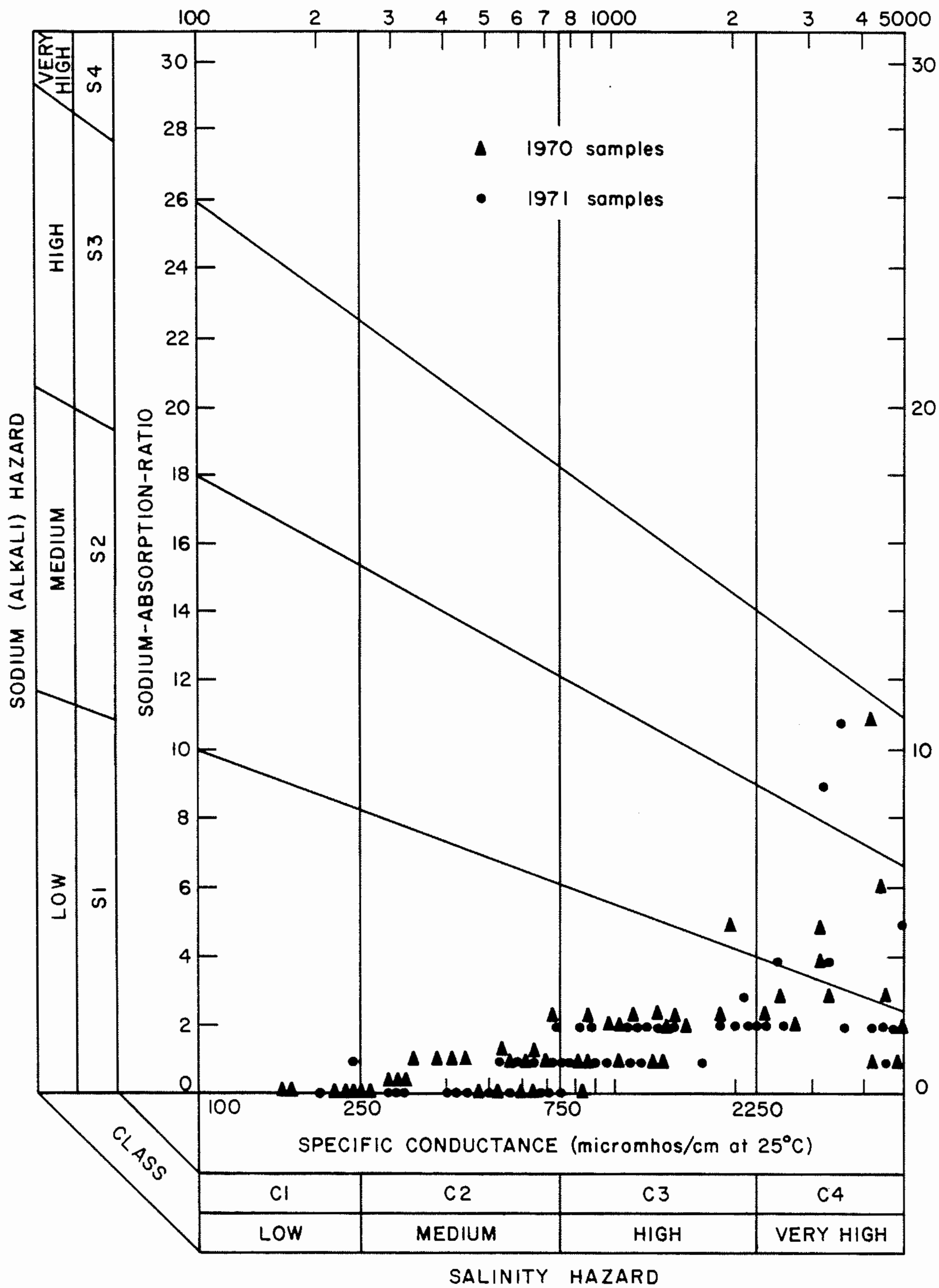


Figure 38. Plot showing quality of lake waters for irrigation in Day County.

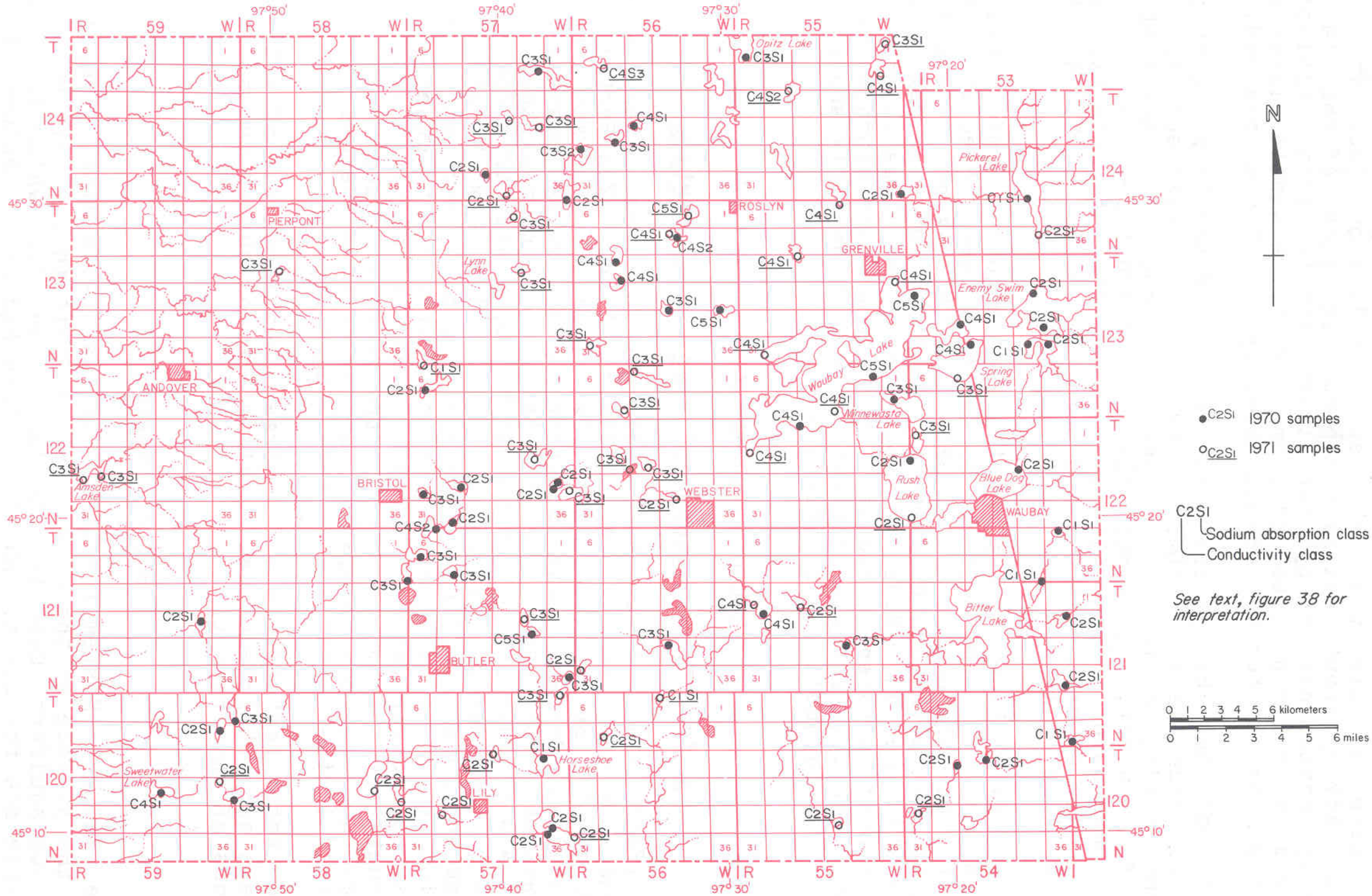


Figure 39. Map showing quality of lake water for irrigation.

construction proved futile. This may be due in part, to the chemical nature of water which changes rapidly from place to place without any apparent relationship to elevation of the lakes; probably contamination by fertilizer runoff from cultivated fields drastically affects the chemistry of the smaller lakes and probably accounts for the erratic quality variations observed.

A few of the lakes in the northern part of the County probably serve as ground-water discharge areas for the Basal aquifer System and in addition to salt concentrated from evapotranspiration of surface water, there must also be an additional salt input from ground-water inflow. The lakes which fit into this type are Opitz and a few of the ones surrounding it in sec. 6, T. 124 N., R. 55 W. (fig. 34).

Nearly every lake in Day County is undergoing some degree of eutrophication. Enemy Swim is by far the least affected at the present time although a small amount of blue-green algae does build up toward the end of summer. The other large lakes, especially Pickerel and Blue Dog show excessive algae blooms and steps should be taken to reduce the phosphate and nitrate inflow to these lakes in order to protect them from an early and premature demise in quality and usefulness.

GROUND-WATER HYDROLOGY

Aquifer Distributions and Physical Properties

Aquifers in Day County can be divided into four categories or systems according to their gross distribution. Von Bertallanfy (1968, p. 38) defines a system as "a set of elements standing in interaction." Probably most aquifers in Day County possess some interaction with each other in terms of ground-water flow, recharge and discharge. This should be especially true for those aquifers composed of glacial outwash. The term "system" as applied to these aquifers also helps to group them according to position in the geological column and according to genetic processes responsible for their origin. The four aquifer systems in the County are, from bottom up: the Bedrock System, the Basal System, the Intermediate System, and the Surface System. They are discussed in that order in the following pages.

The total recharge and discharge relationships of all the aquifers and their chemical quality are discussed in separate sections of this report.

Bedrock System

The Bedrock System includes all water-yielding formations below the surface of the Pierre Shale. Within this system, the only two aquifers used in the County and for which data are available are the Dakota and the Pierre Aquifers. Between these aquifers lie the Graneros Shale, Greenhorn Limestone, Carlile Shale including the Codell Sandstone Member, and the Niobrara Marl. These formations do not appear to be used in the County for water supplies and from the data available about them, their lithologies appear to be too fine-grained to permit enough permeability for them to have significant aquifer potential.

DAKOTA AQUIFER

The Dakota Aquifer is known geologically as the Dakota Formation and it sits between the Precambrian basement on the bottom and the Graneros Shale on top; both of the formations are Cretaceous in age. More commonly, the Dakota is known as the "Artesian Sand" because in many places throughout South Dakota it is under enough hydraulic head that wells which tap it flow. In Day County the formation runs from 150 to 200 feet in total thickness and is composed of two main lenses or "flows" as they are called locally. A test well drilled for the U.S. Department of Interior Desalination Plant in Webster in 1967 revealed that the Dakota in this area was composed of 200 feet of alternating fine sand and shale lenses with the two main "flows" separated by 45 feet of a predominantly shaley lithology.

Since the 1880's development of the Dakota between the Missouri River and the Coteau des Prairies has been so great that the hydraulic head in the aquifer has been reduced drastically in this area. Schoon (1971, figs. 15 and 17) reports that from 1909 to 1953 the hydraulic head in western Day County dropped from approximately 1700 feet to 1350 feet, a total drop of 350 feet. During the 1968 and 1969 summer well inventory program conducted for this project, many owners of Dakota wells throughout western Day County reported that the pressure has been constantly dropping since 1953 and that flow rates now range between 1 and 3 gallons per minute. Today, few wells finished in the Dakota Aquifer in western Day County in the James Basin actually flow and most have to be pumped. A study conducted by Hopkins and Petri (1962, pp. 16 and 17) lists flow measurements made on Dakota wells in 1955 in this area. The flow rate ranged from 0.5 gallon per minute to 3.0 gallons per minute with most falling between 1.25 and 2.00 gallons per minute. These small rates contrast greatly with the flow of a Dakota well drilled at Andover in the 1880's. McClure (1887) reported that this well when first drilled flowed at a rate of 300 gallons per minute with a closed-in pressure of 90 pounds per square inch. Figure 40 shows the potentiometric surface of the Dakota Aquifer during 1968 to 1969.

Such a great decline in head and flow rate is due simply to extensive exploitation during the past 80 years. Schoon (1971) states that the continuing decline of head can be expected in the years to come and by the year 2040, assuming rate of use to remain constant, no Dakota wells will flow in the entire James Basin, including western Day County.

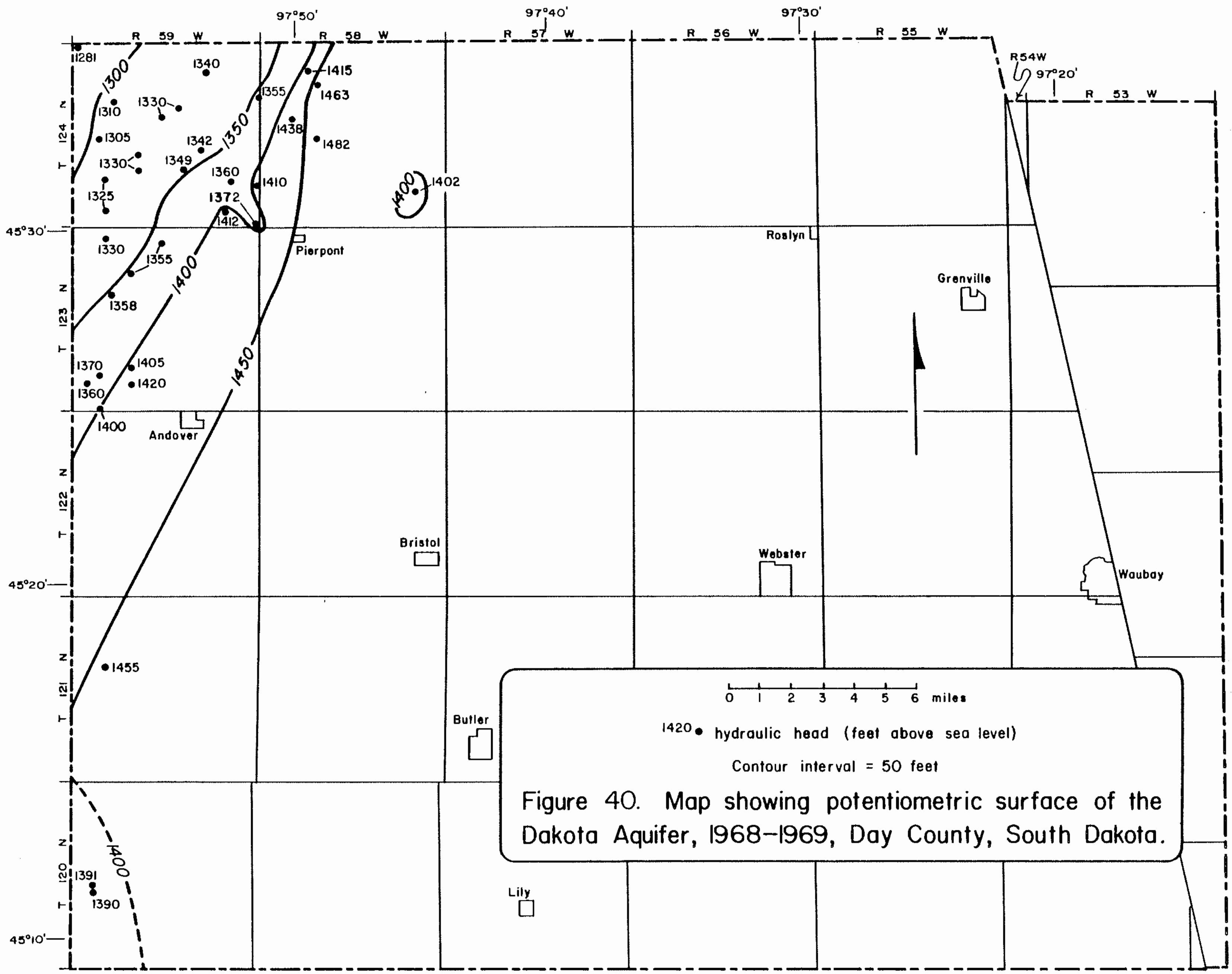


Figure 40. Map showing potentiometric surface of the Dakota Aquifer, 1968–1969, Day County, South Dakota.

Very little is known about storage capacity or permeability of the Dakota Formation as a whole and no known aquifer hydraulic or pumping tests have been performed in Day County. Analysis of grain-sized data from the Webster No. 1 test hole indicates that the permeability in this locality should be quite low. Schreurs and McGrath (1968) estimate from these data that the specific capacity of a well finished in the Dakota at Webster should run about 1 gallon per minute per foot of drawdown.

By far most of the Dakota wells are located in the James Basin region of Day County with very few found on the Coteau des Prairies because the wells on the highlands have to be pumped with a required water lift of 500 feet in places; in addition the permeability of the Dakota Formation decreases eastward with an increase of shale and silt in the material. Although data are scant, well yields can also be expected to drop toward the east as well.

PIERRE AQUIFER

The Pierre Shale is the uppermost of the bedrock formations in Day County and underlies the entire County. In the northwest part of the County where the shale is within 100 to 200 feet from the land surface, it is used extensively as an aquifer with wells penetrating approximately 10 to 20 feet of the weathered and fractured top of shale. The use of the Pierre Formation for water supplies is probably the result of tradition established by a few early drillers. Most of the shale or "slate" wells are of the low-yield pump jack type which have about 10 to 20 feet of perforated pipe penetrating the shale and producing around 3 to 5 gallons per minute. No data concerning permeability or storage properties of the shale are available, but local drillers report that yields of up to 40 gallons per minute can be obtained from properly constructed wells. Because of the high concentration of sulfate and low permeability the Pierre is not considered to be a good aquifer and should not be exploited further except when no other ground-water source is available. Figure 8 shows the contoured surface of the Pierre Shale bedrock in Day County. This map together with topographic maps of the land surface may be used to estimate the approximate depth to bedrock that can be expected at a given locality. The difference between the land surface elevation at a particular point and that of the bedrock surface at the same point may be taken as the thickness of glacial drift at that point.

Where the Pierre and overlying Basal System aquifers are in contact with each other there is interchange of water between them with the Pierre receiving most of its recharge from the Basal System. Figure 41 shows the potentiometric surface of the combined Pierre and Basal System aquifers and shows a decline from 1,800 feet just west of Grenville and Bitter Lake to a low of 1,300 feet near the Brown County border. This indicates a general flow direction from northeast to southwest with some discharge to a few discharge areas around the large lakes (fig. 34).

Basal System

BASAL SYSTEM, GENERAL REMARKS

Throughout most of the County a layer of glacial outwash sand and gravel rests immediately on the surface of the Pierre Shale and drapes over into the bedrock channels incised into the shale. Figures 12 and 13 shows the extent and thickness of the material. Generally, the basal material is composed of clay, silt, sand, gravel, and a large percentage of shale fragments of gravel size. The more permeable lenses and layers in the material are generally separated by more silty and clay-rich layers.

The basal materials in the Sweetwater and Waubay Channels (fig. 24) are considerably rich in marl and clay. In Day County these channel deposits are not considered good aquifer material. The basal deposits in the Webster Channel are generally thicker than the deposits in the other two bedrock channels, but they also contain a high clay and marl content. From inspection of drilling records and geophysical logs, it appears that the Webster Channel deposits might be slightly cleaner and may serve as better aquifers than the Sweetwater and Waubay Channel deposits.

In general, the Basal System is too rich in clay and fine material to be considered a good aquifer, even on the shale uplands away from the channels, except in the case of the Lynn Aquifer (figs. 12 and 13). Occasionally, drilling will reveal an area of the basal outwash which is rather clean and has good aquifer potential, but there is no sure way of predicting beforehand where these areas will be. Patterns may become apparent showing favorable aquifer locations as more data become available.

Although data are too scarce to predict areal patterns of permeability, a few aquifer tests have been made using the slug tests and grain-size data methods (see apps. B, C, and D). From these data the transmissivities can be expected to run between 750 and 4,350 gallons per day per foot; permeabilities may range between 40 and 250 gallons per day per foot squared. Figure 12 shows the thicknesses of the Basal System and figure 13 shows the elevation of the surface of the system. From these two plates it is apparent that the highest elevation of the Basal System is 1,578 feet above sea level and the greatest thickness is 115 feet.

Recharge to the Basal System takes place by slow vertical percolation of meteoric water from the surface of the glacial drift and occurs over the entire County except in the areas surrounding many of the major lakes where the flow direction is reversed and the aquifer discharges water to these lakes. Figure 41 shows

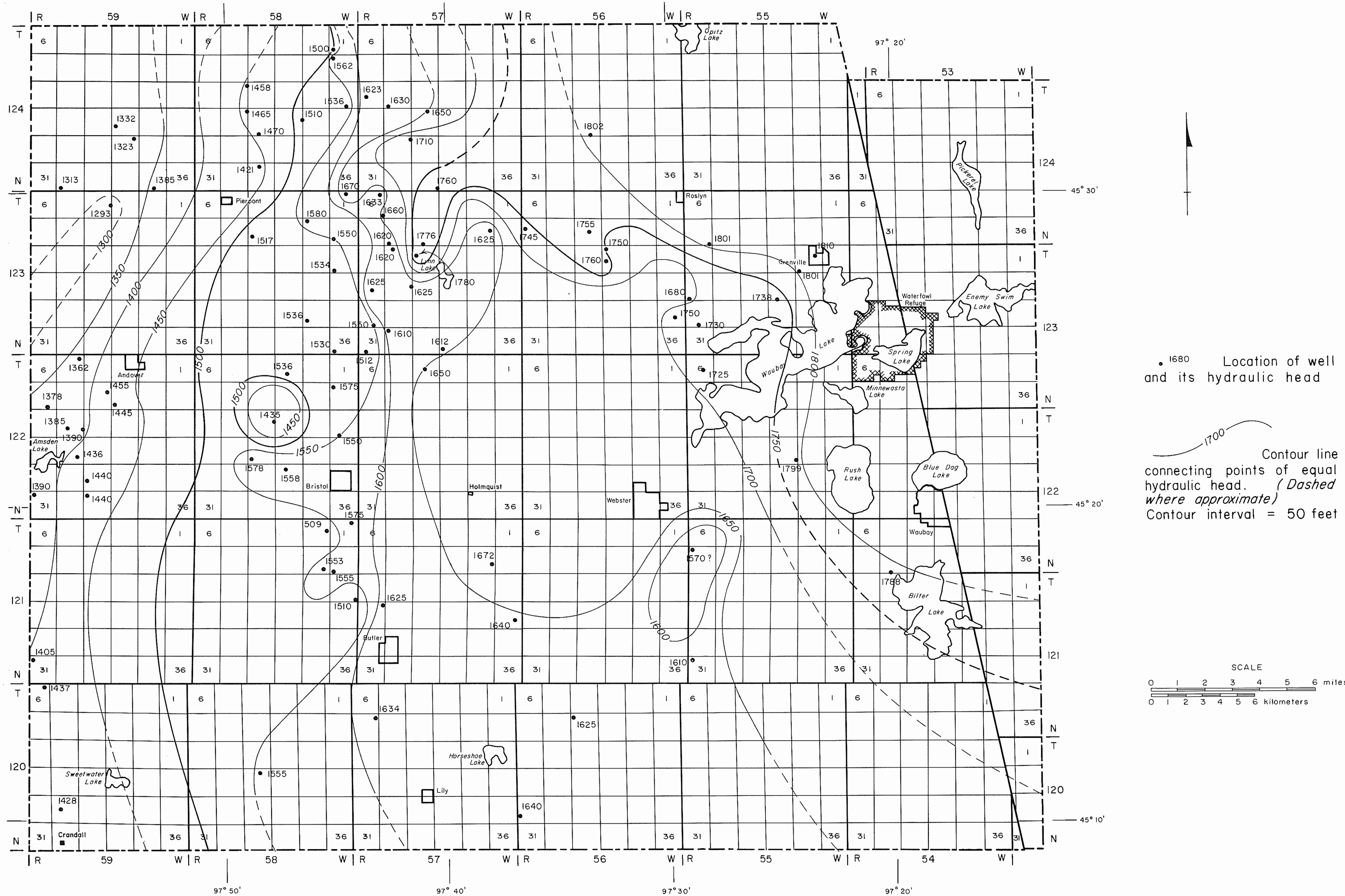


Figure 41. Map showing potentiometric surface of the combined Pierre and Basal System Aquifers, Day County, South Dakota.

over the other, and separated by glacial till (figs. 42, 43, and 44). Figure 42 shows the distribution of these aquifers and the elevations of their tops and bottoms at the locations of drill holes which penetrated them; figure 43 shows the thicknesses of the aquifers and figure 44 shows their depths from the surface.

The 49 aquifers which are shown on figures 42, 43, and 44 have been delineated from test hole and well data. The aquifers as shown constitute the best correlation that could be made from the data available although many of the aquifers may be more or less extensive than shown. In addition to the mapped intermediate aquifers, there are hundreds of small pockets and lenses of sand and gravel which cannot be correlated from one hole to another and thus are not mapped as such in the plates.

Most of the intermediate aquifers are complex in distribution of sediment sizes and thus in distribution of permeabilities. The reason for the erratic nature of these distributions rests in their origin. Day County was covered by glaciers at least three different times. During each advance of the ice, many pockets and lenses of sand and gravel were deposited during periods of melting and as each new glacier advanced across the County many of these aquifers were truncated and in other cases more sand and gravel of different grain sizes were added to the already existing aquifers and still new aquifers were formed.

Permeability values determined from pump tests (discussed in the next two sections of this report) grain-size analyses (app. D) and slug tests (app. C) indicate that the range of transmissivities of the intermediate aquifers is between 400 and 48,500 gallons per day per foot. Location of the various aquifer tests are shown in appendix B. Appendices E and F offer procedural and theoretical explanations for permeability prediction from grain-size data and hydraulic slug tests while appendix G offers a comparison of permeability and transmissivity values computed by grain-size analysis, slug tests, and pump tests.

Using a porosity of 20 percent it is estimated that the total amount of water in storage in all the intermediate aquifers is approximately 900,300 acre-feet. This estimate is conservative because most of the aquifers probably extend somewhat farther than shown on figures 42, 43, and 44 and the calculation does not include the probably hundreds of pockets and lenses that could not be correlated from one hole to another.

Water level measurements of observation wells made over a 2.5-year period in general reveals that the magnitude of fluctuations decreases with increasing depth of the aquifers (see app. H). See figure 45 for locations of observation wells.

Recharge to the intermediate aquifers is for the most part downward from the surface and from upper to lower aquifers. Around most of the major lakes the direction of flow is reversed and the intermediate aquifers receive water from the Basal System that the potentiometric surface of the Basal System slopes from east to west with a drop of about 500 feet from the east side of the County to the west side. Generally then, the major component of flow is westward from the large lakes. From the potentiometric surface configuration it is likely that much of the water fed to the major lakes from the Basal System actually is recharged to the system from the highlands east of the lakes in Roberts and Grant Counties.

LYNN AQUIFER

A section of the Basal System in the northwest part of Day County, in the vicinity of Townships 123 and 124 North and Ranges 56 and 57 West is composed of clean, medium-grained to fine gravel and is named the Lynn Aquifer because of its proximity to Lynn Lake (figs. 12 and 13). The trend of the Lynn Aquifer is northeast to southwest and is separated from the rest of the Basal System on the east by a permeability reduction and on the west by the crest of a Pierre Shale ridge. From interpretation of grain-size data obtained from the aquifer, its structural position, the extent of buried drift sheets surrounding it, and the inferred geologic history, it is apparent that the material comprising the Lynn Aquifer is a mixture of late-Wisconsin and pre-late Wisconsin outwash which collected in a trough formed between the Pierre Shale ridge and the edge of two early drift sheets.

Actually, the outwash drapes over the ridge to the west, but in the trough proper, the permeability is sufficiently higher to allow the trough materials to be separated into a separate aquifer.

Figure 12 shows that the thickness of the Lynn Aquifer ranges from 20 to 80 feet and the elevation of its upper surface varies from 1,467 to 1,578 feet above sea level (fig. 13).

The water in the Lynn Aquifer as in the rest of the Basal System, is under artesian head. Recharge to the Lynn is by vertical percolation and lateral flow from the rest of the Basal System to the east. The piezometric head of the Lynn averages 170 feet higher than the upper surface of the aquifer which indicates that production wells in the aquifer could produce a fairly deep cone of depression without dewatering the top of the aquifer.

Intermediate System

INTERMEDIATE SYSTEM, GENERAL REMARKS

Within the glacial drift, but above the Basal System and below the Surface System are 49 small aquifers which vary in area from 4 to perhaps 50 square miles. They are all composed of outwash sand and gravel and in many cases are superimposed or stacked one

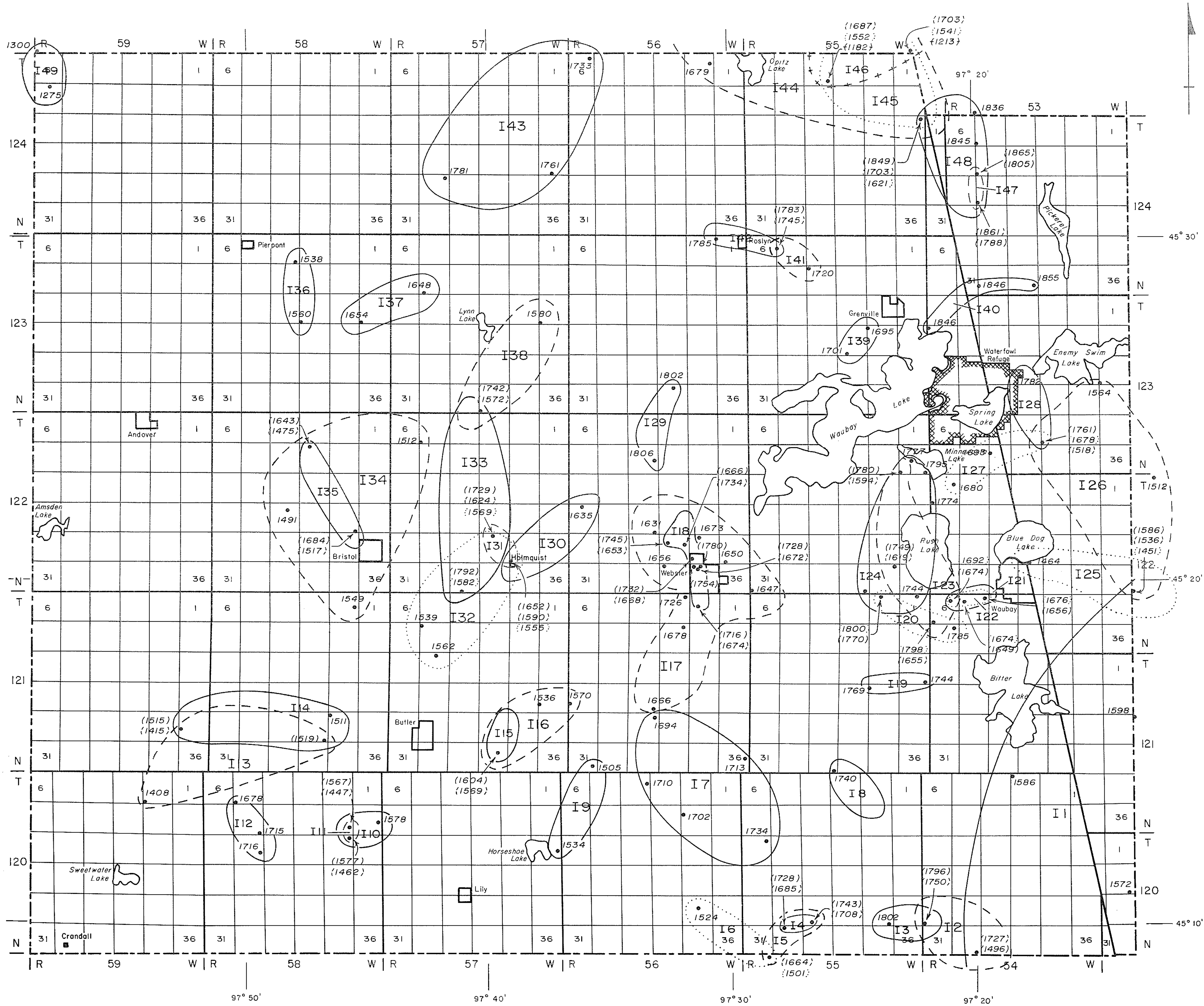


Figure 42. Map showing elevations of tops of aquifers in the Intermediate System.

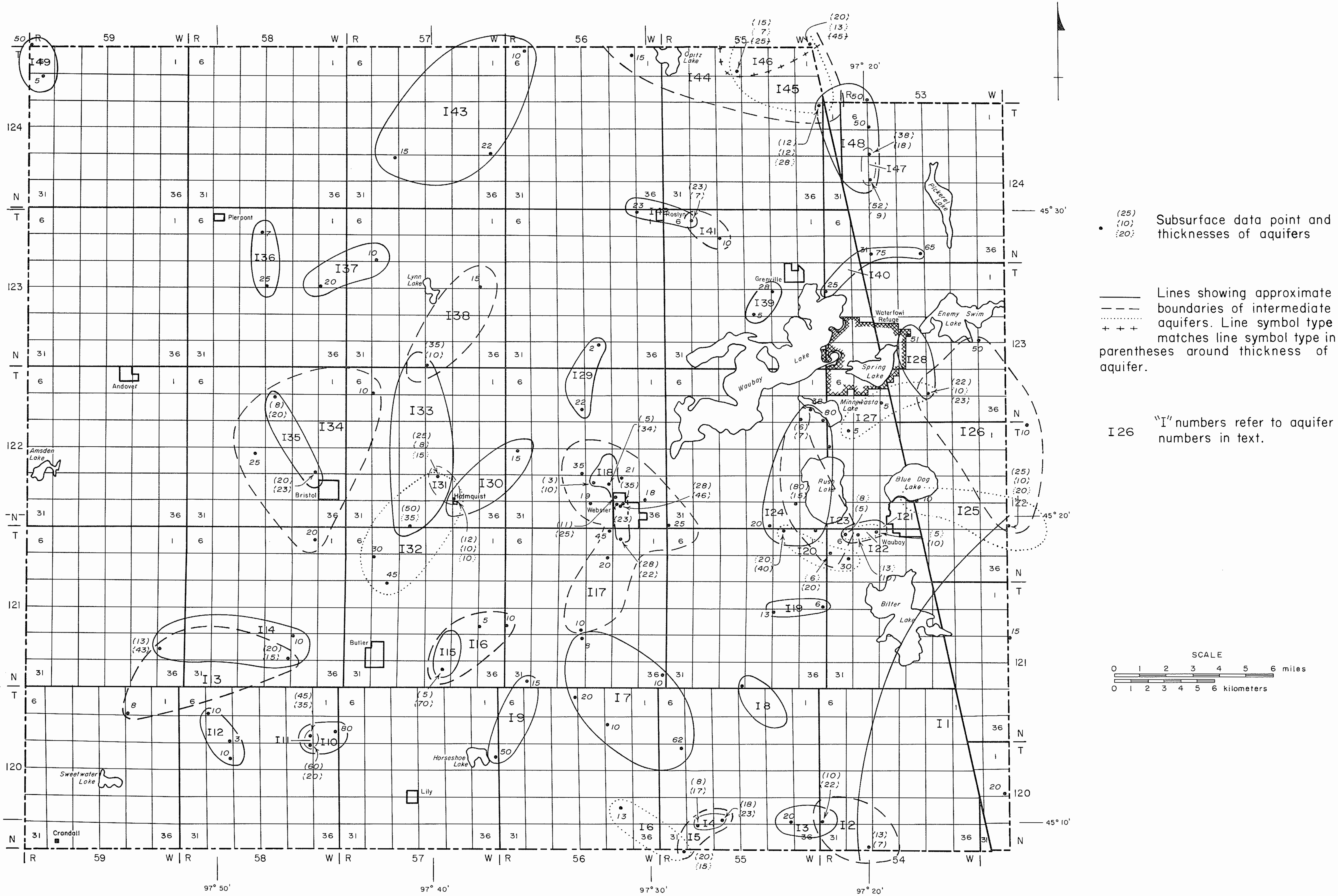


Figure 43. Map showing thicknesses of aquifers in the Intermediate System.

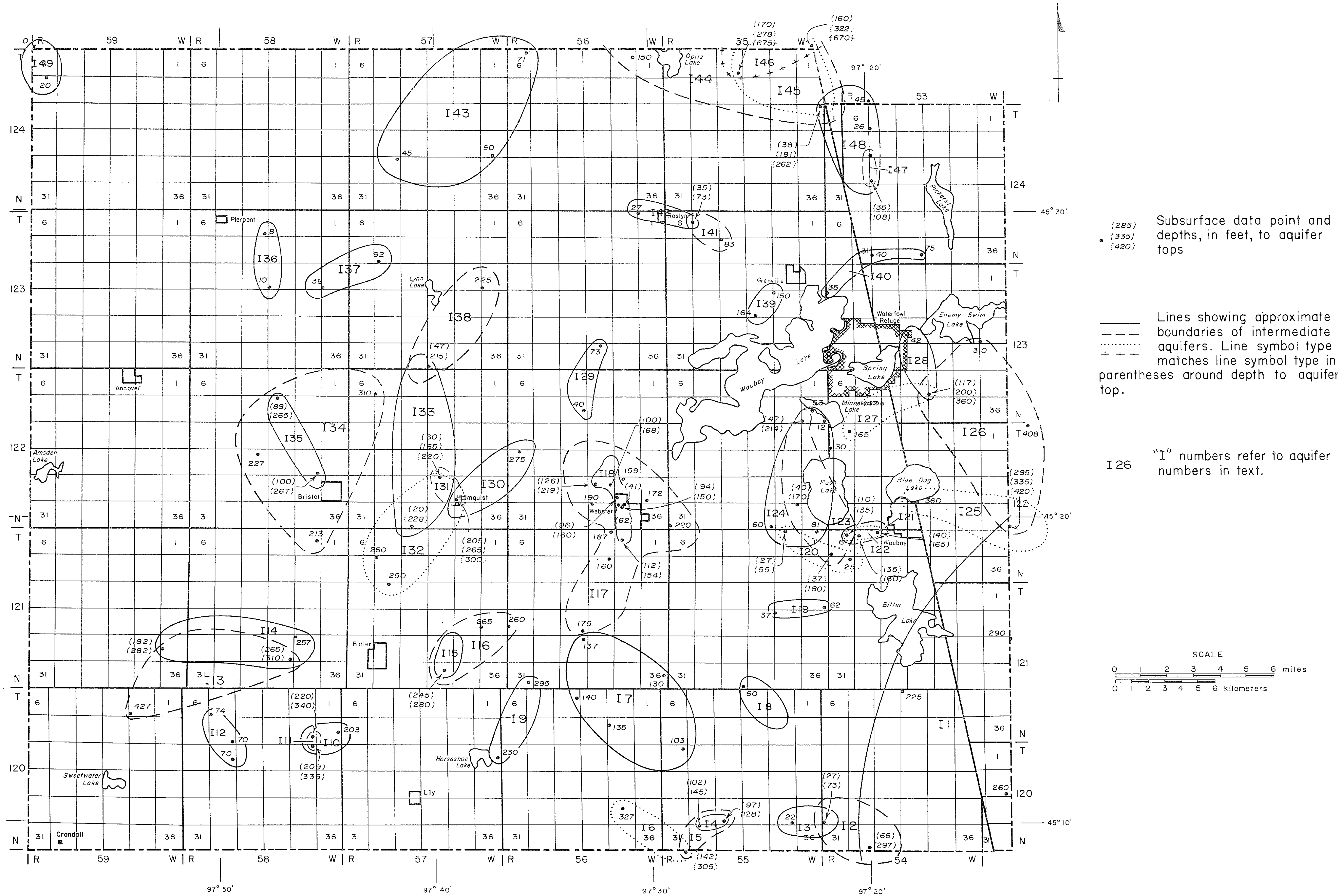
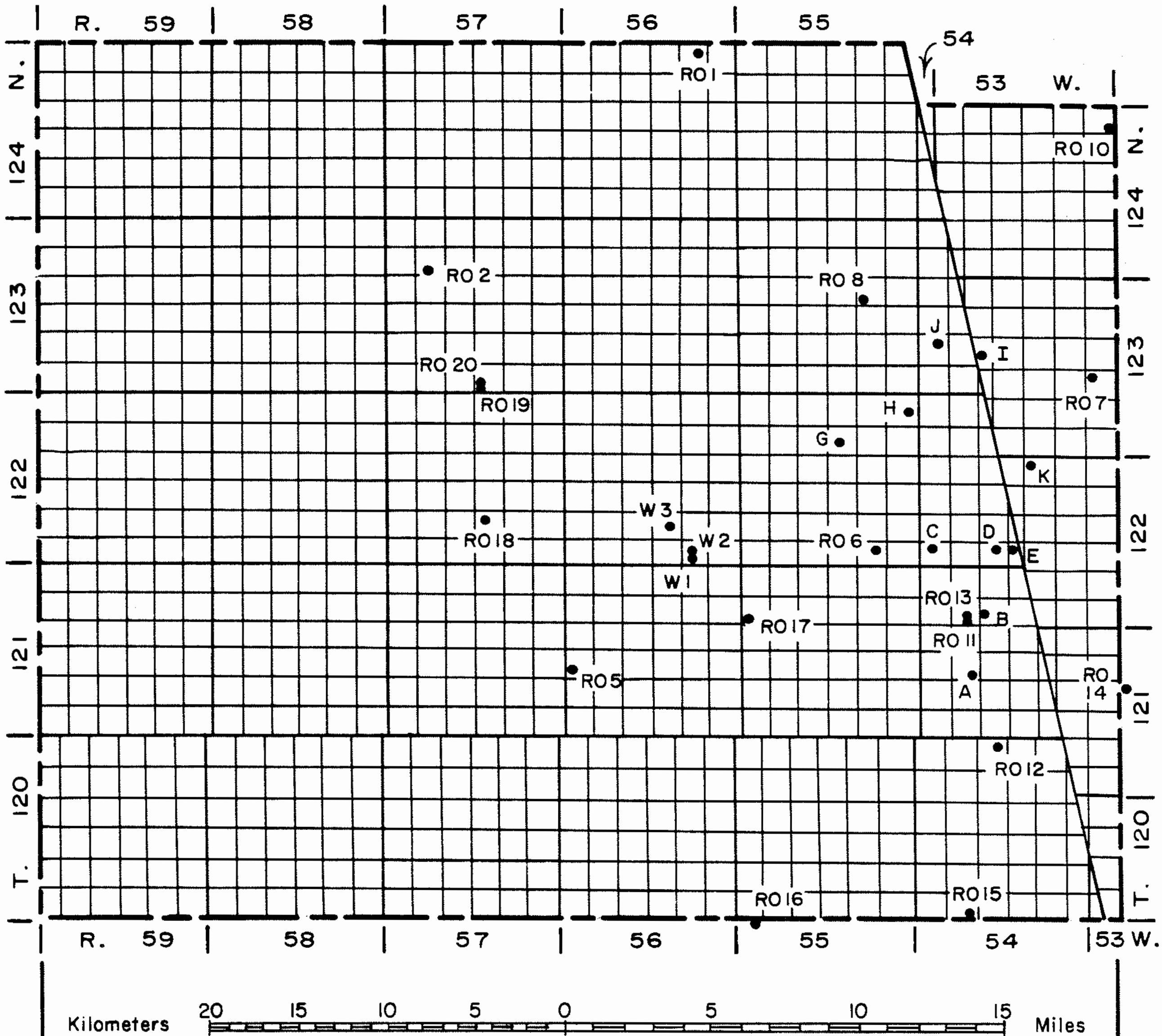


Figure 44. Map showing depths from land surface to tops of aquifers in the Intermediate System.



Well designation corresponds to Appendix H.

Figure 45. Map showing locations of monitored observation wells.

Sectionized Township

6	5	4	3	2	1
7	8	9	10	11	12
18	17	16	15	14	13
19	20	21	22	23	24
30	29	28	27	26	25
31	32	33	34	35	36

and they discharge into the aquifers above them and into the lakes (fig. 34).

UPPER WEBSTER AQUIFER

The Upper Webster Aquifer is listed as Aquifer I-18 on figures 42, 43, and 44, and is one of the two aquifers from which the City of Webster gets its water supply. This aquifer covers an area of approximately 3 square miles and averages 21 feet in thickness. In general outline, the aquifer is sinuous and runs north-south, and is approximately one-half to three-fourths of a mile in width.

During August 1971, a pumping test was performed on the aquifer by personnel of the South Dakota Geological Survey. The results of the test were analyzed by the method of Hantush and Jacob (1955). The test was run for 3.8 days and the rate of discharge from the well was 142 gallons per minute. No vertical leakage was detected. Vertical permeability could not be computed.

Figure 46 shows the location of the pumped well and the observation wells used in the test. The transmissivity and storage values computed for each of the wells are as follows:

Observation Well 1
- Transmissivity: 38,000 gpd/ft
- Storage Coefficient: .0003

Observation Well 2
- Transmissivity: 20,000 gpd/ft
- Storage Coefficient: .0006

Observation Well 3
- Transmissivity: 27,000 gpd/ft
- Storage Coefficient: .0005

LOWER WEBSTER AQUIFER

The Lower Webster Aquifer is shown as I-17 on figures 42, 43, and 44. It is the larger of the two aquifers serving Webster and is tapped by three operational wells within an area one-half mile in diameter. The aquifer covers about 19 square miles with an average thickness of 24 feet.

During August 1971, a pumping test was performed on this aquifer using City Well No. 6 as the pumping well. The duration of the test was 3.8 days with a constant discharge of 215 gallons per minute. No vertical leakage was detected. Vertical permeability could not be computed.

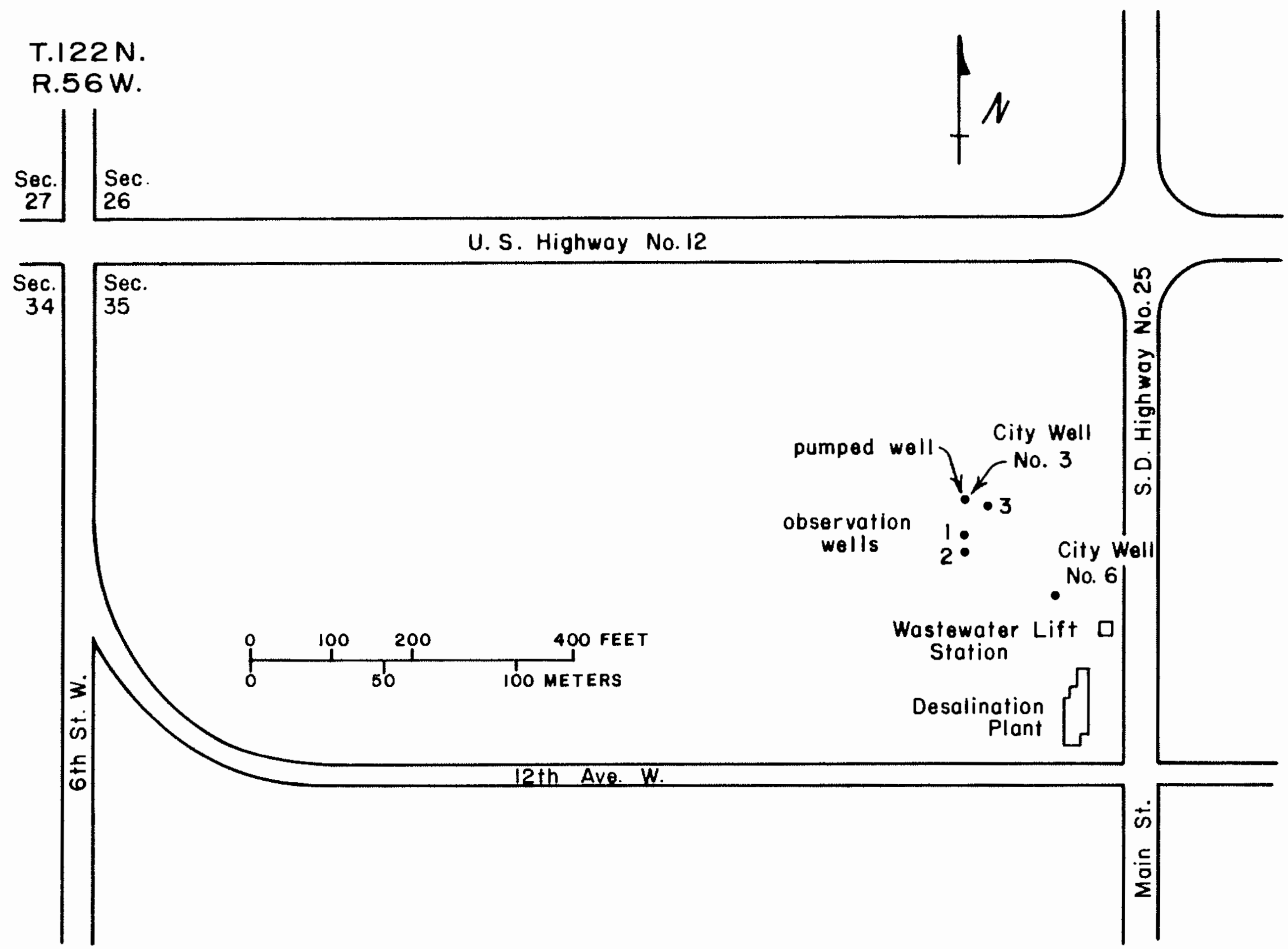


Figure 46. Locations of wells used in pump test of Upper Webster Aquifer.

Two observation wells were used in this study and are shown on figure 47. The data from the test were analyzed by the method of Hantush and Jacob (1955) and the results are shown below:

Observation Well 1
Transmissivity: 38,000 gpd/ft
Storage Coefficient: .0006

Observation Well 2
Transmissivity: 48,500 gpd/ft
Storage Coefficient: .0002

Grain-size analyses were also performed on materials from a test hole one-half mile north and one-half mile west of City Well No. 6 in SE 1/4 SE 1/4 SE 1/4 NE 1/4 sec. 27, T. 122 N., R. 56 W. Using the method of Masch and Denny (1966), the transmissivity of the Lower Webster Aquifer at this point was calculated to be 41,000 gpd/ft which is between that of the two values obtained in observation wells 1 and 2.

WATER POTENTIAL IN THE TWO WEBSTER AQUIFERS

The two aquifers underlying Webster seems to be adequately producing water for the City's present needs which average approximately 500,000 gallons per day. Additional wells could probably be installed to increase the city water supply. If new wells are anticipated in either aquifer, it would be wise to drill them at some distance (at least 1/2 mile) from the present ones to prevent well interference. New wells in the upper aquifer should be drilled north of Well No. 3, because south of this point the aquifer materials become less permeable. A few persons who have wells in these aquifers both north and south of Webster report that the water level in their wells have been dropping during the past 10 years because of pumpage at Webster. It was not possible however to verify these claims. In any case, if new wells are drilled they should be carefully pump-tested to determine their safe yield.

The City of Webster would profit in the long run from a program designed to determine the safe yield of aquifers which supply the City. Such a program is outlined in the section, "Recommendations for Further Studies."

Surface System

SURFACE SYSTEM, GENERAL REMARKS

The Surface System of aquifers comprises all surface sand and gravel deposits which contain water. Although Day County contains an enormous amount of surficial sand and gravel, in many places the deposits are too high in local relief and lack closure to

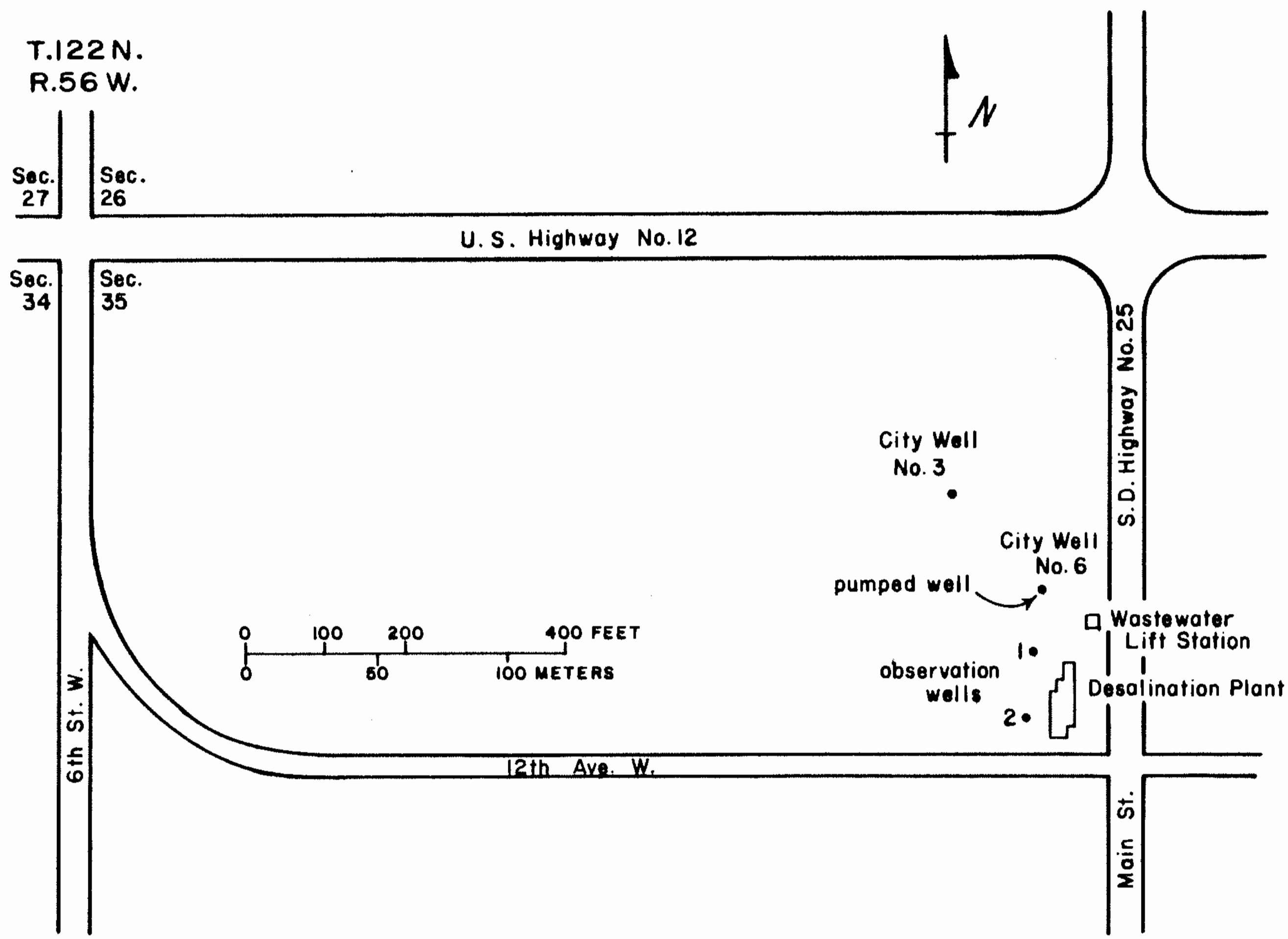


Figure 47. Locations of wells used in pump test of Lower Webster Aquifer.

hold water which percolates into them. For this reason, only the water-bearing deposits have been mapped as aquifers (fig. 48).

The most extensive of the Surface System aquifers is known as the Eastern Lakes Subsystem and is composed of several aquifers surrounding and in direct hydraulic contact with the large lakes in the eastern half of the County (fig. 48).

Elsewhere in the County, a few small surface aquifers can be found around Sweetwater Lake and just southeast of Amsden Lake. Around many of the smaller lakes and ponds in Day County can be found limited bodies of outwash which are often used as water supplies for stock. Frequently, they are not desirable as water supplies for human consumption because of the ease with which their water can become contaminated by barnyard waste and fertilizer runoff from fields and pastures. The thicknesses of most of the very small surface aquifers are not known and their physical properties such as transmissibility and storage coefficient can be expected to vary quite widely.

EASTERN LAKES SUBSYSTEM

The Eastern Lakes Subsystem is by far the most complex in nature when compared with other aquifers in Day County. Actually this subsystem is a group of several aquifers which often connect with each other beneath the surface through buried channels and fairly permeable, sandy till. Because of their similarity of origin and close connection to each other they have been grouped together into one subsystem. The typical structure of this subsystem is characterized by an apron of sand and gravel surrounding each lake that seldom exceeds 25 feet in thickness. Bodies of outwash connect the lakes or feed into the sand and gravel apron around the lakes. These connecting bodies are considerably thicker with a maximum thickness of almost 200 feet between Blue Dog and Bitter Lakes (fig. 48). The connected bodies are often dry in places while in other places water can be obtained from them. Such characteristics are the results of the vertical position of the deposits, i.e., the connecting bodies are sufficiently higher than the lakes they connect or join that eventually, after a rain or snowmelt, most of the water drains out of the higher deposits and into the aquifers around the lakes and into deeper aquifers below the connecting bodies. Thus, although the connecting outwash bodies often do not hold water for an appreciable length of time, they are important as feeders to replenish the lakes and the aquifers surrounding them.

Waubay Aquifer

The thickest part of the Eastern Lakes Subsystem is the Waubay Aquifer which lies between Blue Dog and Bitter Lakes (fig. 48). In the City of Waubay, two city wells tap this aquifer at its thickest part--approximately 200 feet in sec. 34, T. 122 N., R.

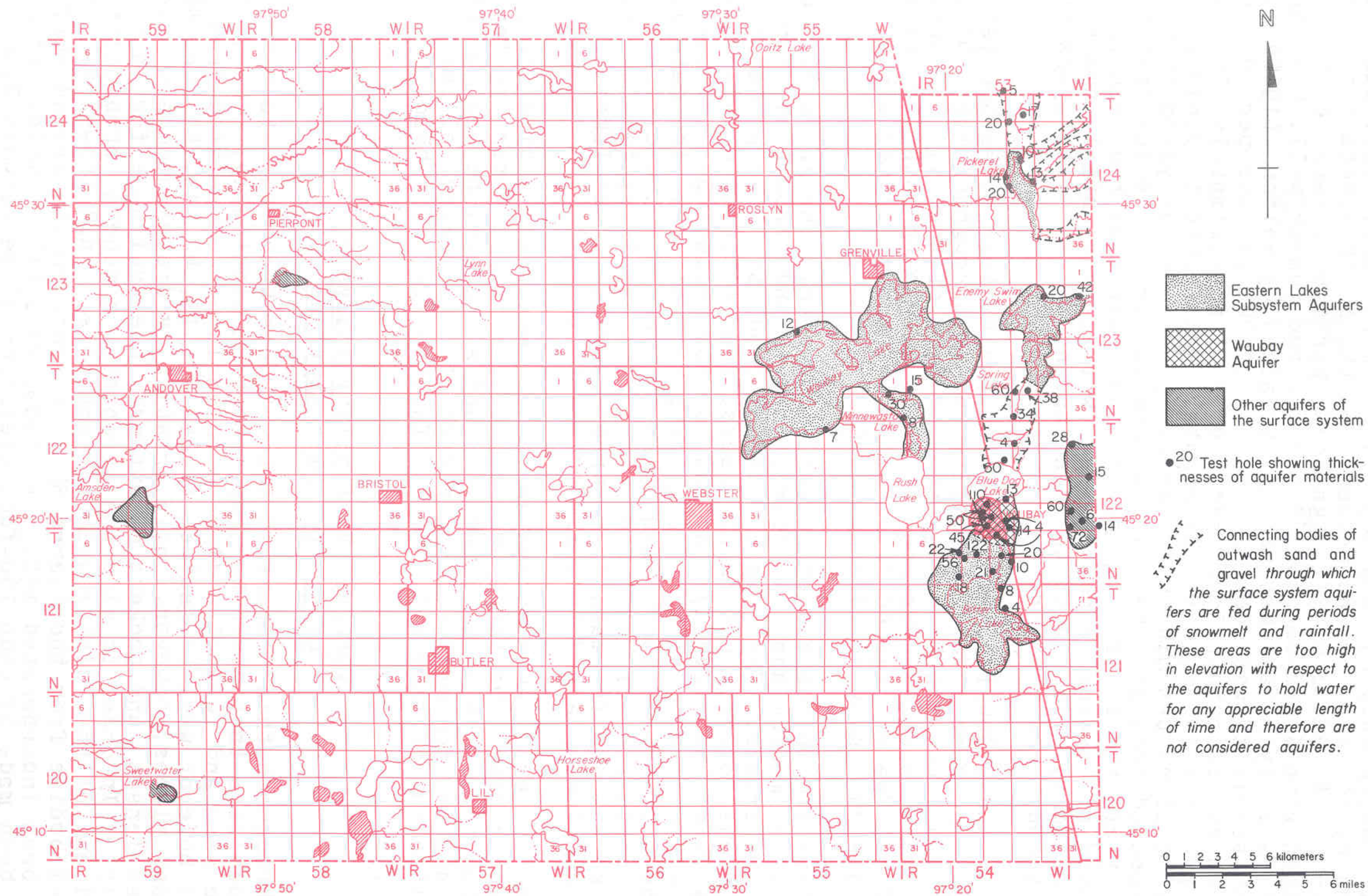


Figure 48. Map of the surface system aquifers.

54 W. During July 29 and 30, 1970, a new city well was pump-tested by the driller and members of the South Dakota Geological Survey. A yield of 120 gallons per minute was eventually obtained with a drawdown of 60 feet in the pumped well. From specific capacity relationships as explained by Walton (1962) the transmissibility was computed to be 3,000 gallons per day per foot which is rather low. Another well approximately 300 feet away produces 100 gallons per minute. This range in yield of 100 to 120 gallons per minute is probably the maximum yield that can be expected from any one well in this aquifer. The low transmissibilty of the aquifer is due to the fact that the aquifer is composed of medium to coarse sand with a substantial amount of silt and clay mixed with the sand and numerous silt layers running through the aquifer.

The Waubay Aquifer, included in the Eastern Lakes Subsystem, contains permeable clay and silty zones throughout most of its extent, but between Blue Dog Lake and City of Waubay, it appears that sand is continuous from the bottom to the surface of the aquifer. The storage coefficient is not known for certain but it probably runs between .001 and .0001.

Elsewhere in the Eastern Lakes Subsystem, the grain size can vary from medium sand to coarse gravel and from clay-rich to clean materials. There is no way of predicting the permeability in any one place, but fairly coarse and clean materials around Enemy Swim Lake might yield 300 to 400 gallons per minute and probably will not exceed 500 gallons per minute. The materials around the edge of Enemy Swim Lake are probably the cleanest and most productive of all the Eastern Lakes Subsystem aquifers because the aquifer materials surrounding the other lakes are too thin and fine-grained to yield much water.

The Eastern Lakes Subsystem is an important aquifer complex for recharging the lakes and the entire ground-water system of Day County. The large areas of sand and gravel at rather high altitude in comparison to the rest of the County allows rapid infiltration of snow melt and rainfall to the drift below.

Vertical Variability Analysis of Aquifer Distributions

Throughout this report an attempt has been made to describe all aquifers that could be mapped deterministically, i.e., all those sand and gravel bodies which could be correlated from one drill hole or well to another (figs. 12, 13, 42, 43, 44, and 48). In many places, however, only erratically distributed and unconnected lenses and pockets of outwash are available for a water supply. In order to give the prospector a general probabilitistic idea of the distribution of aquifers, all known sand and gravel bodies from the Pierre Shale bedrock to the ground surface have been incorporated into a vertical variability model and maps have been made of each 100-foot elevation slice between 2,000 and

1,000 feet above sea level. These maps are shown in appendix I. In general, it can be noted that the areal distribution of sand and gravel closely follows the distribution of mapped aquifers in the same elevation interval as shown in figures 12, 13, 42, 43, 44, and 48. A complete discussion of the theory and interpretation of vertical variability maps can be found accompanying the maps in appendix I.

Quality of Ground Water

There is one major factor that determines the chemistry of the ground water in Day County and that is the chemical composition of the glacial drift. The tills and gravels of the County were predominantly derived from crushed and pulverized marine shales and chalks over which the glaciers passed on their way south. These parent materials are naturally rich in calcium, magnesium, carbonate, and sulfate and it is for this reason that most of the ground water in Day County is of the calcium-magnesium-sulfate type. Figure 49 shows locations of well-water samples and appendix J lists their chemical analyses.

There is little in the way of broad regional patterns of ground-water chemistry in the County except in the case of the shallow intermediate aquifers in the highlands east of the large eastern lakes. In this area where major recharge is taking place the aquifers yield water of significantly less total dissolved solids than in the area west of the lakes. East of the lakes the water is generally less than 800 parts per million in total dissolved solids. Attempts were made to delineate areal patterns of recharge and discharge in intermediate aquifers west of the lakes but only many small cells of 2 to 3 miles in diameter were apparent. There are two reasons for this complexity. One factor is the numerous aquifers which are separated from each other by till of low permeability such that no one aquifer is large enough to collect and channel ground-water flow any great distance so that it would reflect in chemical patterns. Another factor is the fairly thick section of drift (500 feet or more) and the stacked arrangement of aquifers within it coupled with relatively rugged surface topography which sets up numerous small recharge and discharge cells which may reach downward for considerable distance. Although horizontal patterns are not extensive it is apparent from comparison of analyses and depths of wells from which samples were taken that west of the large eastern lakes the total dissolved solids tend to increase with increasing depth of the wells, reflecting the effects of vertical recharge; i.e., as water moves downward through the drift it dissolves more and more mineral matter.

The Basal System does not show any broad chemical patterns either. Probably this is due to the presence of several recharge and discharge areas which may not be apparent at the surface but which may operate within the buried drift.

The specific conductances and sodium absorption ratios of certain wells have been computed and are shown in figure 50. In general, ground-water quality of the glacial drift aquifers (Basal, Intermediate, and Surface Systems) ranges from about 300 to 2,600 parts per million of total dissolved solids. The Pierre Aquifer contains water which in a few places exceeds 3,500 parts per million of total dissolved solids. The Dakota Sandstone water runs from about 2,000 to 2,500 parts per million and is characterized as a sodium-sulfate type.

Areal Recharge and Discharge Relationships

The main recharge area for Day County is the upland areas around the major eastern lakes and the highlands to the east of them. In addition, the wide expanse of outwash in Roberts and Grant Counties contributes significantly to recharge of Day County because of its altitude (over 2,000 feet) and the rapid infiltration allowed by the high permeability of the materials. Appendix H lists water levels in observation wells in the County which were installed by the South Dakota Geological Survey for this project. Figure 45 shows their locations.

Additional recharge to all the aquifers takes place over most of the surface of the County (fig. 34). Recharge and discharge areas of the Basal System as shown in figure 24 are also recharge and discharge areas for intermediate aquifers lying above the Basal System in these areas.

Recharge to subsurface aquifers and discharge from these aquifers to the surface take place through a thick sequence of till and intercalated sand and gravel. Time and expense limitations of this project did not allow the determination of till permeabilities. Todd (1959, p. 53) states that permeabilities of glacial till may range between 0.1 and 10 gallons per day per foot squared. Tills in Day County will probably range this widely in permeability because of their varying contents of sand and gravel. Vertical permeability of till should be less than horizontal permeability because of the compaction caused by the weight of overlying ice and till.

Figures 51, 52, and 53 show typical hydrologic cross sections from east to west across the County and show the general recharge-discharge relationship. Water recharging from the highlands to the east of the lakes seeps down through the drift and into the Basal System. Around Bitter and Waubay Lakes the head of the Basal System is about 20 to 25 feet higher than the elevation of the lake surfaces (fig. 41); this difference causes upward flow.

West of the large lakes the recharge is again from the surface downward to the Basal System and the head on the Basal System drops from about 1,800 feet at Grenville to 1,300 feet at the western edge of the Coteau des Prairies.

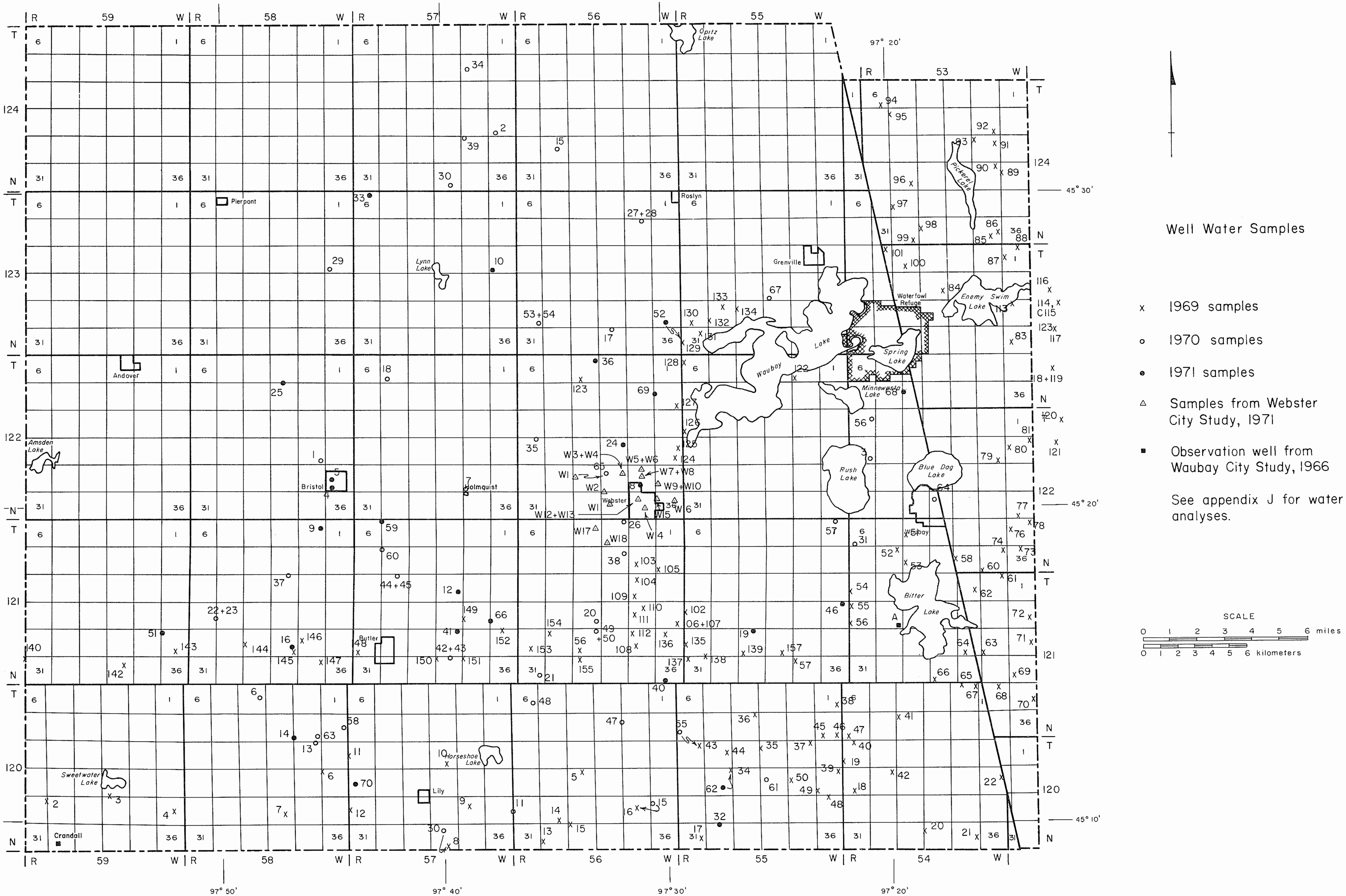


Figure 49. Map showing locations of well water samples by sample number, Day County, South Dakota.

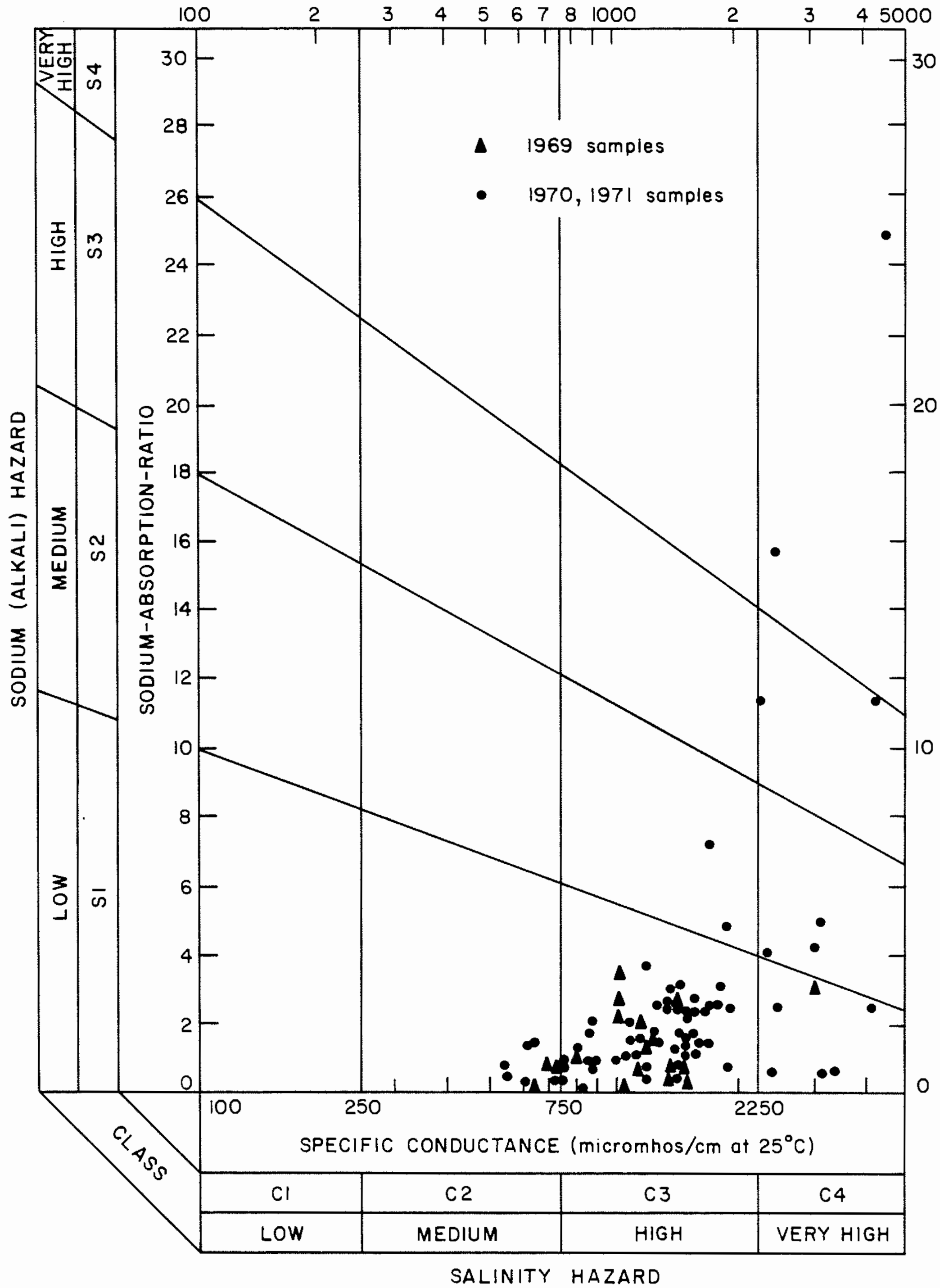


Figure 50. Plot showing quality of well waters for irrigation in Day County.

Figures 51, 52, and 53 also show that west of Grenville and Waubay the heads of the intermediate aquifers are directly correlated with the depths of the aquifers. That is, in a vertical section through the drift, the deeper aquifers will have lower heads generally than the higher ones which indicate that recharge from the surface is taking place.

Along the western edge of the Coteau des Prairies the Basal System discharges its water by slow seepage to streams which cut into it. In this area the recharge-discharge relationship is somewhat more complex due to the presence of the incised stream valleys. In the extreme northwest corner of Day County the Basal System again discharges to the surface (fig. 34).

Throughout the County the Intermediate and Surface Systems possess several small recharge and discharge areas but hydrologic data are not dense enough to precisely define all of them.

Generally, the Basal System acts as the major conduits for ground-water flow in Day County and as such determines and maintains the regional flow pattern for the County. Similar flow patterns in other terranes have been described by Toth (1963) and Freeze and Witherspoon (1966). The Pierre Shale below the upper weathered 10 to 20 feet serves as an essentially impermeable base for this Basal System. Local and intermediate flow paths are confined to the surface and intermediate systems for the most part.

WATER DEMAND AND POTENTIAL IN DAY COUNTY

Water needs in Day County can be grouped into four major categories or demands which include municipal demands, rural domestic and stock-watering demands, irrigation demands, and recreational and wildlife demands.

All municipal water supplies in Day County come from ground water and in most cases present needs are being met as far as quantity of water is concerned. Andover and Pierpont receive water from the Dakota Aquifer and the remaining cities in the County tap the glacial aquifers for their supplies. Pierpont would like to have a source of water of better chemical quality than that of the Dakota Aquifer. Grenville has considered drilling additional wells to augment yield from present wells. Ground water will probably continue to be the best all-around supply of water for cities in Day County because of fairly close proximity of aquifers to most of the demand centers. There is an exception in the cases of Pierpont and Andover which are not near any good intermediate or surficial auqifers; in addition the Basal System in these localities possesses very low permeability.

A few of the cities near large lakes could possibly augment their needs with surface water, but the cost of piping and treatment facilities would have to be calculated.

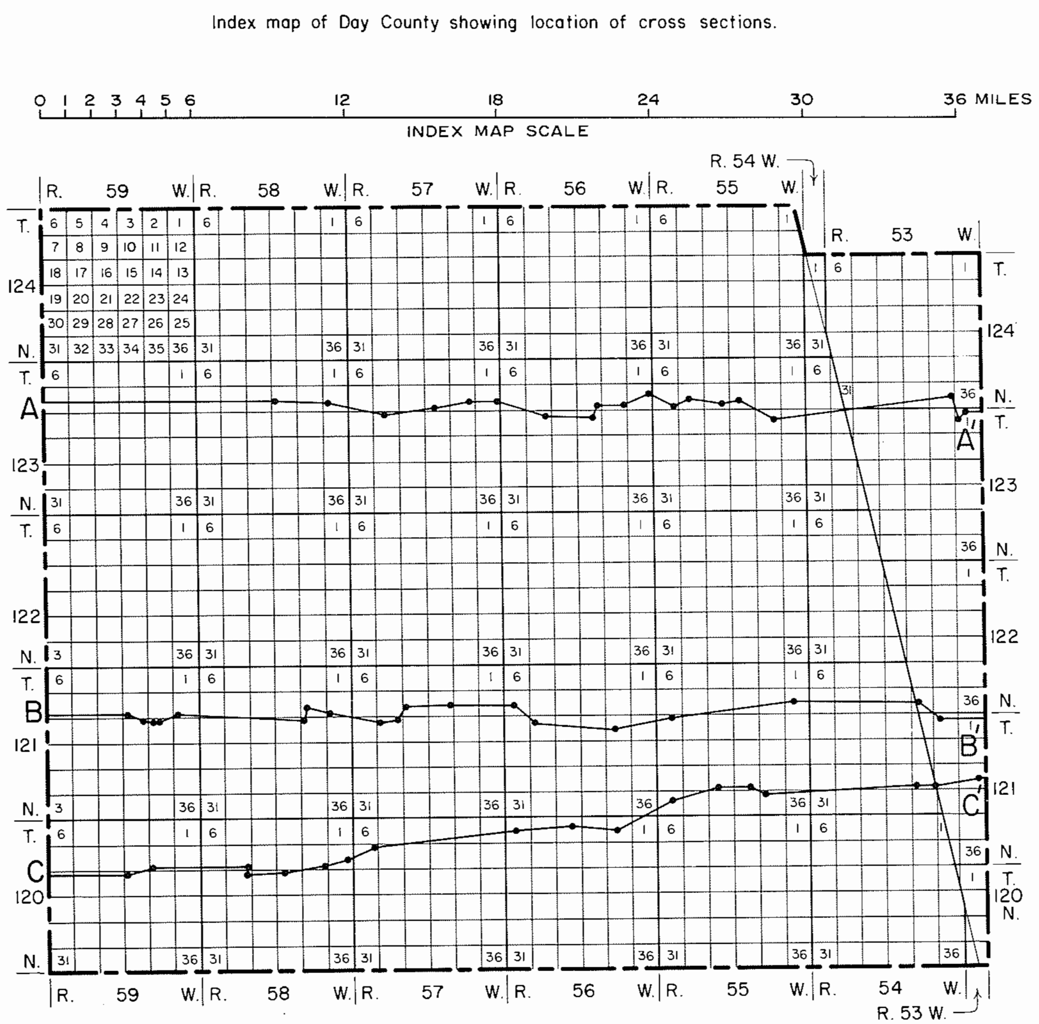


Figure 51. Hydrogeologic cross section, A-A′, of Day County, South Dakota.

Well

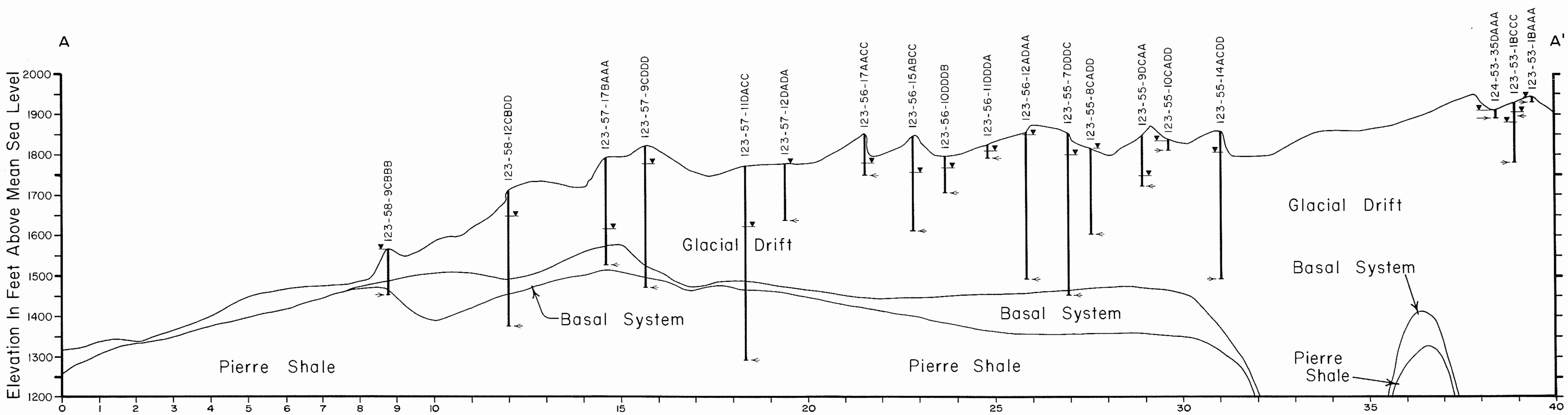
Hydraulic head of well

Arrow indicates location of well screen

Two hydraulic head and well screen symbols on one well indicate two wells with same legal location.

Vertical exaggeration approximately 40X

WEST ← → EAST



Index map of Day County showing location of cross sections.

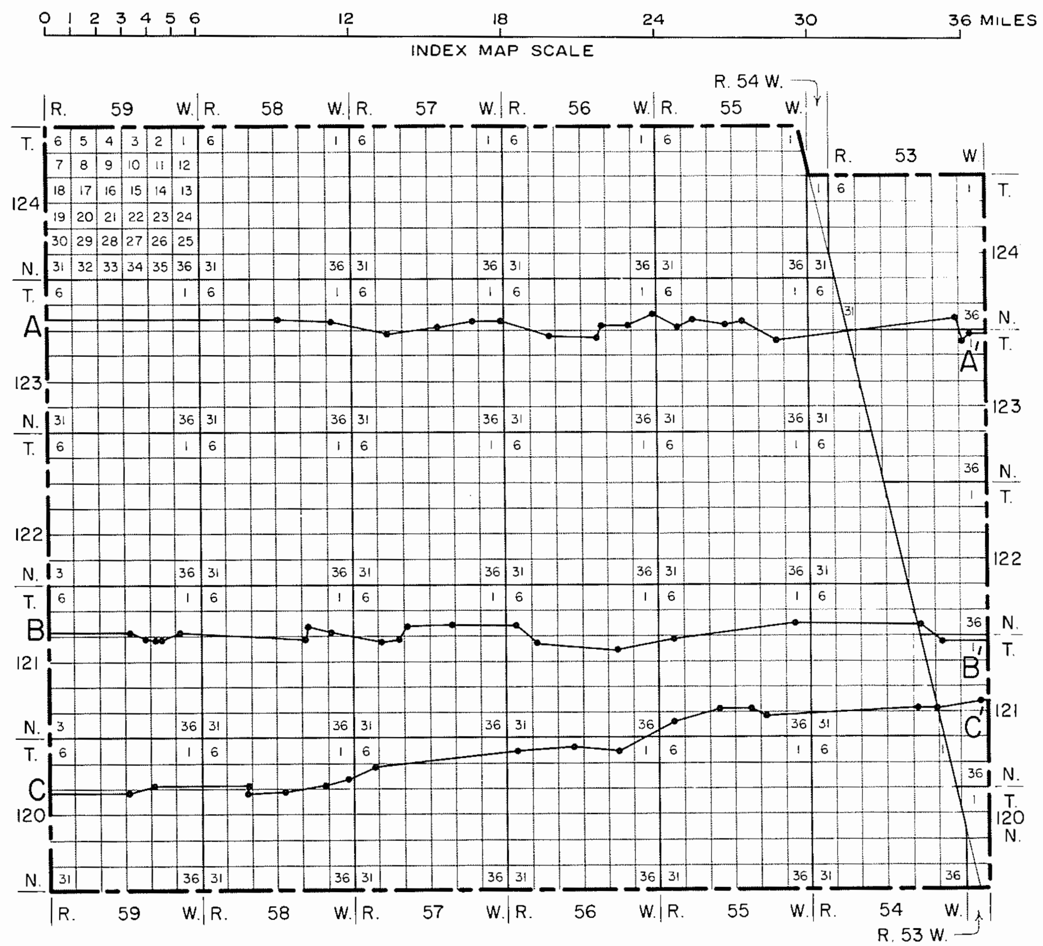


Figure 52. Hydrogeologic cross section, B-B', of Day County, South Dakota.

Well

Hydraulic head of well

Arrow indicates location of well screen

Two hydraulic head and well screen symbols on one well indicate two wells with same legal location.

Vertical exaggeration approximately 40X

WEST ← → EAST

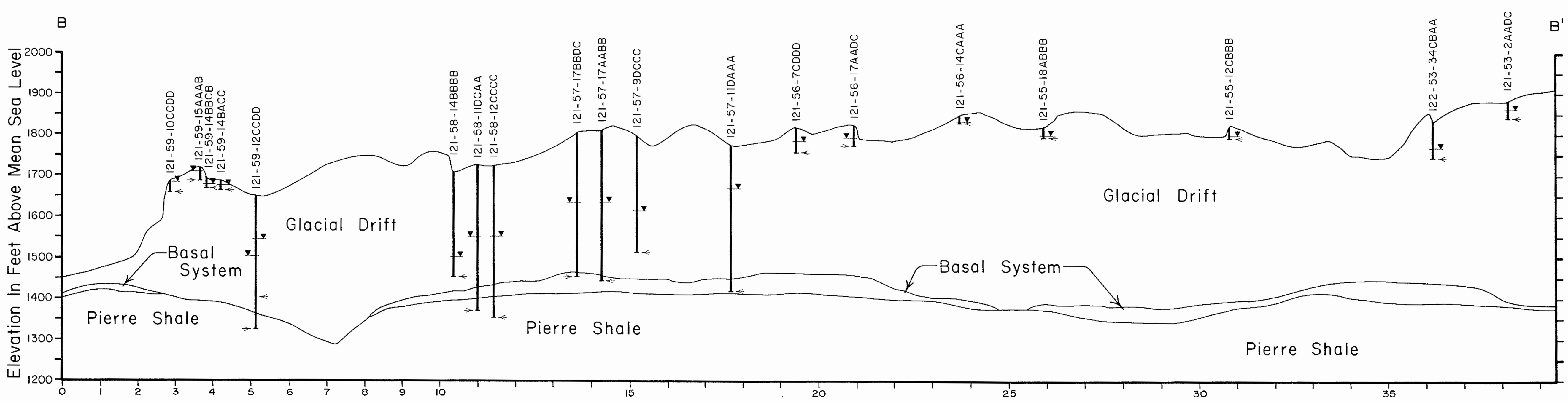
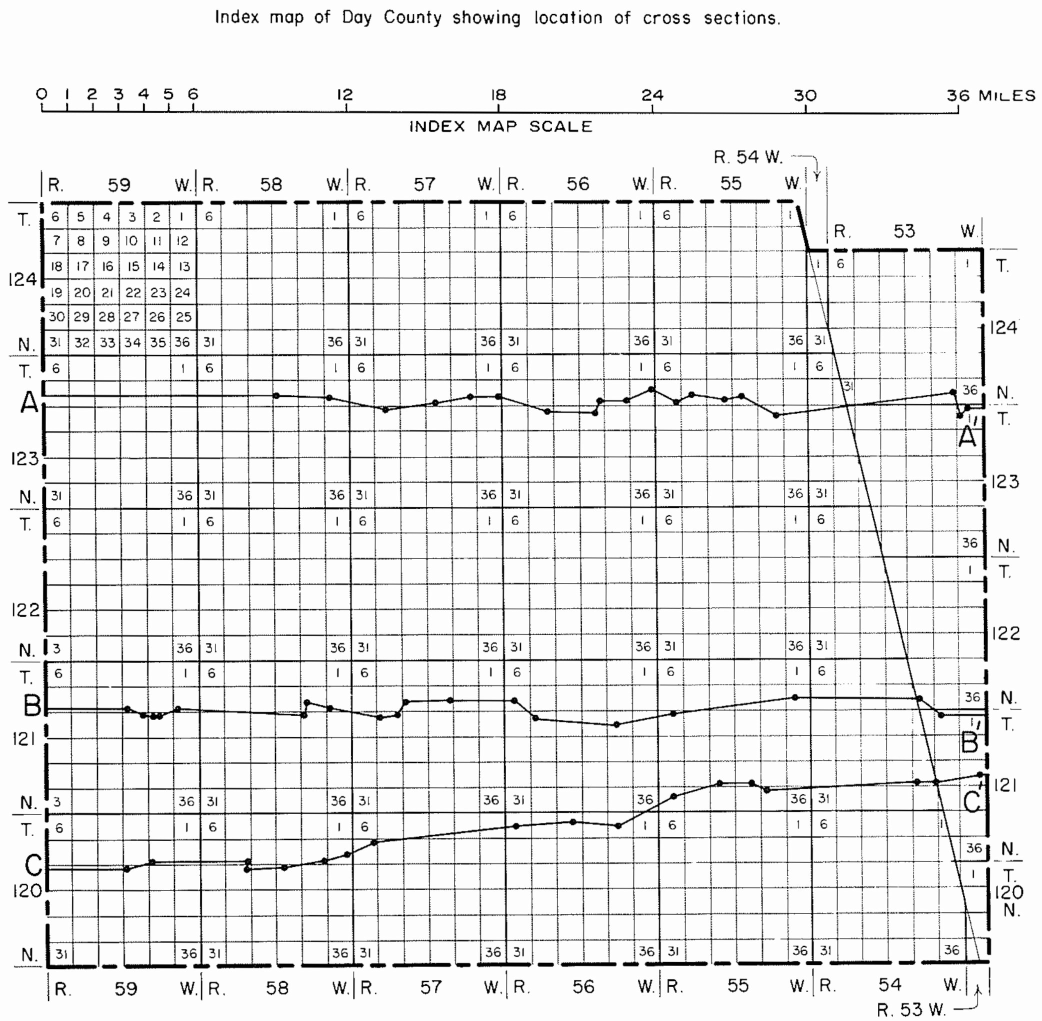


Figure 53. Hydrogeologic cross section, C-C′, of Day County, South Dakota.



| Well

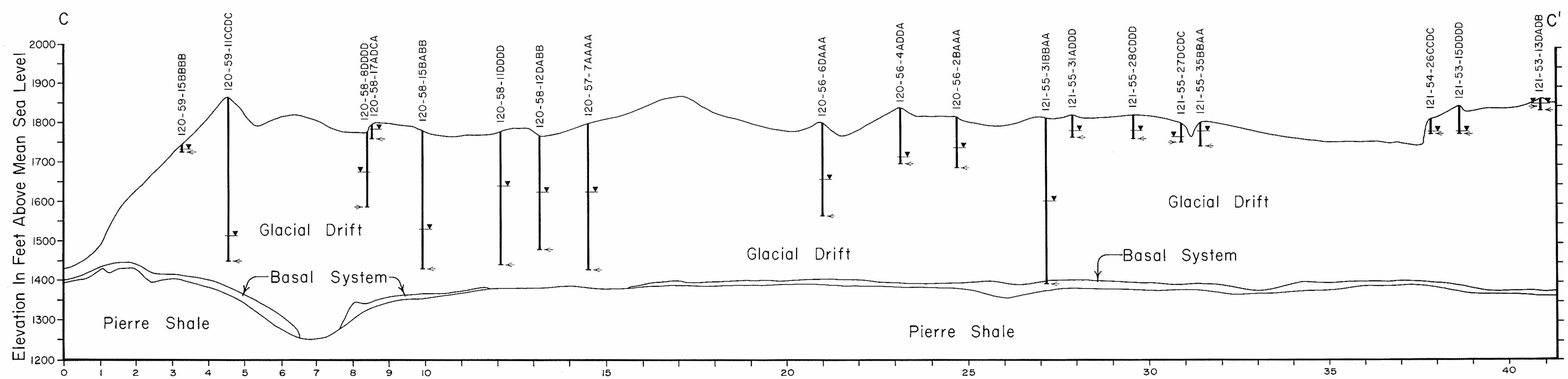
▼ Hydraulic head of well

< Arrow indicates location of well screen

Two hydraulic head and well screen symbols on one well indicate two wells with same legal location.

Vertical exaggeration approximately 40X

WEST ← → EAST



Most farms seem to be able to meet stock and domestic needs through the use of ground water. Some farmers have problems with water of undesirable chemical quality and/or wells of low yield. It is difficult to predict the chemical quality and yield of any new ground-water source but an additional well properly gravel packed and screened should substantially increase most farm water supplies for domestic and stock-watering purposes.

Two suggestions are offered here for improving the yields of wells. First, nearly all wells finished in the Pierre Shale and drift aquifers in Day County are powered by small pump-jack systems which produce perhaps 5 gallons per minute. Most of these wells are constructed of 2- to 3-inch pipe with a 5- to 6-foot length of screen at the bottom. Considerably greater yields could be attained by drilling larger diameter wells (around 4- to 6-inches) with 4- to 6-inch diameter screens. The screen should be gravel packed so that fine material would be filtered out, and properly developed by surging techniques to improve well efficiency. The well could then handle high-capacity submersible pumps. A second suggestion is the construction of multiple aquifer wells. A high-yield well as described above could be drilled through more than one aquifer and each of the aquifers could be screened. Such wells would of course cost more than those presently constructed but should yield considerably more water. There may be some danger of contaminating one aquifer with inferior water of another. This possibility should be weighed against the yield and chemical quality desired.

Irrigation is not yet generally practiced in Day County with the exception of about one-fourth section of land in the southwestern part. One of the purposes of this investigation was to determine if irrigation potential exists in the County and to determine that potential. The results of this study show that irrigation potential by ground water is minimal due to water quality, water quantity, and well yield.

Assuming that an irrigation well should yield a minimum of 500 gallons per minute rules out the possibility of using much ground water for irrigation; few aquifers known at present in the County will produce this amount from single wells. In addition most aquifers contains water too high in dissolved salts to be used for irrigation. A few shallow surface aquifers in the eastern part of the County contain reasonably good water but the supply of water in them is too dependent on seasonal precipitation and their permeabilities are too low to be of extensive use. Holding ponds could be constructed into which water could be pumped when not actually irrigating. This water could be used to supplement irrigation from wells.

The only other available water is found in the many lakes scattered throughout the County. Although the quality of lake water is quite variable from one lake to another several of the large eastern lakes contain water of reasonably good quality for irrigation.

Pengra (1961) computed irrigation needs for Brookings for the years 1942 to 1946 based on the assumption that the amount of irrigation needed should be predicated by the amount of water necessary to maintain soil moisture in the root zone at or above 2 inches of water. During the period of study the average yearly precipitation was 22.15 inches, or .65 inches greater than the Day County average from 1967 to 1972. From similarity in precipitation and other climatic factors the results of Pengra's study at Brookings is extrapolated to Day County to give some idea of irrigation demand and supply for the County. During the period 1942 to 1946 the average yearly total irrigation necessary to maintain 2 inches of soil moisture was 5.11 inches (0.42 feet) of water.

The major lakes in Day County which contains water suitable for irrigation (i.e., water not exceeding a specific conductance of 5,000 micromhos/cm nor sodium absorption ratio of 10.0) include Pickerel, Enemy Swim, SW Waubay, Minnewasta, Spring, Rush, and Blue Dog Lakes where the combined area is approximately 10,500 acres. If these lakes were to be used as sources of irrigation water together they would yield 10,500 acre-feet of water yearly with drawdown of the lake surfaces of 1 foot. Assuming that 0.42 feet of water would be required annually to maintain soil moisture at 2.00 inches then the aforementioned lakes could irrigate 25,000 acres with average drawdown of 1 foot of the lake surfaces or 50,000 acres with 2 feet of drawdown.

An additional small amount could be obtained from the few minor lakes which hold good quality water but hydrographic data for these lakes are too scarce to predict their yield accurately.

In addition to economic and engineering factors such as cost of distribution there are hydrologic and environmental considerations which bear directly on recreational and wildlife demands and which should be carefully studied in implementing irrigation from surface water.

First of all, every major lake with the exception of Pickerel and Enemy Swim lies in ground-water discharge areas of the Basal System. Any significant drawdown of lake levels would probably increase flow from the aquifer into the lakes and in those lakes with lower total dissolved solids it would increase the total dissolved solids of the lake waters. The flow rate of ground water upward into the lakes can be determined with the equation

$$Q = \frac{\Delta h \; P'}{m'} A \qquad (2)$$

where

m' = vertical distance traveled by the water
Δh = head drop across this distance
P' = vertical permeability of the aquifer material
A = horizontal area across which inflow is taking place
Q = rate of flow

Around Bitter and Waubay Lakes h is approximately 50 feet. Lowering the surfaces of these lakes by 1 foot would increase inflow of ground water to them by only 2 percent. However, around Blue Dog Lake h is only 1 foot. If the surface elevation of this lake were decreased 1 foot, ground-water inflow to it would double. The importance of these changes in ground-water inflow to the biochemical balance in the lakes is not known at the present time, but it should be investigated before water from the major lakes is used for irrigation. Secondly, lowering the lake levels too far might prevent their natural discharge and cause a deterioration of quality unless flushing of salts by withdrawal of irrigation water were adequate to reduce salt content of the lakes.

With every irrigation project there is always a drainage problem. Drainage from irrigation on the western slope of the Coteau des Prairies would go mainly into the tributaries of the James River and would be carried out of the County. A small amount of drainage water in this area would collect in closed depressions and evaporate or infiltrate into the drift below.

Drainage water from irrigation in the interior of the Coteau would all go into closed depressions such as potholes and minor lakes and perhaps into the major lakes if irrigation took place within their drainage basins. If this drainage goes back into water bodies from which irrigation water is being taken, salt buildup may take place eventually which could be detrimental to plants and soil and also to the lake water quality. In addition, in areas where there is vertical recharge to the aquifers below the lakes, a deterioration of ground-water quality could take place in time. Therefore, care should be taken in determining irrigation-drainage relationships.

The fourth consideration, the environmental impact, is of special concern in view of the nationwide concern for ecology and environmental protection. Day County is a very ecologically desirable area with its many lakes and marshes supporting abundant fish and wildlife. A considerable amount of revenue comes into the County each year from wetland recreation such as hunting, fishing, and boating. Therefore, careful study should be made of the environmental impact if irrigation from the lakes is to be considered.

The above discussion is not meant to imply that irrigation is certain to be harmful to the environment. Rather, it is hoped that any study of potential irrigation projects will take into consideration the stresses that will be put upon the environment and also the stress limits which the environment can withstand.

RECOMMENDATIONS FOR FURTHER RESEARCH

Further studies of the geology and hydrology of Day County can be grouped under two broad headings; general continuing studies and specific studies.

General continuing studies should include acquisition of data of opportunity; i.e., whenever a hole is drilled for any purpose, information contained from the hole should be used to refine the interpretation given in this study. Such data could be easily obtained in the form of descriptive lithologic logs, borehole geophysical logs, grain-size analyses of drill cuttings and water levels. Water levels are most difficult to determine accurately in an uncased deep hole penetrating more than one aquifer because one can never be certain of which aquifer the water level is representative. Holes which are drilled into important aquifers could be cased with 2-inch internal diameter plastic pipe and fitted with a screen at the bottom for a minimal cost. This added cost would provide very valuable water-level data. Such holes would be of great use east of Pickerel and Enemy Swim Lakes where water-level data for deep aquifers are minimal.

Specific studies include data gathering and analysis for a well-defined problem and/or area. Specific hydrologic studies which would prove useful in Day County are safe yield determination and model studies.

Safe yield or sustained yield is defined by Todd (1964) as ". . . . the amount of water which can be withdrawn annually from a ground-water basin without producing an undesirable result." Undesired results include withdrawing water faster than recharge can replenish it or lowering ground-water levels to the point where costs of pumping become excessive; again, safe yield will be exceeded if pumpage draws water of inferior quality into the well.

Various methods have been developed for determining safe yield. Hill (_in_ Conkling, 1946) plotted annual changes in elevation of ground-water levels against annual draft; safe yield was measured as the draft corresponding to zero change in elevation. Harding evaluated safe yield by plotting total inflow minus total outflow versus annual changes in water level elevation. In this case, maximum outflow which did not produce declining water levels from year to year was taken to be safe yield.

Todd (1959) describes a method based on zero net ground-water level fluctuation. This method consists of first measuring the ground-water elevation at the beginning and end of a period amounting to several years. If the measurements are the same, the safe yield can be interpreted as the average annual net draft on the basin. Admittedly, this technique requires a long time period for accuracy but, in areas where long term records are available, the method can be used to advantage.

The above methods of computing safe yield can be applied in Day County. More specialized methods can be found in Todd (1959) and Kazmann (1956).

Model studies can be used effectively in Day County for determining long-terms effects of pumping in a particular area.

Models may be of the analog or digital type. In the latter case, the model may be constructed by finite difference or finite element techniques.

Once the geology and boundary conditions of a system are known, the model can be programmed to predict the future effects of pumping such as size and shape of the cone of depression, possibility of inflow of low quality water and other effects. Model studies of an area would also prove useful in determining not only horizontal but vertical permeabilities as well.

SUMMARY OF CONCLUSIONS

Important conclusions from the geologic research for this report are summarized below.

1. Above the Precambrian basement the bedrock consists of the Cretaceous sequence (bottom to top), Dakota Sandstone, Graneros Shale, Greenhorn Limestone, Carlile Shale (including Codell Sandstone member), Niobrara Marl, and Pierre Shale. No Paleozoic, Triassic, or Jurassic rocks have been found in Day County.

2. Resting on the Pierre Shale is up to 800 feet of glacial drift of at least three different Pleistocene glaciations which are separated by two buried oxidized zones.

3. The termini of all three glaciations are found in Day County. The first two glaciations (pre-late Wisconsin) came from the east and were stopped by a bedrock ridge in the western part of the County. The last glacier, late Wisconsin, came from the west and terminated along the eastern border of Day County.

4. Between the Pierre Shale and the till is a layer of proglacial outwash up to 115 feet in thickness and covering most of the County.

5. The last drift sheet (late Wisconsin) was emplaced by glacial stagnation as evidenced by numerous moraine plateaus, disintegration ridges, collapsed outwash, and lake sediment. Large shear moraines exist in the western part of the County. Ground moraine is absent throughout the County.

6. Surface outwash (resulting from ablation of stagnant ice) covers several square miles and is an important commodity economically.

7. Several topographically high features in the County were previously believed to be recessional moraines. The results of this study show that none of these features are of recessional origin. The others are now believed to

be end moraines, shear moraines, and stagnation moraines resulting from large thrust sheets of ice out of the James Valley.

8. Previous authors recognized three Wisconsin drifts on the surface of Day County. This study indicates the presence of only one--the late Wisconsin.

9. Previous authors recognized large areas of ground moraine on the surface but this study shows that no ground moraine exists in Day County; all is stagnation moraine.

Important conclusions from hydrologic research are outlined below.

1. Average precipitation is 21 to 22 inches per year. Most runoff from precipitation goes into closed depressions and either evaporates or adds to ground-water recharge. Average potential evapotranspiration from March to October is 22 inches; this amount of actual evapotranspiration never takes place because the soil is seldom if ever fully saturated. Lakes can be expected to lose to evaporation approximately 30 inches of water per year.

2. Streams are all intermittent in Day County. Drainage is all internal except along the western edge of the Coteau des Prairies where streams drain into the James River, and around Lonesome Lake in the southeast corner of the County where drainage may go to the Big Sioux River during periods of high water levels.

3. Approximately 43,400 acres or 6 percent of the area of Day County is comprised of lakes and sloughs. Of this acreage approximately 20,600 acres are distributed among major lakes in the eastern part of the County which hold approximately 165,000 acre-feet of water. Lake levels are highest in May and lowest in November.

   Major lakes are connected hydraulically through surface- and ground-water flow. Bitter and NE Waubay Lakes are sinks for the major lake system.

4. Chemistry of surface water may vary from 200 to 25,000 parts per million total dissolved solids. Lakes having best water for irrigation are Pickerel, Enemy Swim, SW Waubay, Minnewasta, Spring, Rush, and Blue Dog.

5. Four aquifer systems were found to exist in Day County. They are the Bedrock, Basal, Intermediate, and Surface Systems.

   In the Bedrock System the lowest aquifer is the Dakota, composed of the Dakota Formation. This aquifer ranges from 150 to 200 feet in thickness and contains water of a sodium sulfate type. Wells finished in the Dakota seldom yield more than 3 gallons per minute. Few of the wells flow; most have to be pumped.

The second bedrock aquifer is the Pierre composed of Pierre Shale. This aquifer yields water from about 10 to 20 feet of its weathered and fractured upper part. Well yields from the Pierre average 3 to 5 gallons per minute. The water chemistry is of a calcium-magnesium sulfate type. The Pierre is in hydraulic contact with the Basal aquifer above it. The hydraulic gradient of the Pierre is from northeast to southwest.

Both the Dakota and Pierre aquifers are undesirable from the standpoints of yield and/or chemistry and should not be used if better sources are available.

The Basal System is composed of a layer of outwash resting immediately upon the Pierre Shale. The aquifer ranges in thickness from a few feet to a maximum of 115 feet. Permeabilities are generally low ranging from 40 to 250 gpd/ft squared except in the northwest part of the County where a part of the Basal System known as the Lynn Aquifer is composed of material somewhat more permeable than the rest of the System. Water quality in the Basal System is of a calcium-magnesium sulfate chemistry. The hydraulic gradient is from northeast to southwest. In certain areas the Basal System will yield enough water for farm and domestic uses.

The Intermediate System is composed of 49 known aquifers and many more discontinuous layers of sand and gravel. All are comprised of glacial outwash and are located within the drift between the Basal System and the drift surface. Transmissivities of these aquifers range up to 48,500 gpd/ft and the chemical quality is quite variable in total dissolved solids. The chemistry is of a calcium-magnesium sulfate type. Most wells in Day County tap the Intermediate System.

The Surface System is composed of all surface outwash bodies containing water. The largest of these aquifers is the Eastern Lakes Subsystem around the large eastern lakes. The Surface System aquifer ranges in thickness from a few feet to 120 feet. One pump test was performed in the Eastern Lakes Subsystem and yielded a transmissivity of 3,000 gpd/ft. Both the permeability and chemical quality east of the subsystem varies widely. Generally the aquifer east of the large lakes contain lower concentration of dissolved solids than those farther west. The Eastern Lakes Subsystem is not considered a high producer of water.

6. The general flow direction of water in glacial-drift

aquifers and in the Pierre aquifer is from northeast to southwest. Recharge takes place in the eastern highlands and from Pickerel and Enemy Swim Lakes. Some discharge occurs around the other larger lakes. West of the large eastern Lakes recharge is vertical from the surface. Regional flow is controlled by flow in the Basal System and Pierre Aquifer. Intermediate and local flow in the drift is influenced by local highs and lows in the topography. Chemistry of ground water in the drift reflects the influence of vertical recharge in that total dissolved solids tend to increase with increasing depth.

7. Current water demands of stock, domestic, and municipal purposes can be met with use of ground water. Chemical quality of ground water is difficult to predict but well yields can be improved by gravel packing and by use of wells tapping more than one aquifer. Lakes would provide the best water for irrigation from both a chemical quality and quantity standpoint. Pickerel, Enemy Swim, SW Waubay, Minnewasta, Spring, Rush, and Blue Dog Lakes would together yield 10,500 acre-feet of water with 1 foot of drawdown of the lake surfaces. There is a delicate balance in the exchange of water between the lakes and surrounding aquifers. Therefore, care should be taken in determining the environmental effects of potential irrigation projects.

REFERENCES CITED

Antevs, E., 1925, Retreat of the last ice sheet in eastern Canada: Canada Geological Survey Memior 146, 142 p.

Barari, A., 1974, Ground-water investigation for the city of Webster: South Dakota Geological Survey Special Report 57, 28 p.

Bass, N. W., 1926, Kansas Geological Survey Bulletin II.

Bayrock, L. A., 1958, Glacial geology, Galahad-Hardisty district, Alberta: Alberta Research Council Preliminary Report. 57-3, 35 p.

Bedinger, M. S., 1961, Relation between median grain size and permeability in the Arkansas River valley, Arkansas: U.S. Geological Survey Professional Paper 292, p. C-31, Short papers on the geologic and hydrologic sciences, Article 147.

Beffort, J. D., and Hedges, L. S., 1967, Ground water supply for the City of Waubay: South Dakota Geological Survey Special Report 40, 40 p.

Bertallanfy, L. Von, 1968, General system theory: George Braziller Co., 289 p.

Bik, M. J. J., 1967, On the periglacial origin of prairie mounds: North Dakota Geological Survey Miscellaneous Series 30, p. 83-94.

Chamberlin, T. C., 1882, Third annual report: U.S. Geological Survey.

_____ 1896, Journal Geology, v. 4.

Christensen, C. M., 1977, Geology and hydrology of McPherson,

Edmunds, and Faulk Counties, South Dakota, Part I, Geology: South Dakota Geological Survey Bulletin 26.
Christiansen, E. A., 1956, Glacial geology of the Moose Mountain area, Saskatchewan: Saskatchewan Department of Mineral Resources - Report p. 21, 35.
Clayton, L., 1962, Glacial geology of Logan and McIntosh Counties, North Dakota: North Dakota Geological Survey, Bulletin 37.
_____ 1967, Stagnant-glacier features of the Missouri Coteau in North Dakota: in Glacial geology of the Missouri Coteau and adjacent areas, Lee Clayton, and Theodore F. Freers, Chief editors, North Dakota Geological Survey, Miscellaneous Series 30, p. 25-46.
Clayton, L., and Cherry, J. A., 1967, Pleistocene superglacial and ice-walled lakes of west-central North America: North Dakota Geological Survey Miscellaneous Series 30, p. 47-52.
Clayton, L., and Freers, T. F., 1967, Glacial geology of the Missouri Coteau and adjacent areas: North Dakota Geological Survey, Miscellaneous Series 30, 170 p.
Colton, R. B., and Lemke, R. W., 1957, Glacial map of North Dakota: U.S. Geological Survey (unpublished).
Conkling, H., 1946, Utilization of ground-water storage in stream system development: Transactions American Society Civil Engineers, v. III, p. 275-354.
Darton, N. H., 1896, Preliminary report on artesian waters of a portion of the Dakotas: U.S. Geological Survey Annual Report 17, pt. 2, p. 603-694.
_____ 1901, Geology and water resouraces of the southern half of the Black Hills and adjoining regions in South Dakota and Wyoming: U.S. Geological Survey Annual Report 21, pt. 4, p. 489-599.
_____ 1909, Geology and underground waters of South Dakota: U.S. Geological Survey Water-Supply Paper 227.
Domenico, P. A., Stephenson, D. A., and Maxey, G. B., 1964, Ground water in Las Vegas Valley: Desert Research Institute, University of Nevada, Reno, Technical Report 7, 53 p.
Fair, G. M., and Hatch, L. P., 1933, Fundamental factors governing the streamline flow of water through sand: Journal American Water Works Association, 24.
Ferris, J. G., and Knowles, D. B., 1954, Slug tests for estimating transmissibility: U.S. Geological Survey Ground Water Note 26.
Flint, R. F., 1955, Pleistocene geology of eastern South Dakota: U.S. Geological Survey Professional Paper 262.
_____ 1971, Glacial and quaternary geology: John Wiley and Sons, 892 p.
Forgotson, J. M., Jr., 1960, Review and classification of quantitative mapping techniques: American Association Petroleum Geologists Bulletin, v. 44, no. 1, p. 83-100.
Freeze, R. A., and Witherspoon, P. A., 1966, Theoretical analysis of regional groundwater flow; pt. 1, Analytical and numerical solutions to the mathematical model: Water Resources Research, v. 2, no. 4, p. 641-656.
Frye, J. C., and Willman, H. B., 1960, Classification of the

Wisconsin stage in the Lake Michigan glacial lobe: Illinois Geological Survey Circular 285, 16 p.
Geikie, J., 1894, Great ice age, 3rd ed.: Journal Geology, v. 3.
Gilbert, G. K., 1896, U.S. Geological Survey, 17th Annual Report: pt. 2.
Gravenor, C. P., and Kupsch, W. O., 1959, Ice-disintegration features in western Canada: Journal Geology, v. 67, p. 48-64.
Gries, J. P., 1952, Billings Geological Society Guidebook: 3rd Annual Field Conference.
_____ 1954, Cretaceous rocks of the Williston Basin: American Association Petroleum Geologists Bulletin, v. 38, p. 443-545.
Griffith, J. D., 1955, Petrography and petrology of the Cow Run sand, St. Marys, W. Va.: Journal Sedimentary Petrology, 1(1), p. 15-31.
Hansen, D. E., 1967, Geology and ground water resourcs of Divide County, North Dakota, part 1 - geology: North Dakota Geological Survey Bulletin 45, 90 p.
Hantush, M. S., and Jacob, C. E., 1955, Non-steady radial flow in an infinite leaky aquifer: Transaction American Geophysical Union, v. 36(1).
Hattin, D. E., 1965, Stratigraphy of the Graneros Shale in central Kansas: Kansas Geological Survey Bulletin 178.
Hedges, L. S., 1968, Geology and water resources of Beadle County, South Dakota, Part I, Geology: South Dakota Geological Survey Bulletin 18.
_____ 1972, Geology and water resources of Campbell County, South Dakota, Part I, Geology: South Dakota Geological Survey Bulletin 20.
Hopkins, W. B., and Petri, L. R., 1962, Data on wells and test holes, and chemical analysis of ground water in the Lake Dakota Plain area of Brown, Marshall, and Spink Counties, South Dakota: South Dakota State Geological Survey and South Dakota Water Resources Commission, Water Resources Report no. 1, 269 p.
Hoppe, G., 1952, Hummocky moraine regions, with special reference to the interior of Norbotten: Geography Annaler, v. 34, p. 1-72.
_____ 1957, Problems of glacial morphology and the ice age: Geography Annaler, v. 39, no. 1, p. 1-17.
----- 1959, Glacial morphology and inland ice recession in northern Sweden: Geography Annaler, v. 41, no. 4, p. 193-212.
_____ 1963, Subglacial sedimentation, with examples from northern Sweden: Geography Annalaer, v. 45, no. 1, p. 41-49.
Johnson, A. I., 1963, Application of laboratory permeability data: U.S. Geological Survey, open-file report.
Kazmann, R. G., 1956, "Safe yield" in ground water development, reality or illusion?: Proceedings American Society Civil Engineers., v. 82, no. IR3, 12 p.
Koch, N. C., 1972, Major aquifers and sand and gravel resources in Marshall County, South Dakota: South Dakota Geological Survey Water Information Pamphlet no. 1.
_____ 1975, Geology and water resources of Marshall County, South Dakota: South Dakota Geological Survey Bulletin 23, 76 p.
Kohler, M. A., Nordenson, T. J., and Baker, D. R., 1959,

Evaporation maps for the United States: U.S. Weather Bureau Technical Paper 37.
Kozeny, J., 1953, Das wasser in boden, grundwasser bewegung, Hydraulik, p. 380-445.
Krumbein, W. C., and Monk, G. D., 1942, Permeability as a function of the size parameters on unconsolidated sand: American Institute Metallurgical Engineers. Technical Publication 1942.
Kume, J., and Hansen, D. E., 1965, Geology and ground water resources of Burleigh County, North Dakota, part 1 - geology: North Dakota Geological Survey Bulletin 42, 111 p.
Leap, D. I., 1972, Major aquifers and sand and gravel resources in Day County, South Dakota: South Dakota Geological Survey Information Pamphlet no. 3.
_____ 1974, The geology and hydrology of Day County, South Dakota: Ph.D. thesis, Department of Geosciences, The Pennsylvania State University, unpublished, 281 p.
_____ 1986, Geology and water resources of Brown County, South Dakota, Part I, Geology. South Dakota Geological Survey Bulletin 25, 48 p.
Leighton, M. M., 1933, The naming of subdivisions of the Wisconsin glacial age: Science, New Series, v. 77.
Leighton, M. M., and Willman, H. B., 1950, Loess formations of the Mississippi Valley: Journal Geology, v. 58, no. 6.
Lemke, R. W., Laird, W. M., Tipton, M. J., and Lindvall, R. W., 1965, Quaternary geology of northern Great Plains: in the Quaternary of the United States, Review Volume, 7th Congress, International Association Quaternary Research, U.S.A., 1965, H. E. Wright and D. G. Frey, editors, Princeton Univ. Press.
Leverett, F., 1929, Moraines and shore lines of the Lake Superior region: U.S. Geological Survey Professional Paper 154.
_____ 1932, Quaternary geology of Minnesota and parts of adjacent states: U.S. Geological Survey Professional Paper 161.
Masch, F. D., and Denny, K. J., 1966, Grain size distribution and its effect on the permeability of unconsolidated sands: Water Resources Research, v. 2, no. 1, p. 665-677.
McClure, P. F., 1887, Resources of Dakota: Department of Immigration and Statistics, Pierre, South Dakota, 498 p.
Meek, F. B., and Hayden, F. V., 1862, Philadelphia Academy of Natural Science Proceedings, v. 13.
Meek, F. B., in Hayden, F. V., 1876, A report on the invertebrate Tertiary fossils of the upper Missouri Country: Report on the U.S. Geological Survey of the Territories, v. 9.
Parizek, R. R., 1961, Glacial geology of the Willow Bunch Lake area, Saskatchewan: Ph.D. thesis, University of Illinois.
_____ 1967, Glacial ice-contact rings and ridges: Geological Society of America Special Paper 123, INQUA volume, p. 49-102.
Pengra, R. F., 1961, Using climatic water balance to determine irrigation needs in South Dakota: Agricultural Experiment Station, South Dakota State University, Bulletin 496, 24 p.

Rothrock, E. P., 1935, Geology and water resources of Day County, South Dakota: South Dakota Geological Survey, Report of Investigation 25.
_____ 1943, A geology of South Dakota, Pt. 1, The Surface: South Dakota Geological Survey Bulletin 13.
Schoon, R. A., 1971, Geology and hydrology of the Dakota Formation in South Dakota: South Dakota Geological Survey Report of Investigation 104.
Schreurs, R. L., and McGrath, M. P., 1968, History of 1,601 foot deep test hole and shallow production well No. 6 at Webster, South Dakota: Webster Engineering and Development Report no. 1.
Shimek, B., 1909, Geological Society American, Bulletin 20.
Stalker, A. Mac. S., 1960, Ice-pressed drift forms and associated deposits in Alberta: Canada Geological Survey Bulletin 57, 38 p.
Steece, F. V., 1961, Preliminary map of the Precambrian surface of South Dakota: South Dakota Geological Survey Mineral Resources Investigations, map 2.
Steece, F. V., Tipton, M. J., and Agnew, A. F., 1960, Glacial geology of the Coteau des Prairies, South Dakota: in South Dakota Geological Survey Guidebook, 11th Annual Mid-Western Friends of the Pleistocene eastern South Dakota.
Steece, F. V., and Howells, L. W., 1965, Geology and ground water supplies in Sanborn County, South Dakota: South Dakota Geological Survey, Bulletin 17.
Stephenson, D. A., 1967, Hydrogeology of glacial deposits of the Mahomet bedrock valley in east-central Illinois: Illinois State Geological Survey, Circular 409, 51 p.
Stokes, W. L., 1966, Essentials of earth history: Prentice Hall Inc., 2nd ed.
Tester, A. C., 1931, The Dakota stage of the type locality: Iowa Geological Survey, Annual Report of 1929, v. 35, p. 195-332.
Thornbury, W. D., 1969, Principles of geomorphology: 2nd ed.: John Wiley and Sons Inc., 594 p.
Thornthwaite, C. W., 1948, An approach toward a rational classification of climate, Geography Review, v. 38, p. 55-94.
Thorpe, James, and others, 1952, (Map of) Pleistocene eolian deposits of the United States, Alaska, and parts of Canada. Scale 1:2,500,000 (in colors): Geological Society America, New York.
Thwaites, F. T., 1943, Pleistocene of part of northeastern Wisconsin: Geological Society America Bulletin, v. 54.
Tipton, M. J., 1958a, Geology of the Florence quadrangle, South Dakota: South Daokta Geological Survey map.
_____ 1958b, Geology of the Still Lake quadrangle, South Dakota: South Dakota Geological Survey map.
_____ 1959a, Geology of the Chester quadrangle, South Dakota: South Dakota Geological Survey map.
_____ 1959b, Geology of the Dell Rapids quadrangle, South Dakota: South Dakota Geological Survey map.
Todd, D. K., 1959, Groundwater hydrology: John Wiley and Sons Inc., New York, 336 p.
_____ 1964, Groundwater in Handbook of Applied hydrology, sec.

13, p. 1-13, 55, Ven Te Chow (ed.); McGraw Hill, New York.
Todd, J. E., 1909, Description of the Aberdeen-Redfield district: U.S. Geological Survey Geologic Atlas, Folio 165.
Toth, J.A., 1963, A theoretical analysis of groundwater flow in small drainage basins: Journal Geophysical Research, 68, p. 4795-4812.
Townsend, R. C., and Jenke, A. L., 1951, The problem of the origin of the Max moraine of North Dakota and Canada: American Journal Science, v. 249, p. 842-858.
U.S.D.A., 1966, Water and related land resources, James River Basin and designated Missouri River Sub Basins: Report based on a cooperative survey by the South Dakota Water Resources Comm., Oahe Conservancy Sub-District, Lower James Conservancy Sub-District and the U.S. Department Agriculture, 136 p.
Veihmeyer, F. J., 1964, Evapotranspiration: in Chow, Van Te, editors Handbook of applied hydrology: McGraw Hill, p. 11, 1-11, 38.
Walton, W. C., 1962, Selected and analytical methods for well and aquifer evaluation: Illinois State Water Survey, Bulletin 49, 81 p.
Wilcox, L. V., 1955, Classification and use of irrigation waters: U.S. Department Agriculture Circular, no. 969, 19 p.
Winters, H. A., 1963, Geology and ground water resources of Stutsman County, North Dakota: North Dakota Geological Survey, Bulletin 41, 84 p.
Wood, A., and Hedges, L. S., 1964, Ground water supply for the city of Langford: South Dakota Geological Survey Special Report 29.

APPENDIX A. Chemical analyses of lake waters, Day County, South Dakota

Hardness reported in grains per gallon, specific conductance in micromhos/cm at 25 degrees C. All other analyses with exception of pH in parts per million. All surface-water analyses by the South Dakota Geological Survey. See figure 37 for locations of samples.

Sample No. (1)	Total dissolved solids (2)	Hardness (3)	Calcium (4)	Magnesium (5)	pH (6)	Chloride (7)	Sulfate (8)	Iron (9)	Manganese (10)	Carbonate (11)	Bicarbonate (12)	Nitrate (13)	Sodium (14)	Potassium (15)	Specific Conductance (16)
1970 SAMPLES															
1	4972	2620	20	627	8.0	94	3720	.02	.20	93.0	462	3.0	292	163	-----
3	256	224	30	37	7.6	2	30	.03	.0	10.1	230	2.0	7	9	-----
5	214	124	22	17	7.8	1	5	.10	.13	38.8	153	5.5	3	14	-----
6	3550	1710	126	341	8.3	18	2450	.10	.30	-----	620	5.0	303	119	-----
9	3254	1190	82	240	7.9	95	1840	.11	.46	166.	578	3.0	400	157	-----
10	1426	758	57	150	8.0	37	525	.18	.35	42.4	443	6.0	103	66	-----
13	1952	710	78	126	7.7	35	969	.27	.35	113.	504	6.0	300	88	-----
15	308	196	28	31	7.5	5	33	.16	.13	138.	113	5.5	10	23	-----
17	1164	610	82	99	8.1	19	331	.06	.23	121.	515	4.0	106	46	-----
18	1144	700	83	120	7.9	16	350	.17	.35	74.8	520	4.5	72	55	-----
19	876	538	90	76	7.9	19	256	.03	.20	115.	389	1.0	39	36	-----
21	392	197	32	29	8.0	9	79	.06	.20	24.2	234	1.0	29	32	-----
22	288	226	25	40	7.8	2	35	.02	.05	22.2	214	2.0	6	8	-----
25	1840	1040	82	204	7.9	66	825	.18	.30	101.	646	5.0	129	70	-----
26	176	139	25	19	7.5	1	4	.03	.0	-----	169	3.0	4	4	-----
27	596	312	62	38	7.6	12	188	.12	.25	25.0	314	5.0	40	32	-----
29	718	329	49	51	9.0	32	63	.06	.13	-----	398	7.0	84	40	-----
31	6400	2770	118	604	7.5	66	5180	.17	.49	-----	317	5.0	60	138	-----
33	518	380	45	65	7.7	7	104	.03	.07	-----	313	4.0	16	16	-----
35	1472	640	129	78	8.0	25	425	.16	.23	28.2	660	4.5	124	62	-----
37	316	235	43	32	7.9	5	26	.13	.28	13.7	252	5.0	6	8	-----
39	18374	7460	225	1680	9.3	285	11000	.12	.25	282.	425	4.5	1441	357	-----
41	4332	2580	62	591	8.1	59	3290	.10	.09	101.	513	1.5	132	132	-----
42	1032	602	71	104	7.8	9	450	.03	.23	44.4	278	1.0	35	34	-----
44	1504	834	65	164	8.1	49	288	.22	.51	168	714	3.5	118	88	-----
46	424	269	22	52	7.8	3	60	.12	.09	22.6	307	3.5	20	26	-----
47	578	363	33	69	8.2	7	144	.10	.23	12.9	324	2.5	26	24	-----
49	4342	1600	174	285	7.6	116	3450	.05	.43	88.8	423	2.0	518	171	-----
50	3180	1400	36	320	9.1	67	2300	.06	.13	97.0	362	5.0	323	119	-----
54	2412	1220	78	250	7.8	55	1520	.03	.20	68.6	407	3.0	142	118	-----
55	2628	1280	138	228	8.0	42	1350	.17	.30	88.8	788	5.0	248	71	-----
56	5964	3160	106	706	8.1	142	4500	.07	.20	-----	551	4.5	321	181	-----
57	172	149	38	14	8.0	3	6	.08	.13	-----	222	4.0	4	24	-----
59	540	246	43	34	7.7	1	101	.12	.23	27.4	306	2.0	50	19	-----
61	320	190	27	30	7.8	6	58	.19	.20	63.8	206	3.5	20	19	-----
62	19690	9180	40	2210	8.2	545	14500	.03	.20	334.	943	2.5	1375	428	-----

1970 SAMPLES -- continued.

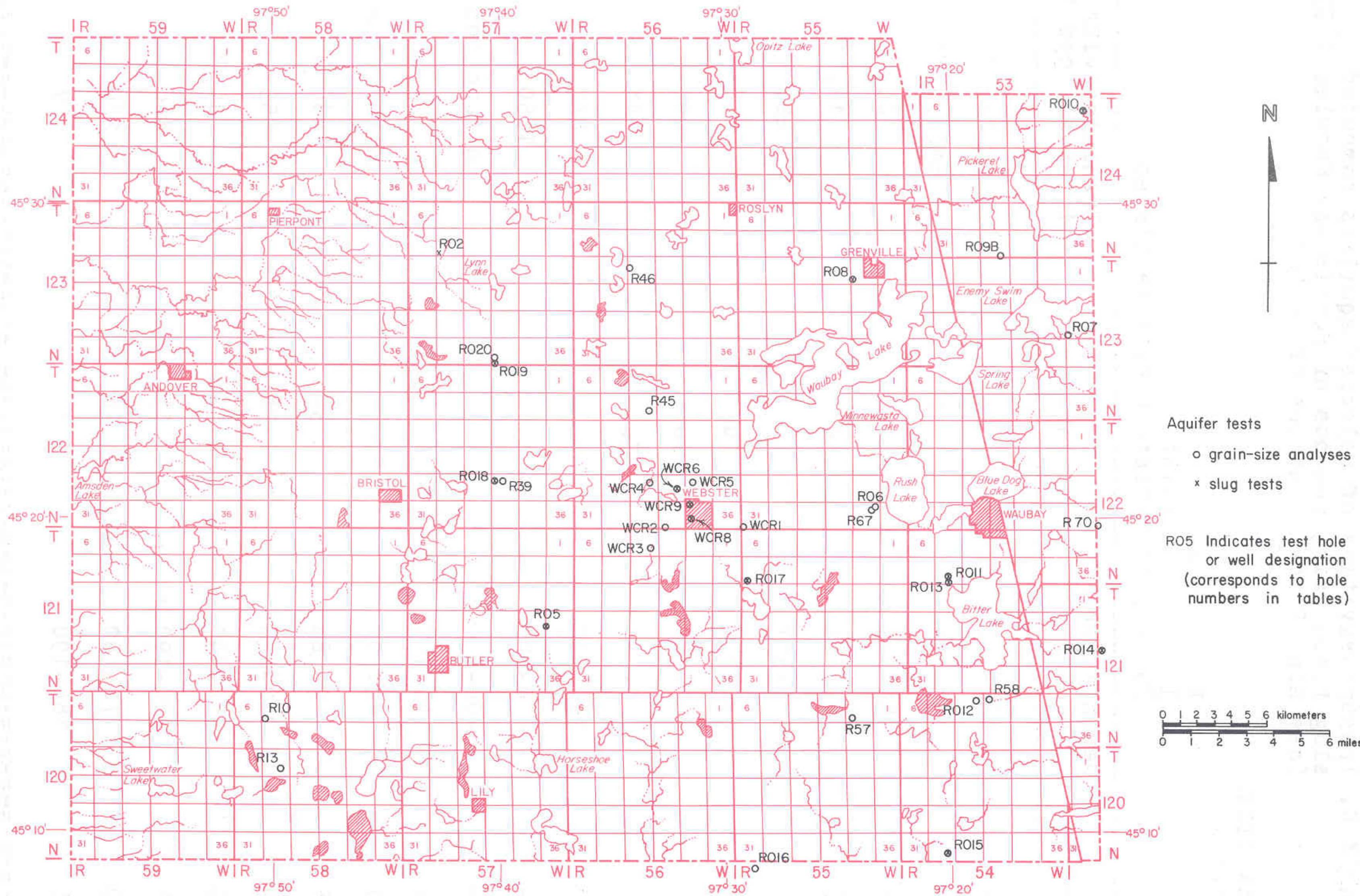
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
63	906	449	62	72	8.0	10	178	.26	.17	17.8	605	5.0	97	---	-----
64	4722	1400	66	301	7.9	138	3580	.29	.63	170.	557	4.0	82	43	-----
65	13434	6280	140	1450	7.7	265	7000	.11	.40	272.	717	4.5	763	150	-----
66	988	425	84	53	8.2	38	488	.02	.13	-----	176	8.0	103	300	-----
67	230	181	40	20	7.5	6	7	.15	.05	19.4	208	6.5	4	13	-----
68	1518	712	44	147	7.9	35	638	.21	.35	34.4	413	4.0	116	8	-----
69	656	422	65	64	7.7	11	256	.16	.09	17.2	267	5.0	21	81	-----
70	1072	508	66	84	7.9	3	312	.16	.58	64.6	389	6.5	100	27	-----
72	582	369	39	67	7.9	---	225	.20	.20	75.8	211	3.0	26	40	-----
74	2740	1460	56	322	7.9	114	1700	.11	.30	24.2	489	4.0	156	26	-----
75	602	311	36	54	7.8	2	175	.08	.20	-----	325	3.0	40	81	-----
76	240	224	55	22	7.9	4	32	.07	.17	-----	246	4.5	6	34	-----
78	588	392	87	42	7.8	7	144	.09	.11	15.4	317	5.0	21	9	-----
79	5924	3080	42	726	7.9	134	4550	.03	.05	105.	466	3.0	313	27	-----
80	486	267	59	30	7.7	8	119	.12	.20	-----	258	7.0	17	169	-----
81	840	516	45	99	7.7	9	325	.24	.30	66.6	285	5.0	36	39	-----
84	294	233	17	47	8.0	4	8	.18	.25	9.7	306	5.5	15	41	-----
85	4548	2120	180	408	7.4	52	3880	.19	.49	-----	321	5.0	300	11	-----
86	664	494	79	72	8.4	1	281	.17	.05	33.2	184	4.0	28	112	-----
87	19180	9220	114	2180	8.4	526	6800	.15	.09	234.	893	4.0	1406	24	-----
88	486	364	53	56	8.4	21	140	.03	.13	-----	336	6.0	15	20	-----
89	204	201	40	25	8.1	3	37	.08	.09	-----	205	2.5	6	6	-----
90	11800	5450	173	1220	8.1	231	7000	.39	.59	-----	670	5.0	1125	393	-----
91	10600	4420	112	1010	8.5	228	6000	.03	.13	22.2	233	5.0	1125	250	-----
92	702	449	50	79	7.9	18	80	.08	.13	24.2	460	3.0	29	51	-----
94	296	221	68	13	7.7	4	43	.08	.13	-----	237	3.0	10	21	-----
95	2684	1600	38	367	8.3	62	1480	.09	.25	129.	681	1.5	174	100	-----
96	2108	900	60	183	7.8	35	1360	.12	.33	133.	442	2.0	231	64	-----
98	452	234	78	10	8.3	17	50	.15	.20	-----	327	5.0	28	45	-----
99	832	489	45	92	8.7	37	104	.08	.20	-----	468	6.0	26	74	-----
100	1316	838	60	168	7.8	32	494	.10	.09	-----	514	6.0	66	57	-----
101	228	165	40	16	7.8	1	17	.17	.02	-----	214	5.0	3	27	-----
102	458	249	49	31	7.8	10	110	.07	.20	-----	249	2.0	34	27	-----
104	254	205	48	21	7.8	2	36	.07	.09	-----	213	3.0	4	4	-----

1971 SAMPLES

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
1	234	161	32	20	9.3	3	2	.18	.23	51.6	76	---	6	18	237
2	436	288	48	41	9.0	4	125	.06	.07	16.7	146	.9	12	14	428
3	2862	1550	165	278	8.2	41	1538	.13	.23	35.0	406	1.1	141	94	2210
4	1986	1100	19	257	8.9	30	1075	.06	.20	102.	273	1.5	112	78	1680
5	384	268	57	31	8.4	6	15	.08	.30	22.8	207	1.4	9	27	441
6	816	486	59	83	8.9	21	69	.05	.68	109.	336	1.6	33	55	736
7	412	249	56	27	8.5	12	15	.11	.11	24.4	193	1.3	13	37	418
8	684	422	75	57	8.6	4	238	.11	.20	39.6	164	1.3	33	14	654
9	578	361	74	43	8.6	8	89	.06	.25	32.0	211	1.1	18	29	550
10	522	288	53	38	8.3	19	20	.05	.07	38.0	258	.8	28	46	542
11	440	266	50	35	7.9	5	13	.05	.20	25.8	214	1.1	9	39	434
12	976	515	98	66	8.4	17	580	.03	.05	32.0	134	1.1	84	11	900
13	1006	512	96	67	8.5	16	590	.03	.00	25.8	132	1.0	84	11	908
14	266	117	23	15	10.0	3	9	.02	.03	48.6	51	.6	14	16	242
15	846	400	56	64	8.3	5	250	.01	.20	28.8	254	1.1	67	43	772
16	988	505	70	80	8.5	17	345	.02	.11	27.4	250	1.9	75	45	900
17	426	271	53	34	7.6	3	23	.03	.17	25.8	200	1.3	14	34	435
18	2480	1250	118	233	8.4	23	1360	.06	.33	10.6	184	2.1	128	75	1890

1971 SAMPLES -- continued.

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
19	772	359	36	66	8.2	17	98	.07	.25	42.6	339	1.9	84	46	862
20	1514	734	95	121	8.3	3	712	.05	.25	16.7	255	2.8	119	31	1290
21	978	515	77	79	7.8	15	540	.03	.13	18.2	183	1.3	60	33	900
22	1708	842	107	140	8.6	15	925	.03	.25	-----	160	2.5	103	53	1350
23	1822	800	59	159	8.4	31	762	.06	.37	70.0	349	1.5	156	75	1540
24	3136	1300	43	291	8.7	48	2080	.02	.30	94.2	237	.9	327	91	2500
25	7492	3090	299	572	9.1	94	3900	.03	.13	6.1	132	1.0	655	231	5050
26	918	471	49	85	8.6	19	406	.03	.09	42.6	190	1.0	69	44	945
27	590	368	58	55	8.6	9	71	.06	.17	51.6	269	1.0	30	24	596
28	1360	649	75	112	8.4	24	494	.09	.13	53.2	346	1.5	116	53	1180
29	1364	676	70	122	8.3	27	500	.12	.13	57.8	371	2.0	110	56	1210
30	4280	1360	125	256	7.9	63	2900	.03	.09	88.2	265	1.1	733	88	3270
31	25104	9540	323	2130	8.4	474	15400	.08	.20	60.8	167	1.3	2250	500	13600
32	4960	2450	57	563	8.6	84	3150	.07	.13	116.	261	.6	406	94	3320
33	1482	852	38	185	8.8	15	838	.06	.23	32.	184	1.5	45	36	1220
34	6644	3380	113	756	9.4	128	3700	.05	.13	140.	178	2.5	329	156	4180
35	5828	2970	198	604	9.0	57	3600	.06	.11	30.4	175	2.5	284	138	3700
36	3462	1790	238	292	8.0	11	2200	.03	.27	-----	140	1.0	142	66	2380
37	276	198	28	31	8.6	5	48	.07	.03	25.8	109	1.4	6	6	316
38	6220	3200	65	741	7.9	140	3650	.03	.17	97.2	310	1.1	316	175	4270
39	7184	3660	102	831	7.5	151	4150	.02	.13	137.	342	1.0	348	208	4760
40	3158	1640	51	369	8.3	125	1580	.03	.05	68.4	279	1.0	206	94	2480
41	2864	1610	19	381	8.6	54	1710	.11	.07	158.	458	1.0	142	94	2240
42	3266	781	52	159	8.3	22	525	.03	.05	78.	231	1.0	36	39	1130
43	660	444	66	69	7.7	5	202	.05	.20	22.8	213	1.0	15	13	641
44	794	483	61	81	7.6	11	215	.33	.07	12.2	260	8.3	23	34	749
45	490	293	68	31	8.7	4	71	.09	.05	60.8	161	1.1	18	20	442
46	2820	1420	119	274	7.9	151	1750	.05	.11	70.0	281	.5	168	69	2270
47	3060	1490	88	310	8.3	67	2200	.06	.09	09.	203	.5	161	138	2350
48	406	244	56	26	7.2	2	33	.07	.03	19.8	204	.9	7	34	408
49	522	325	47	51	8.6	4	142	.07	.13	46.6	175	1.3	19	26	492
R 1	732	458	68	71	8.0	6	162	.03	.09	29.6	308	2.6	28	28	-----
R 2	690	434	70	64	8.0	11	124	.06	.03	64.8	340	2.4	21	49	-----
R 3	4436	2760	52	642	8.0	59	3050	.07	.03	102.	404	3.0	132	142	-----
R 4	1106	533	122	56	8.2	34	640	.05	.07	26.8	144	1.0	106	9	-----
R 5	9208	3640	192	771	8.6	246	5920	.08	.07	93.0	251	2.9	1190	250	-----
R 6	656	250	37	39	8.8	7	238	.09	.07	56.4	185	2.1	74	21	-----
R 7	6296	3100	110	689	9.1	64	4100	.05	.13	147.	135	.9	376	100	-----
R 8	19748	9490	291	2140	8.4	295	1900	.01	.03	90.2	106	1.6	1750	375	-----
R 9	502	338	53	50	8.0	5	119	.02	.03	16.9	214	.8	14	15	-----
R10	5324	3020	35	715	8.8	100	3550	.02	.07	189.	29	1.1	288	150	-----
R11	306	239	32	39	8.4	3	31	.03	.07	24.0	189	1.5	6	8	-----
R12	286	223	47	26	8.1	4	34	.03	.00	11.3	186	1.1	4	4	-----
R13	24240	12100	31	2930	8.7	630	14200	.06	.13	440.0	90	2.3	1620	469	-----
R14	361	198	30	30	7.5	5	34	.09	.17	-----	161	1.8	12	25	-----
R15	2036	1120	71	230	8.6	58	888	.01	.11	74.8	298	1.0	128	75	-----



Appendix B. Map showing locations of aquifer tests.

APPENDIX C. Transmissivities of selected aquifers computed by slug tests using methods of Ferris and Knowles (1954) (see app. B for locations of tests)

EXPLANATION:

Aquifers

B = Basal
I = Intermediate
Iu = Intermediate undifferentiated

Hole	Depth interval tested	Aquifer	Transmissivity of interval (gpd/ft)
RO 2	180-190	B	149.0
RO 5	270-275	I 16	malfunction
RO 6	50- 60	I 24	20.2
RO 7	70- 80	Iu	13.7
RO 8	370-377	B	227
RO 10	290-300	Iu	158.9
RO 11	30- 40	Iu	2090
RO 12	80- 85	Iu	141
RO 13	360-370	B	840
RO 14	290-300	I 1	1650
RO 15	400-410	Iu	malfunction
RO 16	140-150	I 5	116
RO 17	50- 60	Iu	malfunction
RO 18	70- 80	I 33	1480
RO 19	210-220	I 38	555
RO 20	330-340	B	40.2
WCR 8	180-190	I 17	886
WCR 9	70- 80	I 18	286
WCR 6	180-190	I 17	197

APPENDIX D. List of grain-size analyses of selected aquifers in Day County, South Dakota, and permeabilities and transmissivities computed from the grain-size parameters by method of Masch and Denny (1966) (see app. B for locations of tests)

EXPLANATION:

Aquifers
- B = Basal
- I = Intermediate (number indicates which intermediate aquifer) (see figs. 42, 43, and 44 for locations)
- Iu = Intermediate undifferentiated

Abbreviations
- P.C. = Laboratory coefficient of permeability (obtained graphically by method of Masch and Denny (1966))
- I.W. = Interval width (thickness of zone analyzed)
- T = Transmissivity (T = (P.C.) x (I.W.))

Hole No. (1)	Location T. (2)	R. (3)	sec. (4)	Depth Interval From (5)	To (6)	Aqui-fer (7)	Median size Phi (8)	Dis-per-sion (9)	P.C. (10)	I.W. (11)	T. (12)	
R 10	120	58	5 SW SW SW	30	40	Iu	2.50	2.41	68	10	680	
R 13	120	58	17 NE NE NE SE	470	480	B	- .25	2.07	90	10	900	1,950
R 13	120	58	17 NE NE NE SE	480	490	B	.25	2.89	50	10	500	
R 13	120	58	17 NE NE NE SE	490	500	B	.15	2.81	55	10	550	
R 39	122	57	27 NE NE NE NW	70	80	I 33	-1.25	2.80	45	10	450	4,350
R 39	122	57	27 NE NE NE NW	320	330	B	.87	2.61	60	10	600	
R 39	122	57	27 NE NE NE NW	330	340	B	1.05	2.60	60	10	600	
R 39	122	57	27 NE NE NE NW	340	350	B	1.25	2.38	65	10	650	
R 39	122	57	27 NE NE NE NW	350	360	B	.60	1.36	250	10	2,500	
R 44	123	57	34 SW SW SW SW	320	330	B	1.10	2.45	65	10	650	1,250
R 44	123	57	34 SW SW SW SW	330	340	B	1.80	2.58	60	10	600	
R 45	122	56	9 SE SE SE NE	380	390	B	.80	2.52	60	10	600	1,200
R 45	122	56	9 SE SE SE NE	390	400	B	1.22	2.60	60	10	600	
R 46	123	56	16 SW SW SW NW	390	400	B	0.00	2.20	70	10	700	1,600
R 46	123	56	16 SW SW SW NW	400	410	B	- .20	1.99	90	10	900	
R 57	120	55	2 SE SE SW SW	200	210	Iu	0.00	2.00	90	10	900	
R 57	120	55	2 SE SE SW SW	440	450	B	0.05	2.13	75	10	750	
R 58	120	54	3 NW NW NW NW	120	130	Iu	.75	2.58	60	10	600	

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	
R 58	120	54	3 NW NW NW NW	130	140	Iu	1.25	2.33	65	10	650	1,250
R 67	122	55	35 NE NE NE	40	50	I 24	.40	1.65	140	10	1,400	
R 67	122	55	35 NE NE NE	50	60	I 24	.76	1.12	360	10	3,600	
R 67	122	55	35 NE NE NE	60	70	I 24	.40	1.31	260	10	2,600	
R 67	122	55	35 NE NE NE	70	80	I 24	- .50	1.93	90	10	900	10,300
R 67	122	55	35 NE NE NE	80	90	I 24	-1.52	2.43	50	10	500	
R 67	122	55	35 NE NE NE	90	100	I 24	.55	2.33	65	10	650	
R 67	122	55	35 NE NE NE	100	110	I 24	.24	2.35	65	10	650	
R 70	122	52	19 SW SW SW SW	290	300	I 1	- .02	1.87	100	10	1,000	
R 70	122	52	19 SW SW SW SW	300	310	I 1	.80	2.47	60	10	600	1,600
WCR 1	122	55	31 SW SW SW SW	230	240	I 17	-1.95	2.14	80	10	800	
WCR 2	122	56	34 SW SW SE SW	390	400	B	.45	2.45	60	10	600	
WCR 2	122	56	34 SW SW SE SW	400	410	B	.60	2.32	65	10	650	1,250
WCR 3	121	56	4 NE SE NE SE	10	20	Iu	.74	1.74	120	10	1,200	
WCR 4	122	56	28 NE NE NE NE	210	220	I 17	- .80	1.68	170	10	1,700	
WCR 4	122	56	28 NE NE NE NE	220	230	I 17	- .12	1.70	150	10	1,500	4,100
WCR 4	122	56	28 NE NE NE NE	230	240	I 17	.40	1.98	90	10	900	
WCR 4	122	56	28 NE NE NE NE	420	430	Iu	-1.10	1.62	200	10	2,000	
WCR 5	122	56	26 NE NE NE NW	160	170	I 17	-1.85	1.51	310	10	3,100	
WCR 5	122	56	26 NE NE NE NW	170	180	I 17	- .95	2.21	70	10	700	3,800
WCR 5	122	56	26 NE NE NE NW	200	210	Iu	0.00	1.61	160	10	1,600	
WCR 5	122	56	26 NE NE NE NW	360	370	Iu	.62	2.65	55	10	550	2,150
WCR 6	122	56	27 SE SE SE NE	170	180	I 17	-1.37	0.85	3,100	10	31,000	
WCR 6	122	56	27 SE SE SE NE	180	190	I 17	- .85	1.38	370	10	3,700	41,500
WCR 6	122	56	27 SE SE SE NE	190	200	I 17	-1.10	1.25	680	10	6,800	
WCR 8	122	56	35 NE SE NE NW	170	180	I 17	-2.01	1.72	170	10	1,700	
WCR 8	122	56	35 NE SE NE NW	180	190	I 17	-1.08	2.48	58	10	580	2,280
WCR 9	122	56	35 SE NW NE NW	50	60	I 18	2.30	1.21	135	10	1,350	
WCR 9	122	56	35 SE NW NE NW	70	80	I 18	.75	1.32	240	10	2,400	6,750
WCR 9	122	56	35 SE NW NE NW	80	90	I 18	.81	1.50	300	10	3,000	
RO 5	121	57	24 NW NW SW	260	270	I 16	4.39	3.84	65	10	650	
RO 5	121	57	24 NW NW SW	270	275	I 16	3.10	4.04	55	5	275	1,200
RO 5	121	57	24 NW NW SW	275	280	I 16	2.48	4.03	55	5	275	
RO 6	122	55	35 NE NE NE NE	0	10	I 24	.80	2.65	58	10	580	
RO 6	122	55	35 NE NE NE NE	10	20	I 24	1.25	2.20	72	10	720	
RO 6	122	55	35 NE NE NE NE	20	30	I 24	.25	1.67	140	10	1,400	
RO 6	122	55	35 NE NE NE NE	30	40	I 24	1.30	2.08	80	10	800	8,830
RO 6	122	55	35 NE NE NE NE	40	50	I 24	-1.20	2.04	88	10	880	
RO 6	122	55	35 NE NE NE NE	50	60	I 24	- .10	1.54	200	10	2,000	

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	
RO 6	122	55	35 NE NE NE NE	50	70	I 24	.30	1.51	180	10	1,800	
RO 6	122	55	35 NE NE NE NE	70	80	I 24	- .10	2.28	65	10	650	
RO 7	123	53	13 SW SW SW SW	70	80	Iu	- .75	1.83	100	10	1,000	
RO 8	123	55	14 SW SW SW SW	370	377	B	1.30	2.83	56	7	392	
RO 9B	124	53	33 SE SE SE SE	10	20	Iu	-1.10	2.92	46	10	460	
RO 9B	124	53	33 SE SE SE SE	20	30	Iu	.65	3.72	45	10	450	2,070
RO 9B	124	53	33 SE SE SE SE	30	40	Iu	1.20	3.28	52	10	520	
RO 9B	124	53	33 SE SE SE SE	40	50	Iu	.80	2.38	64	10	640	
RO 9B	124	53	33 SE SE SE SE	60	70	I 40	1.00	3.53	50	10	500	
RO 9B	124	53	33 SE SE SE SE	70	80	I 40	1.50	3.94	45	10	450	
RO 9B	124	53	33 SE SE SE SE	80	90	I 40	.35	3.09	50	10	500	2,300
RO 9B	124	53	33 SE SE SE SE	90	100	I 40	1.65	4.01	35	10	350	
RO 9B	124	53	33 SE SE SE SE	100	110	I 40	2.70	3.85	50	10	500	
RO 10	124	53	1 SE SE SE SE	290	300	Iu	-1.10	3.07	45	10	450	
RO 11	121	54	8 SW SW SW SE	20	30	Iu	1.15	1.50	150	10	1,500	
RO 11	121	54	8 SW SW SW SE	30	40	Iu	.50	1.36	250	10	2,500	4,900
RO 11	121	54	8 SW SW SW SE	40	50	Iu	1.65	1.87	90	10	900	
RO 12	120	54	4 NE NE NE NE	70	80	Iu	4.85	3.34	65	10	650	
RO 12	120	54	4 NE NE NE NE	80	85	Iu	.30	1.36	250	10	2,500	3,150
RO 13	121	54	8 SW SW SW SE	320	330	B	.63	2.83	50	10	500	
RO 13	121	54	8 SW SW SW SE	330	340	B	0.00	3.32	45	10	450	2,200
RO 13	121	54	8 SW SW SW SE	350	360	B	.75	3.42	50	10	500	
RO 13	121	54	8 SW SW SW SE	360	370	B	1.35	2.11	75	10	750	
RO 14	121	52	18 NW NW NW NW	290	300	I 1	-1.10	1.37	400	10	4,000	
RO 15	120	54	32 SE SE SE SE	390	400	Iu	1.49	2.66	60	10	600	
RO 15	120	54	32 SE SE SE SE	400	410	Iu	1.79	2.72	60	10	600	1,200
RO 16	119	55	6 NE NE NE NE	140	150	I 5	.20	1.32	300	10	3,000	
RO 17	121	55	7 SW SW SW SW	40	50	Iu	1.70	3.10	55	10	550	
RO 17	121	55	7 SW SW SW SW	50	60	Ju	.12	1.95	90	10	900	1,450
RO 18	122	57	27 NE NW NW NW	50	60	I 33	.10	1.64	160	10	1,600	
RO 18	122	57	27 NE NW NW NW	60	70	I 33	.65	1.31	270	10	2,700	5,800
RO 18	122	57	27 NE NW NW NW	70	80	I 33	.30	1.65	150	10	1,500	
RO 19	123	57	34 SW SW SW SW	210	220	I 38	-0.15	2.72	54	10	540	
RO 20	123	57	34 SW SW SW SW	330	340	B	1.55	1.55	140	10	1,400	

APPENDIX E

Permeability prediction from grain-size data

Permeability and storage properties of aquifers are probably the most difficult and expensive parameters to determine accurately due to the necessity of pump tests. In lieu of such tests, many investigators have attempted to predict permeability ranges from grain-size data of the aquifer materials; Krumbein and Monk (1942), Fair and Hatch (1933), Kozeny (1953), Bedinger (1961), Johnson (1963), and Griffith (1955). It was decided to use the method of Masch and Denny (1966) because their method is quite flexible for natural conditions and includes a more flexible arrangement of sedimentary parameters. In addition, the method includes a set of curves for predicting permeability from grain-size data. No grain-size method is accurate enough to predict permeabilities with the precision of a pumping test, but they are useful in predicting ranges of values. The steps by which the aquifer materials were analyzed and used for permeability prediction in this report are listed as follows:

1. Samples from 10-foot intervals were bagged in the field during drilling operations.

2. In the laboratory, the samples were sieved on a rotap and separated in 10 size fractions of phi classes -3.75, -2.75, -1.75, -1.00, 0.00, 1.25, 2.00, 3.00, 4.25, and 8.50.

3. A computer program was written which computed and plotted a cumulative frequency curve on the data for each sample interval.

4. From the cumulative frequency curve phi values corresponding to certain percentiles were read off: Ø5, Ø16, Ø25, Ø50, Ø75, Ø84, Ø95.

5. Next, the following statistics were computed with a computer program from the values obtained in step 4:

   a. Dispersion (inclusive standard deviation)

   $$\sigma_1 = (\phi 84 - \phi 16)/4 + (\phi 95 - \phi 5)/6.6 \qquad (3)$$

   The values of this expression range from 0 for very well sorted sediments to 4 for poorly sorted ones.

   b. Inclusive skewness

   $$SKI = (\phi 16 + \phi 84 - 2\phi 50)/2(\phi 84 - \phi 16) + (\phi 5 + \phi 95 - 2\phi 50)/2(\phi 95 - \phi 5) \qquad (4)$$

   This variable describes the degree of assymetry for a given distribution; its value may run from +1 to -1 as the distribution changes from strongly fine skewed to strongly coarse skewed respectively.

c. Peakedness (graphic kurtosis)

$$KG - (\phi 95 - \phi 5)/2.44\ (\phi 75 - \phi 25) \qquad (5)$$

Values of this expression run from 0 for very platykurtic distributions whose extremes are better sorted than their central parts, to approximately 4.5 for very leptokurtic distributions whose central portions are better sorted than their extremes.

6. Finally a set of curves in Masch and Denny (1966, fig. 8) was enlarged to include a wider range of phi values (fig. 1) and by matching values of median grain size and dispersion with similar values on the curves, the permeability for each sample was predicted. Permeability values are tabulated in appendix G.

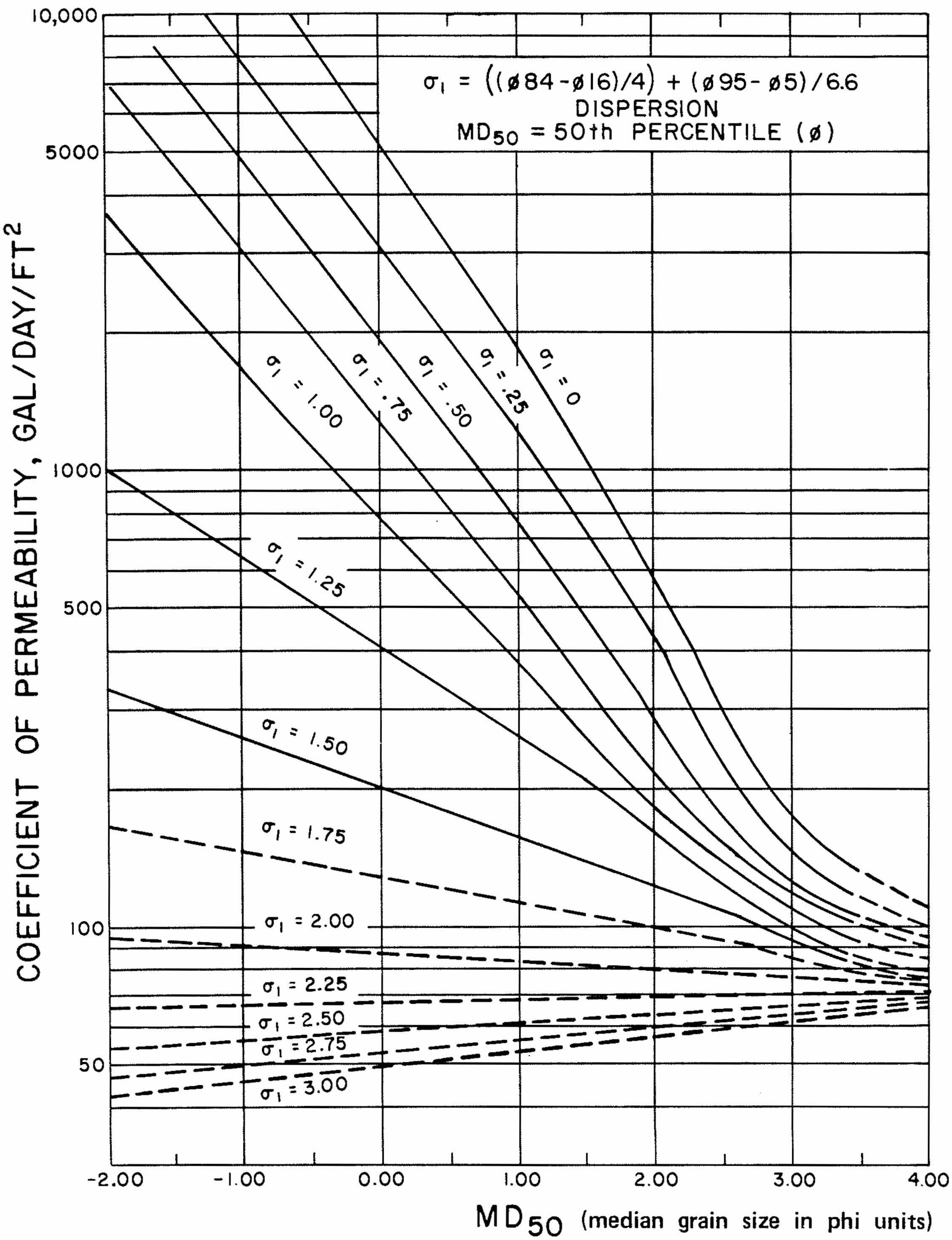


Figure 1. Curves for determining permeability from grain size analyses, after Masch and Denny (1966).

APPENDIX F

Transmissivity determination by hydraulic slug tests

Ferris and Knowles (1954) developed a method of determining transmissivity by the instantaneous injection of a slug of water into a well. Ferris and Knowles reported that the same equations were applicable if instead of injection, a measured slug of water were withdrawn from the well. It was impractical to inject water in the observation wells and a method equivalent to withdrawal was developed.

The observation wells used in this study were constructed with 1-3/4 inch I.D. No. 10 screen, 18 inches long, fitted at the bottom and emplaced in the aquifer to be tested. After a screen was emplaced, approximately 2,000 gallons of water were forced down the pipe, out through the screen and up the hole in order to clean out as much drilling mud as possible. The system was flushed until the water turned clear. Usually, collapse of aquifer sediments around the screen began within a few minutes after flushing began.

Approximately 2 months later the wells were pumped out with an air compressor to remove fine sand and silt which had collected inside the screen.

Testing instrumentation is shown in figure 1. The apparatus for testing consisted of two main parts. The first part, the wellhead manifold, was constructed from a 3-inch tee. The lower opening was attached to the top of the observation well casing. The top opening held a pneumatically-sealable rubber gromett through which ran an 8-channel sensor cable. In the side of the manifold was a compressed air inlet with a control valve and 90 degrees from the inlet was placed an air pressure gauge. The middle opening of the manifold held a blow-off valve which released compressed air from the well instantaneously when its hold-down yoke was knocked loose with a hammer blow.

The second part consisted of a control panel and a 6-volt battery for a power source. The control panel contained a milliampmeter and a 7-channel selector switch. The aforementioned sensor cable ran from the control panel down through the well-head manifold into the water. Each of the eight separate wires in the cable ended in an electrode and were spread at 5-foot intervals for a distance of 35 feet. The bottom electrode was a ground and the others were used to make contact with varying water levels in the wells.

In testing, compressed air was forced into the manifold from a tank until the water level was reduced to the lowest contact electrode (30 feet). After the air was introduced the gauge on the manifold was monitored until the well air pressure fell to a constant value indicating dissipation of the cone of impression.

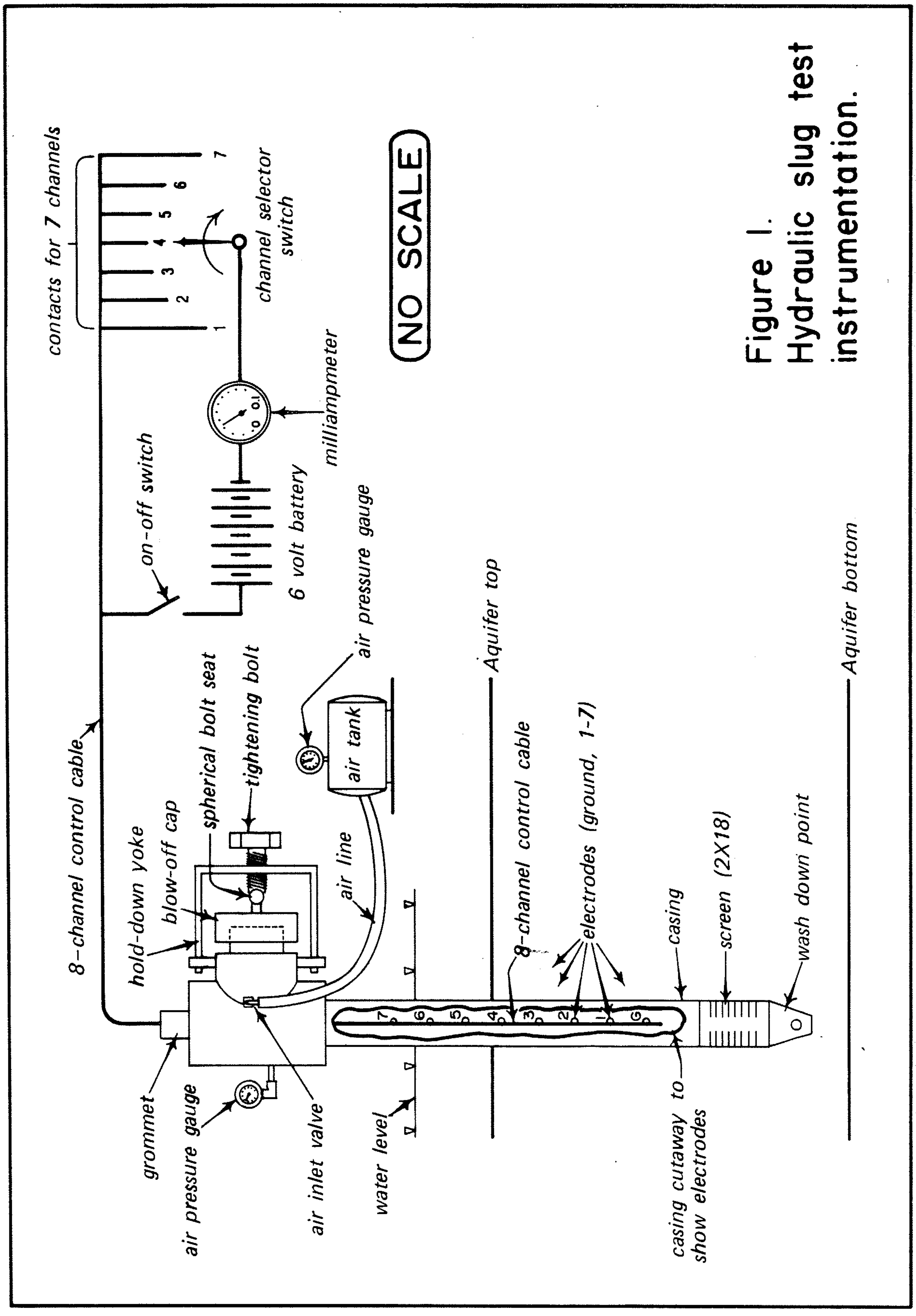


Figure I. Hydraulic slug test instrumentation.

The blow-off cap was released and at the same time a stop watch was started and the times of contact of the rising water level with each electrode were recorded. After the water level contacted one electrode the selector switch was turned to complete the circuit for the next electrode. After the water has risen to its original level, the data were used to compute transmissivity by the method of Ferris and Knowles (1954).

In analyzing the results of tests by this method the following steps were employed:

1. The residual head was computed for each water level measurement. That is, the difference between the measured head and the static head were computed for each measurement.

2. The total elasped time in minutes from start to recovery to time of each water level measurement was recorded and each time value was divided into 1.0 to obtain reciprocals of time for each measurement.

3. On rectangular coordinate paper each residual head value was plotted along the ordinate against its corresponding time reciprocal along the abscissa. The resulting curve was linear for the first three or four points and then became convex: upward for the remaining measurements.

4. An arbitrary point along the straight section of the above curve was chosen and its value of residual head and time reciprocal were inserted into Ferris and Knowles's equation.

$$T = \frac{(114.6)\ (Q)\ (1/tm)}{s} \qquad (6)$$

where

- T = transmissivity in gallons per day per foot
- Q = amount of water in gallons displaced during the test
- tm = time of the chosen measurement in minutes
- s = residual head at time tm in feet

Nineteen observation wells were used in the analyses. Of these, three tests malfunctioned by not allowing the water levels to recover after depression, probably because the screens were plugged by fine sand. Values determined by this method are tabulated in appendix G.

APPENDIX G

Comparison of permeability and transmissivity values computed by grain-size analyses, slug tests, and pump tests

Both grain-size and slug test methods are applicable to small areas, i.e., they do not tell anything about any large area or volume of an aquifer under investigation, but for the small area around the sampled zone or well screen they appear to be fairly accurate.

The slug tests only determine aquifer properties in a cylindrical volume immediately surrounding the well screen; in these investigations a volume 18 inches long and a few inches wide. Therefore, the test results may not be indicative for the entire thickness of the aquifer in this case. Of course, if the screen completely penetrates the aquifer the results should be applicable to the entire aquifer thickness. The grain-size analyses were usually performed on samples from 10-foot section of the aquifer and these results are applicable to greater thicknesses of the aquifer. Pump tests determined transmissivity of a much larger, three-dimensional volume of an aquifer than the other two tests and actually compute an average transmissivity inclusive of many differing local transmissivities in the aquifer.

Table 1 shows a comparison of transmissivity values obtained by all three methods; pump test results are shown only in WCR 8 and WCR 9. The table shows that the closest comparisons between grain-size results and slug tests were obtained from tests in holes RO 8, RO 10, RO 11, RO 13, RO 14, RO 18, RO19, WCR 8, and WCR 6. Over half of the slug tests compare favorably with grain-size tests. The differences between grain-size permeabilities and slug test permeabilities in the remaining tests are probably due to the presence of zones of greatly differing permeabilities within the 10-foot sections. In such cases, the observation well screen might open to a low permeability zone while the grain-size test spanned all permeabilities in the section.

Comparison of pump test transmissivities with those of grain-size analyses in WCR 8 and WCR 9 (table 1) show considerable discrepancy which is probably due to the fact that the aquifer permeabilities varies laterally as well as vertically. The pump tests yield results of a large volume of the aquifer which can be quite different from a small volume analyzed by slug tests or grain-size methods. In WCR 6, in the Lower Webster Aquifer, the transmissivity computed by grain-size analyses was 41,500 gallons per day per foot. Although this location is about a mile from the location of the pump test of the Lower Webster Aquifer, the results of the two tests agree quite well; the pump test showed transmissivity values ranging from 38,000 to 48,500 gallons per day per foot. This closeness of results probably indicates that the materials in the aquifer at the location of WCR 6 is quite representative of the entire Lower Webster Aquifer. Also, in WCR

TABLE 1. Comparison of permeability and transmissivity values obtained from slug tests, grain-size analyses, and pump tests in Day County, South Dakota

(Data are listed for only those holes and intervals in which two or more of the above tests were performed.)

Hole (1)	Depth interval tested (2)	Transmissivity by slug tests (gpd/ft) determined directly (3)	Permeability computed from slug test transmissivities transmissivity/interval width (gpd/ft2) (4)	Permeability from grain-size analysis (gpd/ft2) determined directly (5)
RO 5	260-270	Malfunction	------	65
	270-275	-------	------	55
	275-280	-------	------	55
RO 6	0- 10	-------	------	58
	10- 20	-------	------	72
	20- 30	-------	------	140
	30- 40	-------	------	80
	40- 50	-------	------	88
	50- 60	20.2	2.02	200
	60- 70	-------	------	180
	70- 80	-------	------	65
RO 7	70- 80	13.7	1.37	100
RO 8	370-377	227	32.4	56
RO 10	290-300	159	15.9	45
RO 11	20- 30	-------	------	150
	30- 40	2,090	209	250
	40- 50	-------	------	90

(1)	(2)	(3)	(4)	(5)
RO 12	70- 80	-------	------	65
	80- 85	141	28.2	500
RO 13	320-330	-------	------	50
	330-340	-------	------	45
	350-360	-------	------	50
	360-370	840	84	75
RO 14	290-300	1,650	165	400
RO 15	390-400	-------	------	60
	400-410	Malfunction	------	60
RO 16	140-150	116	11.6	300
RO 17	40- 50	-------	------	55
	50- 60	Malfunction	------	90
RO 18	50- 60	-------	------	160
	60- 70	-------	------	270
	70- 80	1,480	148	150
RO 19	210-220	555	55.5	54
RO 20	330-340	40.2	4.02	140
WCR 6	170-180	-------	------	3,100
	180-190	197	19.7	370
	190-200	-------	------	680
WCR 8	170-180	-------	------	170
	180-190	886	88.6	58
WCR 9	50- 60	-------	------	135
	60- 70	-------	------	-----
	70- 80	286	28.6	240
	80- 90	-------	------	300

Hole (1)	Transmissivity from grain-size permeability (gpd/ft) (permeability x interval width): For interval (2)	For total section (3)	Transmissivity from pump test (gpd/ft) determined directly Total section (4)	Permeability from pump test (Transmissivity/interval width) (gpd/ft2) Average for all intervals (5)
RO 5	650		------	-----
	275	1,200	------	-----
	275		------	-----
RO 6	580		------	-----
	720		------	-----
	1,400		------	-----
	800	8,830	------	-----
	880		------	-----
	2,000		------	-----
	1,800		------	-----
	650		------	-----
RO 7	1,000		------	-----
RO 8	392		------	-----
RO 10	450		------	-----
RO 11	1,500		------	-----
	2,500	4,900	------	-----
	900		------	-----
RO 12	650	3,150	------	-----
	2,500		------	-----
RO 13	500		------	-----
	450		------	-----
	500	2,200	------	-----
	750		------	-----
RO 14	4,000		------	-----

(1)	(2)	(3)	(4)	(5)
RO 15	600		------	-----
	600	1,200	------	-----
RO 16	3,000		------	-----
RO 17	550		------	-----
	900	1,450	------	-----
RO 18	1,600		------	-----
	2,700	5,800	------	-----
	1,500		------	-----
RO 19	540		------	-----
RO 20	1,400		------	-----
WCR 6	31,000		------	-----
	3,700	41,500	------	-----
	6,800		------	-----
WCR 8	1,700			2,425
	580	2,280	48,500	2,425
WCR 9	1,350			500
	------	6,750	20,000	500
	2,400			500
	3,000			500

9 permeability values obtained from grain-size analyses and pump tests are within the same order of magnitude.

In conclusion, it seems that both the grain-size analyses and the slug tests are good methods for determining spot permeabilities. No aquifer tests can surpass a pump test in large-area accuracy but the two methods provide reasonably good information for small areas.

Storage properties are not possible to obtain by these methods, but several such tests throughout an aquifer should provide a reasonable estimate of the average transmissivity of an aquifer. For best results, slug tests should be performed in wells whose screens completely penetrate the aquifer and grain-size samples should be taken of the entire section from top to bottom.

APPENDIX H

Water levels in monitored observation wells in Day County, South Dakota

Wells were installed by the South Dakota Geological Survey
Water levels in feet below land surface
(See fig. 45 for locations of wells)

EXPLANATION:

Aquifers
- B = Basal
- I = Intermediate (number indicates which intermediate aquifer) (see figs. 42, 43, and 44 for locations)
- Iu = Intermediate undifferentiated
- S = Surface system

Well No.	Location Township	Location Range	Section	Elevation	Depth	Aquifer	Date	Water Level
RO 1	124N	56W	2 SE NE NE NE	1829.3	290	Iu	9/ 2/72	214.5
							11/17/72	230.2
							1/26/73	231.1
RO 2	123N	57W	8 SE SW SW SW	1740.4	178	B	6/21/71	126.0
							7/19/71	126.3
							9/ 8/71	126.6
							9/ 2/72	109.5
							11/17/72	123.1
							1/26/73	123.5
RO 5	121N	57W	24 NW NW SW	1801	280	1 16	6/21/71	144.2
							7/22/71	145.6
							9/ 2/72	143.7
							11/17/72	143.7
							1/26/73	143.5
RO 6	122N	55W	35 NE NE NE NE	1789	80	1 24	6/21/71	11.5
							7/20/71	11.0
							9/ 9/71	11.7
							9/ 3/72	8.1
							11/17/72	8.75
							1/25/73	8.5
RO 7	123N	53W	13 SW SW SW SW	1874	81	Iu	6/21/71	17.3
							7/20/71	21.8
							9/ 3/72	19.2
							11/18/72	20.95
							1/26/73	20.65

Well No.	Location Township	Location Range	Section	Elevation	Depth	Aquifer	Date	Water Level
RO 8	123N	55W	14 SW SW SW SW	1850	377	B	6/21/71	49.9
							7/22/71	50.3
							9/ 4/72	49.3
							11/18/72	48.75
							1/26/73	48.8
RO 10	124N	53W	1 SE SE SE SE	2028	300	Iu	6/21/71	162.2
							7/20/71	161.8
							9/ 4/72	160.4
							11/18/72	160.10
							1/26/73	159.95
RO 11	121N	54W	8 SW SW SW SE	1789	60	Iu	6/21/71	7.1
							7/20/71	6.6
							9/13/72	6.2
							11/17/72	6.45
							1/25/73	6.3
RO 12	120N	54W	4 NE NE NE NE	1811	90	Iu	6/21/71	18.2
							7/20/71	20.5
							9/ 9/71	21.89
							9/ 3/72	17.3
							11/16/72	18.1
RO 13	121N	54W	8 SW SW SW SE	1789	370	B	6/21/71	1.4
							7/20/71	1.9
							9/ 3/72	1.4
							11/17/72	1.55
							1/25/73	1.3
RO 14	121N	52W	18 NW NW NW NW	1863	300	I 1	6/21/71	93.6
							7/20/71	93.8
							9/ 3/72	92.1
							11/16/72	91.75
							1/25/73	91.9
RO 15	120N	54W	32 SE SE SE SE	1793	410	Iu	6/21/71	28.5
							7/20/71	33.5
							9/ 3/72	15.3
							11/16/72	15.35
							1/25/73	10.75
RO 16	119N	55W	6 NE NE NE NE	1806	150	I 5	6/21/71	62.1
							7/22/71	61.8
							9/ 3/72	58.7
							11/16/72	60.55
							1/25/73	60.5
RO 17	121N	55W	7 SW SW SW SW	1825	80	Iu	6/21/71	9.6

Well No.	Location Township	Range	Section	Elevation	Depth	Aquifer	Date	Water Level
							7/22/71	9.4
							9/ 2/72	3.7
							11/17/72	5.3
							1/27/73	6.1
RO 18	122N	57W	27 NE NW NW NW	≃1789	85	I 33	6/21/71	22.9
							7/19/71	23.1
							9/ 2/72	24.5
							11/17/72	19.9
							1/26/73	22.8
RO 19	123N	57W	34 SW SW SW SW	1787	230	I 38	6/21/71	120.0
							7/19/71	119.8
							9/ 2/72	124.5
							11/17/72	116.2
							1/26/73	116.1
RO 20	123N	57W	34 SW SW SW SW	1787	341	B	6/21/71	150.2
							7/19/71	177.4
							9/ 2/72	173.0
							11/17/72	175.9
							1/26/73	175.7
W 1	122N	56W	35 NE SE NE NW	1819	200	I 17	9/ 4/72	111.7
							11/18/72	108.75
							1/27/73	108.75
W 2	122N	56W	35 SE NW NE NW	1814	80	I 18	9/ 4/72	26.45
							11/18/72	25.75
							1/27/73	24.50
W 3	122N	56W	27 SE SE SE NE	1834	200	I 17	9/ 4/72	114.6
							11/17/72	119.9
							1/27/73	120.1
A	121N	54W	20 SE SE SE SE	1780	15	S	7/ /70	5.73
							9/22/70	7.50
							10/ 6/70	7.69
							10/22/70	7.74
							11/ 4/70	7.77
							11/17/70	7.22
							12/ 1/70	7.08
							12/15/70	6.72
							12/29/70	6.79
							1/15/71	6.84
							2/ 9/71	7.14
							2/25/71	6.25
							3/10/71	7.23
							3/24/71	7.29

Well No.	Location Township	Range	Section	Elevation	Depth	Aquifer	Date	Water Level
							4/ 6/71	7.04
							4/20/71	7.19
							5/ 4/71	
							5/18/71	4.99
							6/ 1/71	4.94
							9/ 3/72	4.7
							11/17/72	5.6
							1/25/73	5.8
B	121N	54W	9 SW SW NW SW	1800	25	S	7/ /70	13.9
							9/22/70	14.04
							10/ 6/70	14.09
							10/22/70	14.10
							11/ 4/70	14.08
							11/17/70	14.05
							12/ 1/70	14.10
							12/15/70	13.91
							12/29/70	13.81
							1/15/71	13.80
							2/ 9/71	13.80
							2/25/71	13.80
							3/10/71	13.79
							3/24/71	13.80
							4/ 6/71	13.80
							4/20/71	13.85
							5/ 4/71	13.79
							5/18/71	13.90
							6/ 1/71	13.80
							9/ 3/72	13.15
							11/17/72	13.6
							1/25/73	13.85
C	122N	54W	31 NW NE NE NE	1800	10	S	7/ /70	2.75
							9/22/70	3.90
							10/ 6/70	4.30
							10/22/70	3.87
							11/ 4/70	1.99
							11/17/70	pipe gone
D	122N	54W	33 NE NE NE NE	1830	50	S	7/ /70	34.2
							9/22/70	34.90
							10/ 6/70	34.74
							10/22/70	35.00
							11/ 4/70	35.02
							11/17/70	34.94
							12/ 1/70	34.91
							12/15/70	34.71
							12/29/70	34.59
							1/15/71	34.63

Well No.	Location Township	Range	Section	Elevation	Depth	Aquifer	Date	Water Level
							2/ 9/71	buried in snow
							2/25/71	33.76
							3/10/71	33.72
							3/24/71	34.36
							4/ 6/71	34.37
							4/20/71	34.13
							5/ 4/71	34.08
							5/18/71	34.05
							6/ 1/71	33.85
							9/ 3/72	33.7
							11/17/72	pipe bent, could not measure
							1/25/73	
E	122N	54W	34 NE NE NE NW	1810	20	S	7/ /70	5.05
							9/22/70	7.00
							10/ 6/70	7.07
							10/22/70	9.12
							11/ 4/70	6.96
							11/17/70	6.79
							12/ 1/70	6.74
							12/15/70	6.41
							12/29/70	6.42
							1/15/71	6.42
							2/ 9/71	6.37
							2/25/71	6.36
							3/10/71	6.28
							3/24/71	5.94
							4/ 6/71	5.82
							4/20/71	5.73
							5/ 4/71	5.83
							5/18/71	5.03
							6/ 1/71	5.80
							9/ 3/72	5.24
							11/17/72	6.74
							1/25/73	6.54
G	122N	55W	10 NE NE NE SW	1790	20	S	7/ /70	3.07
							9/22/70	3.85
							10/ 6/70	3.97
							10/22/70	3.97
							11/ 4/70	3.70
							11/17/70	3.65
							12/ 1/70	3.62
							12/15/70	3.62
							12/29/70	3.73
							1/15/71	3.90

Well No.	Location Township	Range	Section	Elevation	Depth	Aquifer	Date	Water Level
							2/ 9/71	3.80
							2/25/71	3.60
							3/10/71	4.38
							3/24/71	4.39
							4/ 6/71	1.72
							4/20/71	2.31
							5/ 4/71	2.09
							5/18/71	4.96
							6/ 1/71	2.07
							9/ 3/72	2.25
							11/18/72	3.25
							1/25/73	3.25
H	122N	55W	1 SE SE SE NE	1810	25	S	7/ /70	8.75
							9/22/70	10.06
							10/ 6/70	10.25
							10/22/70	10.39
							11/ 4/70	10.48
							11/17/70	10.52
							12/ 1/70	10.56
							12/15/70	10.51
							12/29/70	10.37
							1/15/71	10.53
							2/ 9/71	10.49
							2/25/71	10.51
							3/10/71	10.50
							3/24/71	10.48
							4/ 6/71	7.79
							4/20/71	7.91
							5/ 4/71	7.80
							5/18/71	7.80
							6/ 1/71	7.71
							9/ 3/72	6.0
							11/18/72	7.45
							1/25/73	7.9
I	123N	53W	17 SW SW SW SE	1800	15	S	7/ /70	6.91
							9/22/70	8.28
							10/ 6/70	8.45
							10/22/70	8.45
							11/ 4/70	8.24
							11/17/70	6.61
							12/ 1/70	6.67
							12/15/70	6.55
							12/29/70	6.87
							1/15/71	8.59
							2/ 9/71	8.16
							2/25/71	7.43
							3/10/71	7.34

Well No.	Location Township	Location Range	Section	Elevation	Depth	Aquifer	Date	Water Level
							3/24/71	7.59
							4/ 6/71	6.89
							4/20/71	6.90
							5/ 4/71	5.15
							5/18/71	5.54
							6/ 1/71	5.46
							9/ 3/72	pipe bent, could not measure
							11/18/72	
							1/25/73	
J	123N	54W	30 NE NE NE NE	1795	20	S	7/ /70	4.6
							9/22/70	5.53
							10/ 6/70	5.87
							10/22/70	5.92
							11/ 4/70	5.79
							11/17/70	2.99
							12/ 1/70	5.07
							12/15/70	5.28
							12/29/70	5.73
							1/15/71	6.34
							2/ 9/71	7.53
							2/25/71	7.15
							3/10/71	7.25
							3/24/71	7.23
							4/ 6/71	6.90
							4/20/71	6.03
							5/ 4/71	5.30
							5/18/71	5.00
							6/ 1/71	4.89
							9/ 3/72	3.2
							11/18/72	4.0
							1/25/73	4.95
K	122N	53W	3 NW NW NW NW	1852	40	S	7/ /70	28.7
							9/ 3/72	28.1
							11/18/72	28.1
							1/26/73	28.15

APPENDIX I

Theory of vertical variability analysis

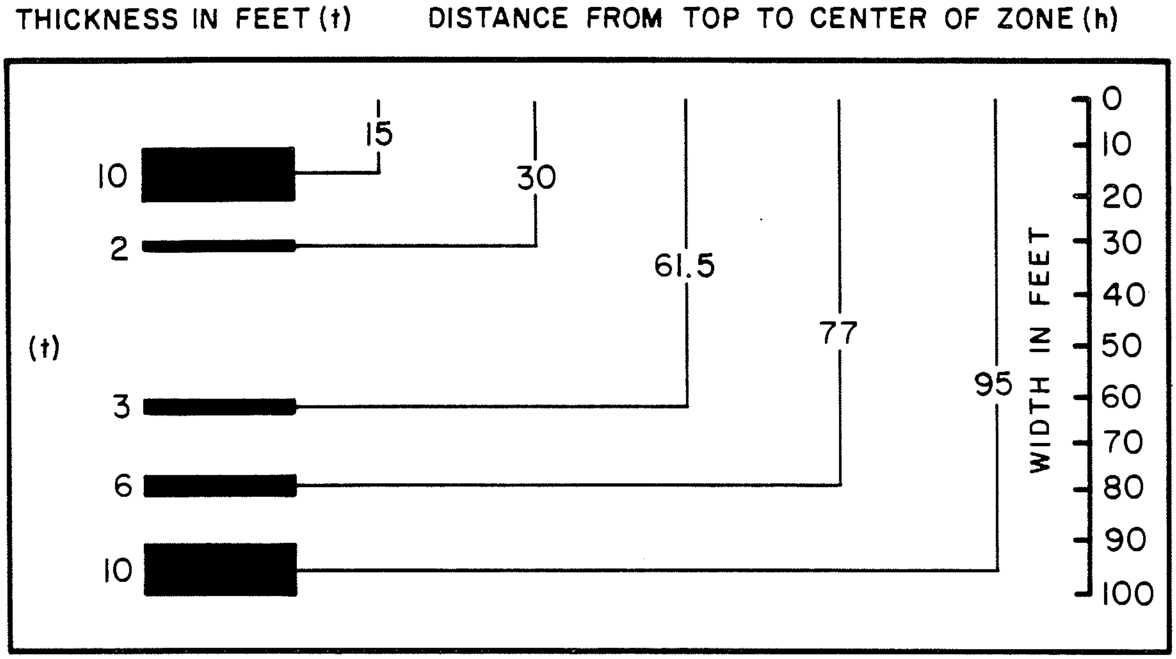
Vertical variability analysis is extremely useful in analyzing distributions of geologic formations in areas where the materials are erratically distributed. Historically, it was developed for use in the petroleum industry to determine statistical distributions and vertical intervals of greatest concentrations of oil sands (Forgotson, 1960). Since then it has been used in the field of hydrology for analyzing aquifer distribution in vertical sections by Domenico, Stephenson, and Maxey (1964), and Stephenson (1967).

In attempting to analyze and correlate aquifers in Day County from information from 350 wells and test holes it soon became apparent that the distributions were very erratic and complex and in addition, there were probably thousands of outwash lenses which could not be correlated with each other. Thus, it was decided to treat the sand and gravel distribution of the entire Pleistocene column statistically in order to make some predictions as to expected areas and elevations where most potential aquifers could be found.

Vertical variability analysis as used in this report yields the following parameters for each hole penetrating a preselected elevation interval or slice of the earth materials in the county:

1. Number of zones or strata of sand and gravel.
2. Cumulative thickness of all zones.
3. Center of gravity of all zones in feet below top of interval.
4. Relative center of gravity as percent of interval width below interval top.
5. Approximate variance.
6. Approximate standard deviation or spread of all materials in distance away from the center of gravity.
7. Relative standard deviation or spread of all materials away from center of gravity measured as percent of interval width.
8. Class - five statistical classes which are combinations of standard deviation and center of gravity and serve to illustrate the position of the material in the interval and its spread.

The importance and derivations of the above variables are illustrated by analysis of a hypothetical example. Figure 1 shows the method of analysis of a 100-foot wide interval having five zones or lenses of outwash sand and gravel. After all the variables have been computed there are five possible classes into which the results of the analysis will place the material distribution of the interval in question.



Interval width = 100 feet
Number of zones = 5

zone number	distance from top (h)	thickness of zone (t)	ht	h^2t
1	15	10	150	2250
2	30	2	60	1800
3	61.5	3	184.5	22693.5
4	77	6	462	35574
5	95	10	950	90250
	sums:	A=31	B=1806.5	C=152567.5

center of gravity: B/A = 58.3 feet below interval top (7)

relative center of gravity: ((B/A)/width) x 100 = 58.3% of width below top (8)

approximate variance: AV = (C-(B /A)) /A = 1525.7 (9)

approximate standard deviation: ASD = AV = 39.06 feet added and subtracted from center of gravity (10)

relative standard deviation: RSD = (ASD/width) x 100 = 39.06 of interval width (11)

class = 4

Figure I. Method of parameter computation for vertical variability analysis.

Description of the five statistical classes

Class	Statistics	Interpretation
1	RCOG $\leqq$ 50% RDS $\leqq$ 10%	Most material in upper half of interval Spread small; lenses closely spaced
2	RCOG > 50% RDS $\leqq$ 10%	Most material in lower half of interval Spread small; lenses closely spaced
3	RCOG $\leqq$ 50% 10% < RSD $\leqq$ 50%	Most material in upper half of interval Spread large; lenses widely spaced
4	RCOG > 50% 10% < RSD $\leqq$ 50%	Most material in lower half of interval Spread large; lenses widely spaced
5	---------	No material in interval

In the example shown in figure 1, the materials fall into class 4. By using the vertical variability maps one can estimate the position in an elevation interval where most of the aquifer material will be found and also how closely arranged the various lenses are to each other.

A three-program FORTRAN IV package (see Leap, 1974) was written to perform the vertical variability analysis and to plot the results in map form (figs. 2 to 11). The first program VERVAR (print mode) can be used to perform the analysis and print out the results in tabular form. The second program VERVAR (punch mode) also performs the analysis and punches out results on a set of cards. The third program VPLOT takes the punched cards and plots out the data on a line printer in map form. After the map has been plotted, the data points are contoured according to the class which divided the area into smaller areas of different class for purposes of predicting the nature of aquifer materials in new holes drilled in the various areas.

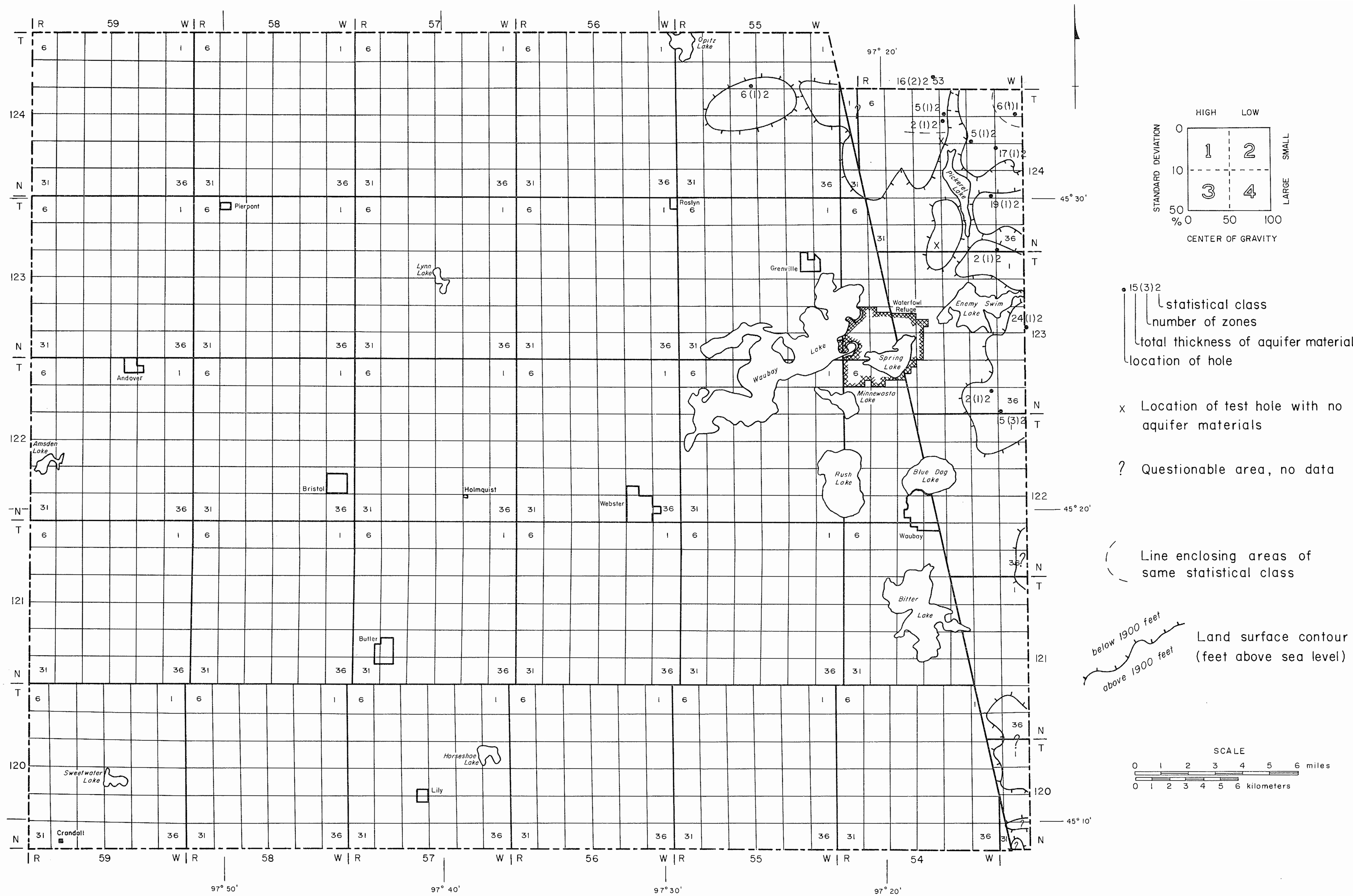


Figure 2. Vertical variability map of drift aquifer materials in Day County, South Dakota. (Elevation interval, 2000 to 1900 feet above mean sea level)

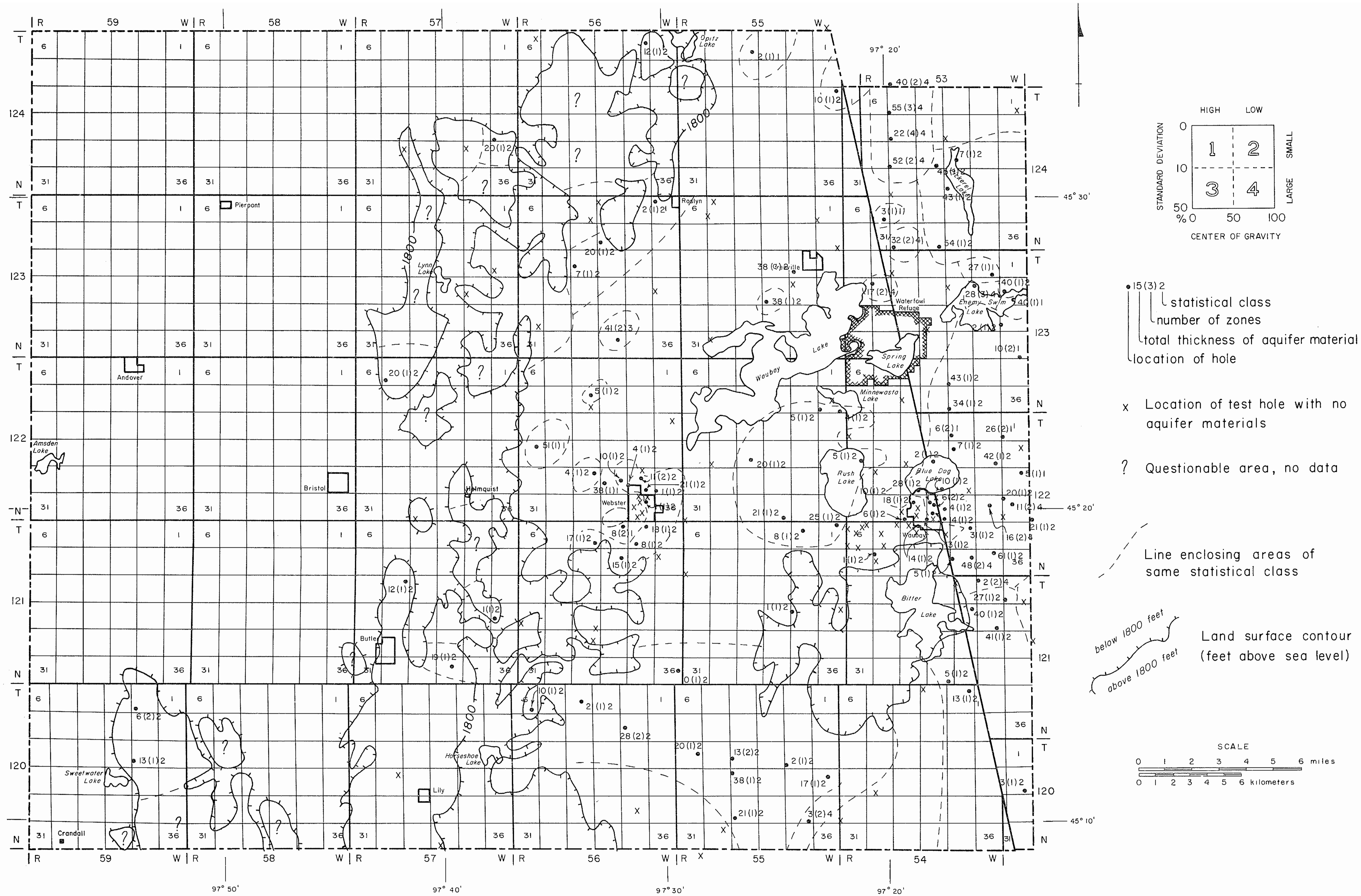


Figure 3. Vertical variability map of drift aquifer materials in Day County, South Dakota. (Elevation interval, 1900 to 1800 feet above mean sea level)

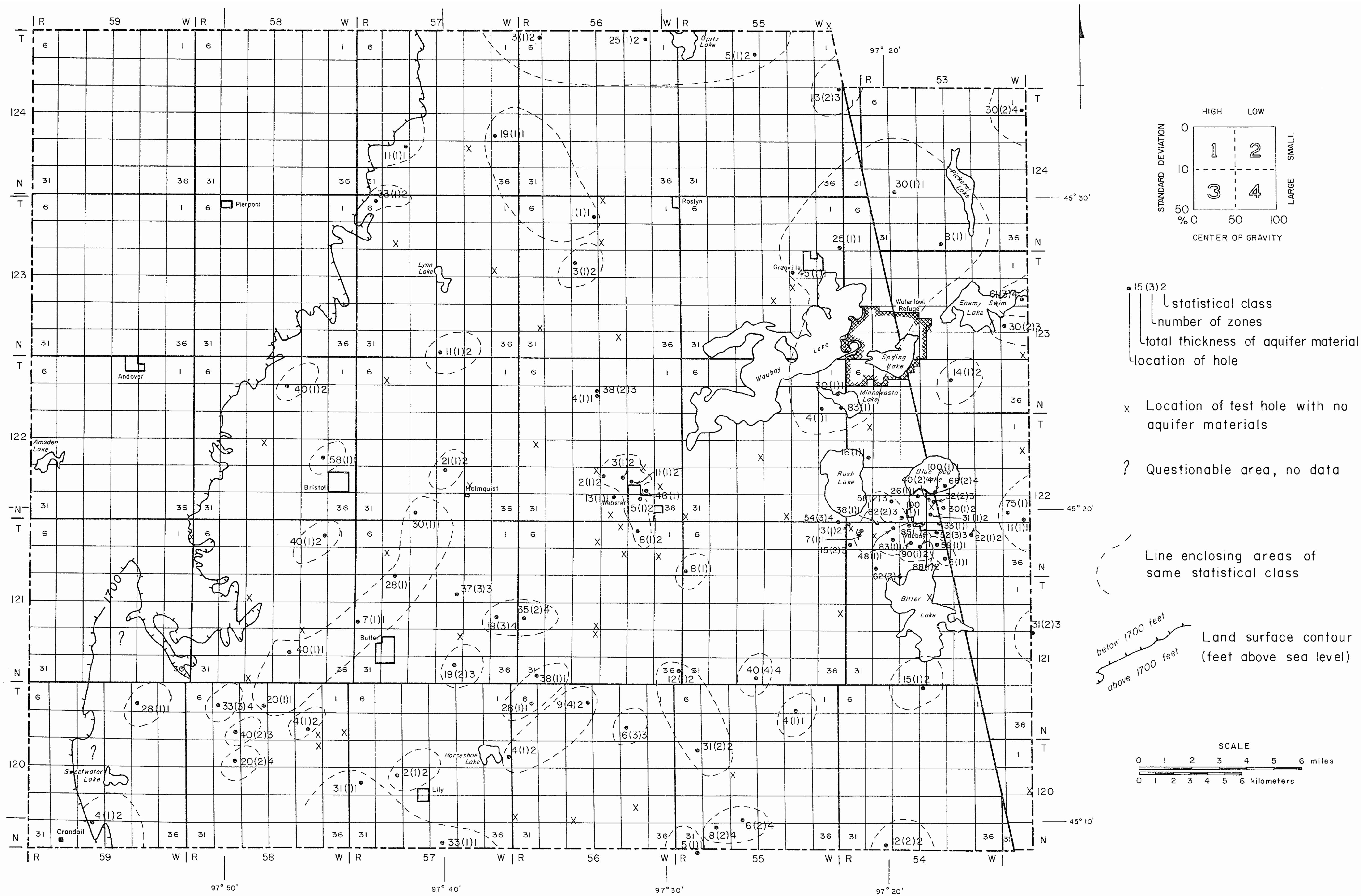


Figure 4. Vertical variability map of drift aquifer materials in Day County, South Dakota. (Elevation interval, 1800 to 1700 feet above mean sea level)

Appendix I-6

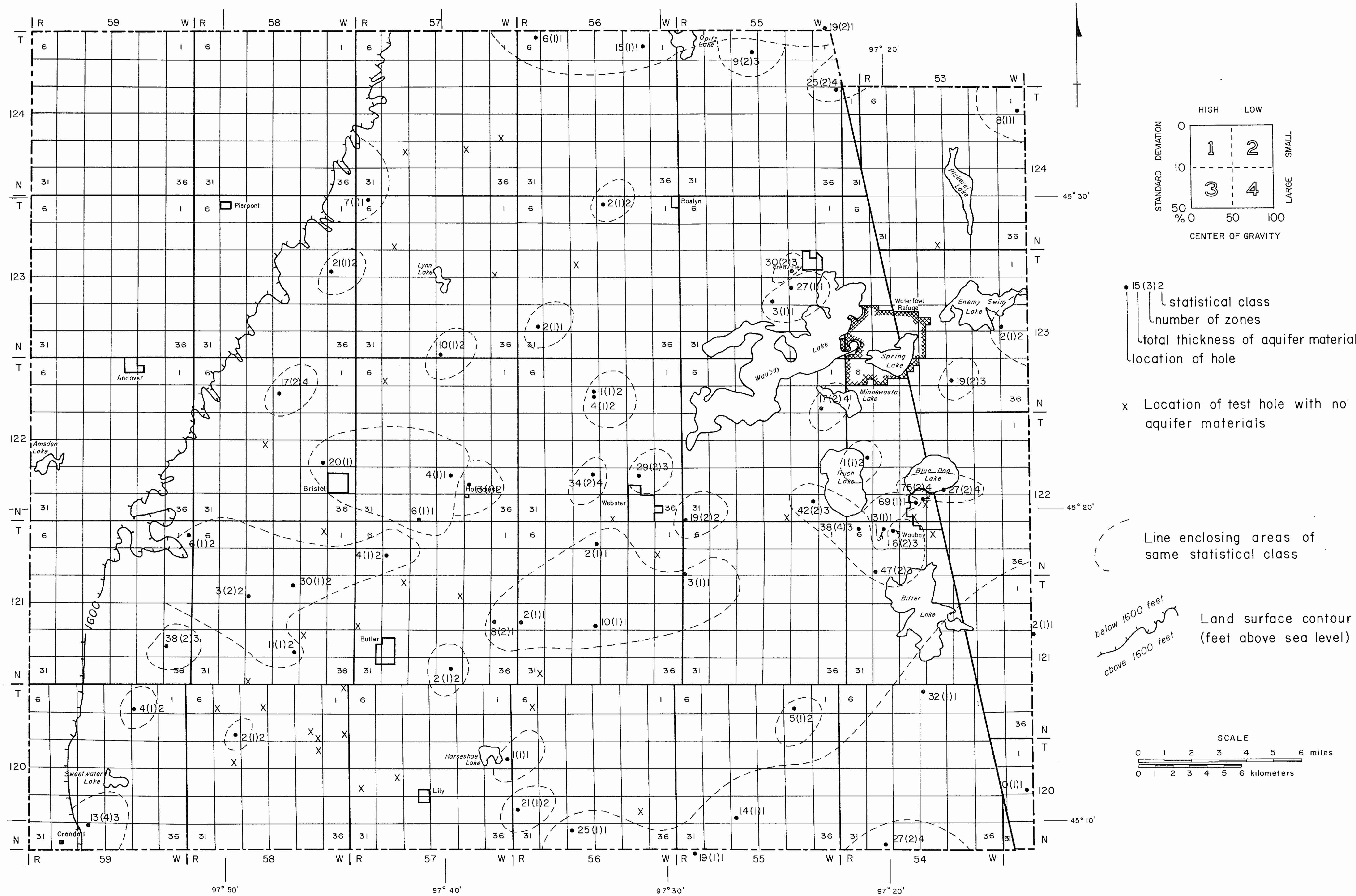


Figure 5. Vertical variability map of drift aquifer materials in Day County, South Dakota. (Elevation interval, 1700 to 1600 feet above mean sea level)

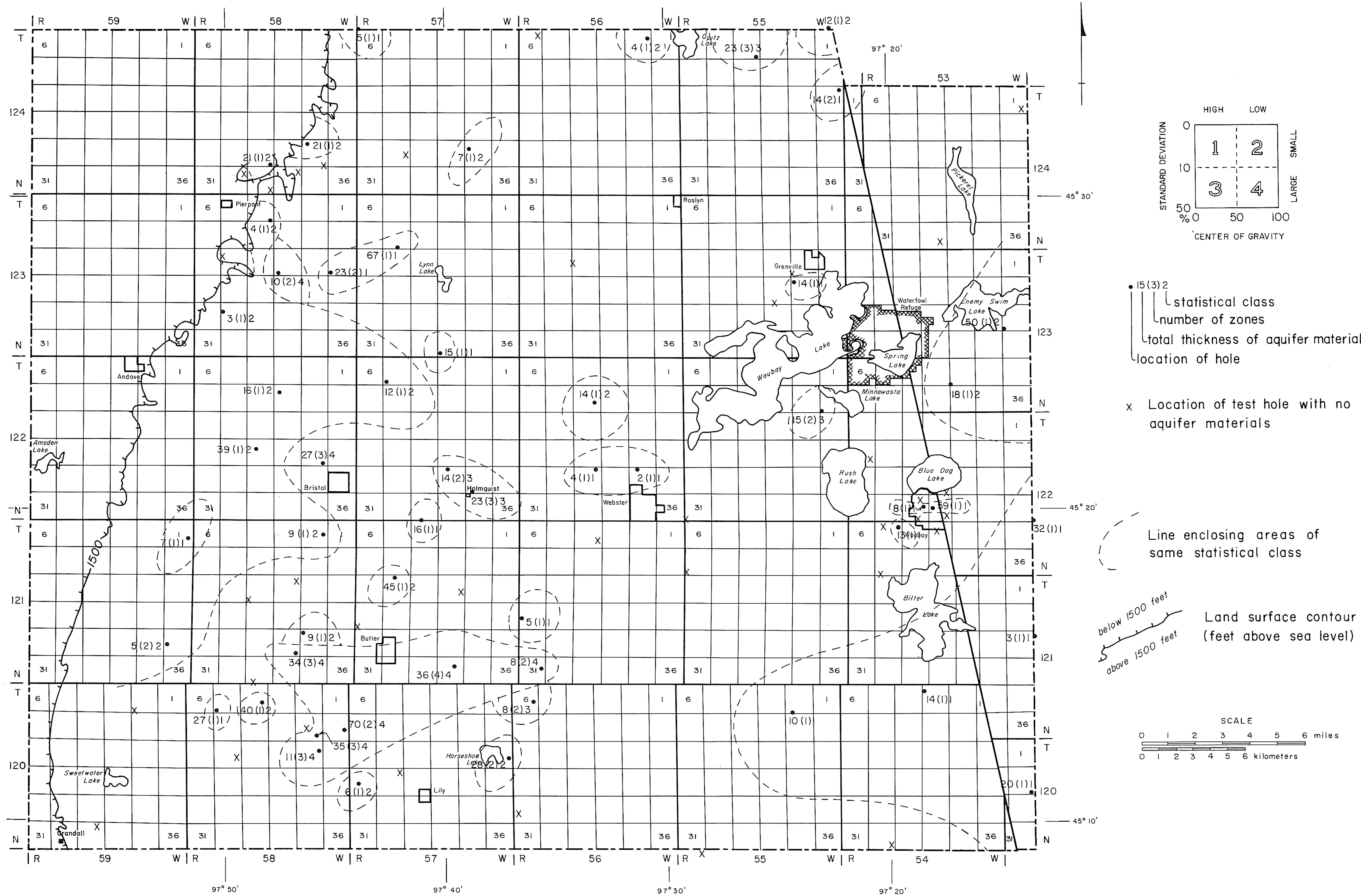


Figure 6. Vertical variability map of drift aquifer materials in Day County, South Dakota. (Elevation interval, 1600 to 1500 feet above mean sea level)

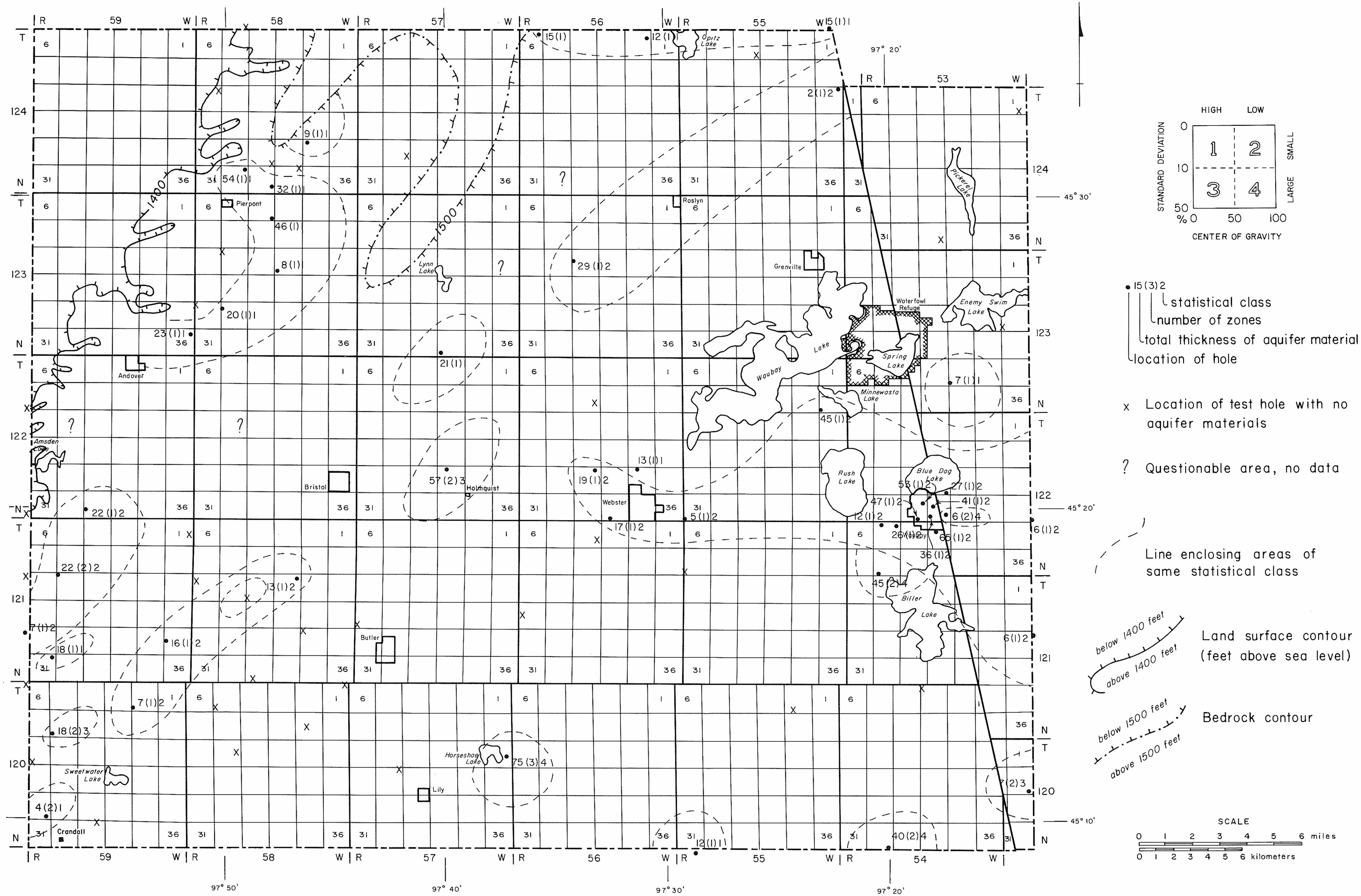


Figure 7. Vertical variability map of drift aquifer materials in Day County, South Dakota. (Elevation interval, 1500 to 1400 feet above mean sea level)

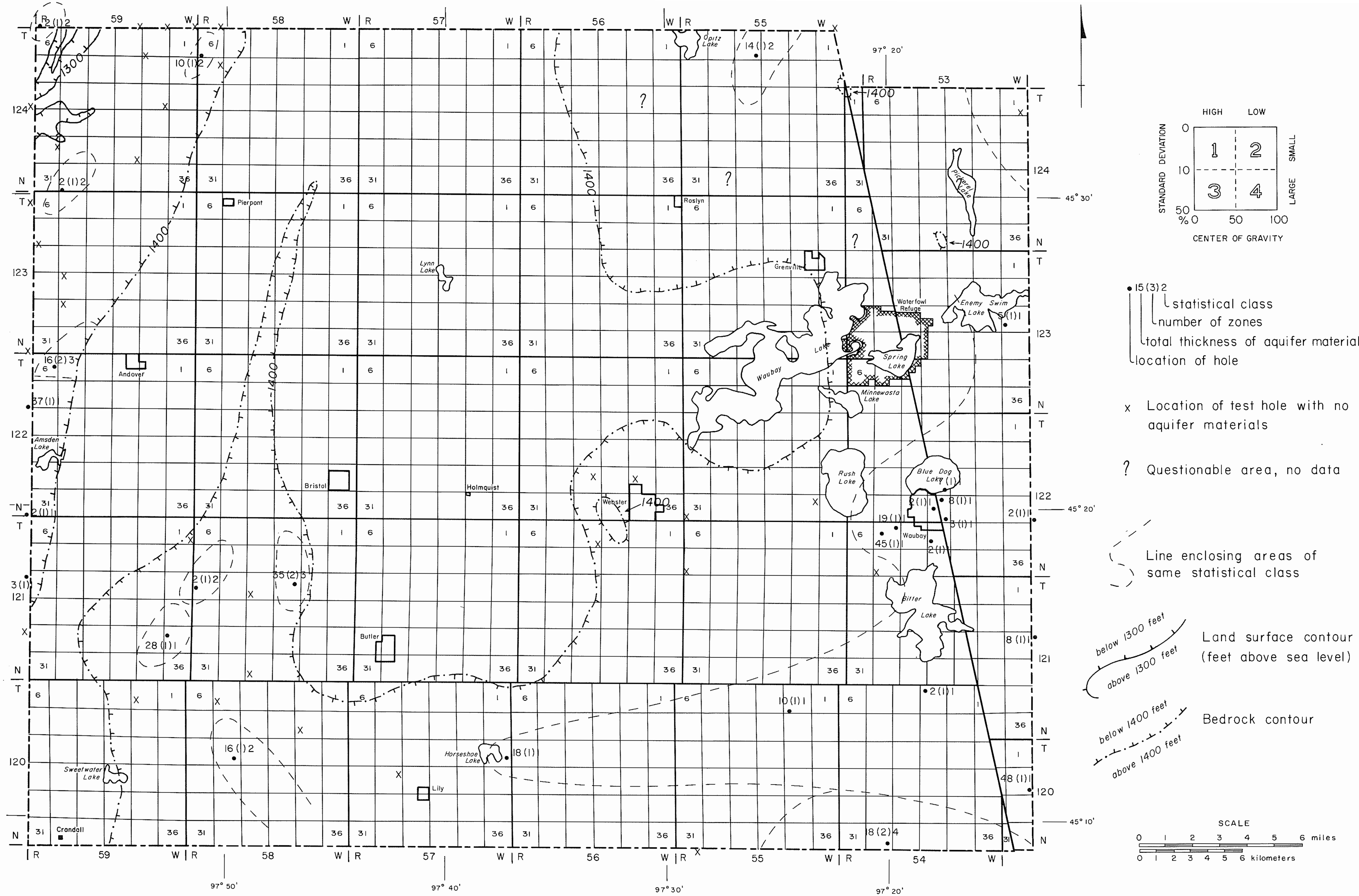


Figure 8. Vertical variability map of drift aquifer materials in Day County, South Dakota. (Elevation interval, 1400 to 1300 feet above mean sea level)

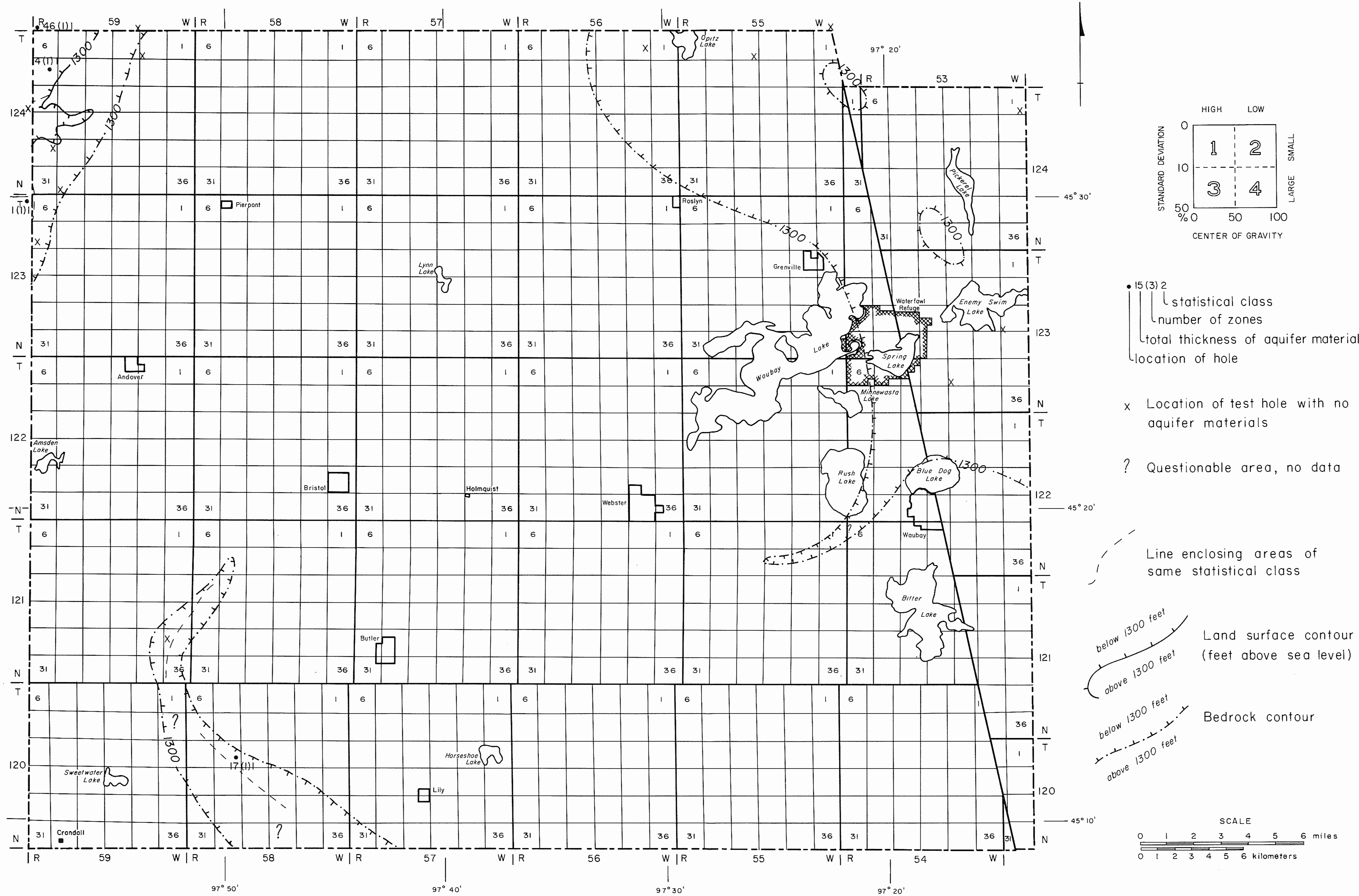


Figure 9. Vertical variability map of drift aquifer materials in Day County, South Dakota. (Elevation interval, 1300 to 1200 feet above mean sea level)

Appendix I-11

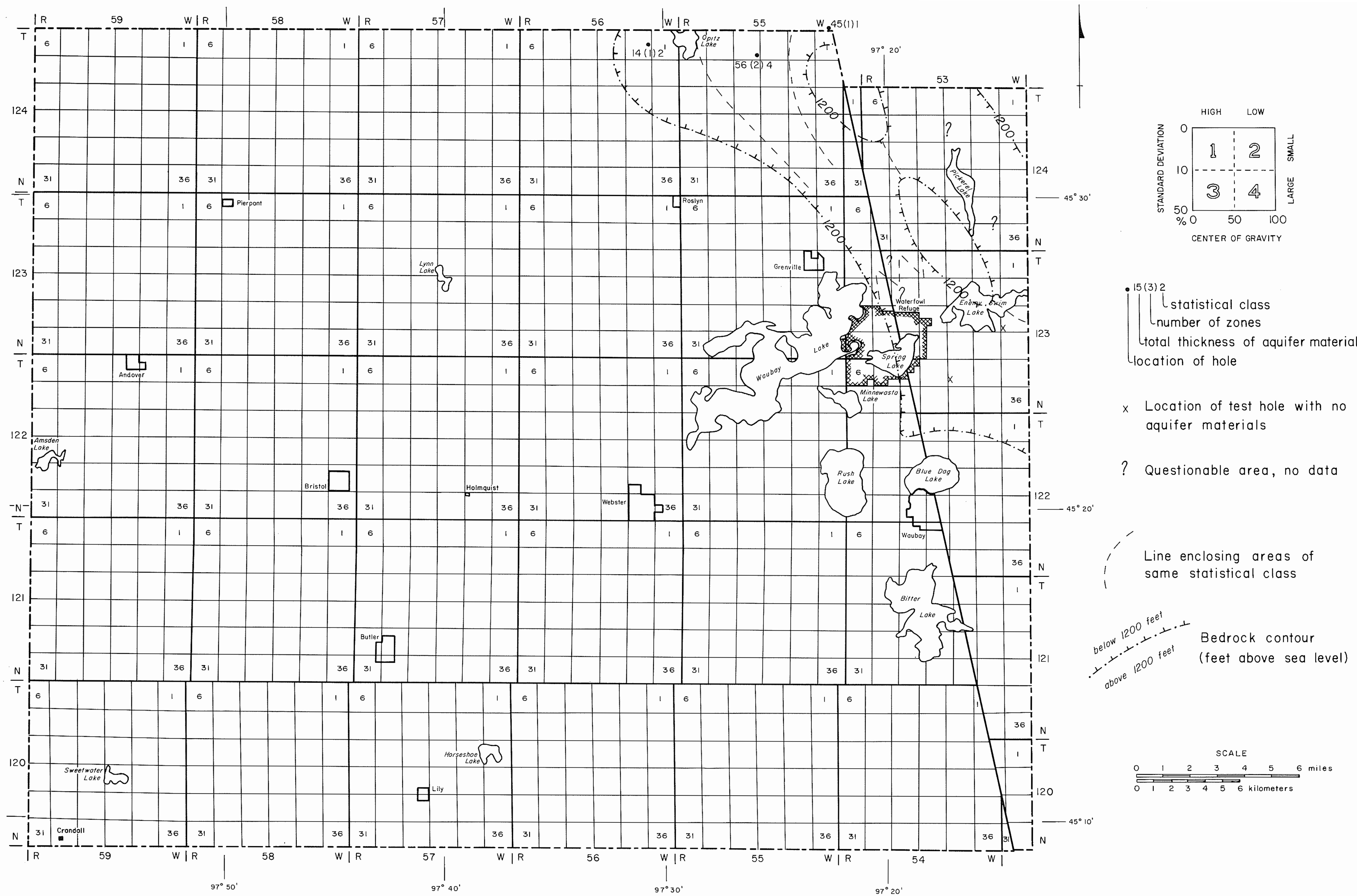


Figure 10. Vertical variability map of drift aquifer materials in Day County, South Dakota. (Elevation interval, 1200 to 1100 feet above mean sea level)

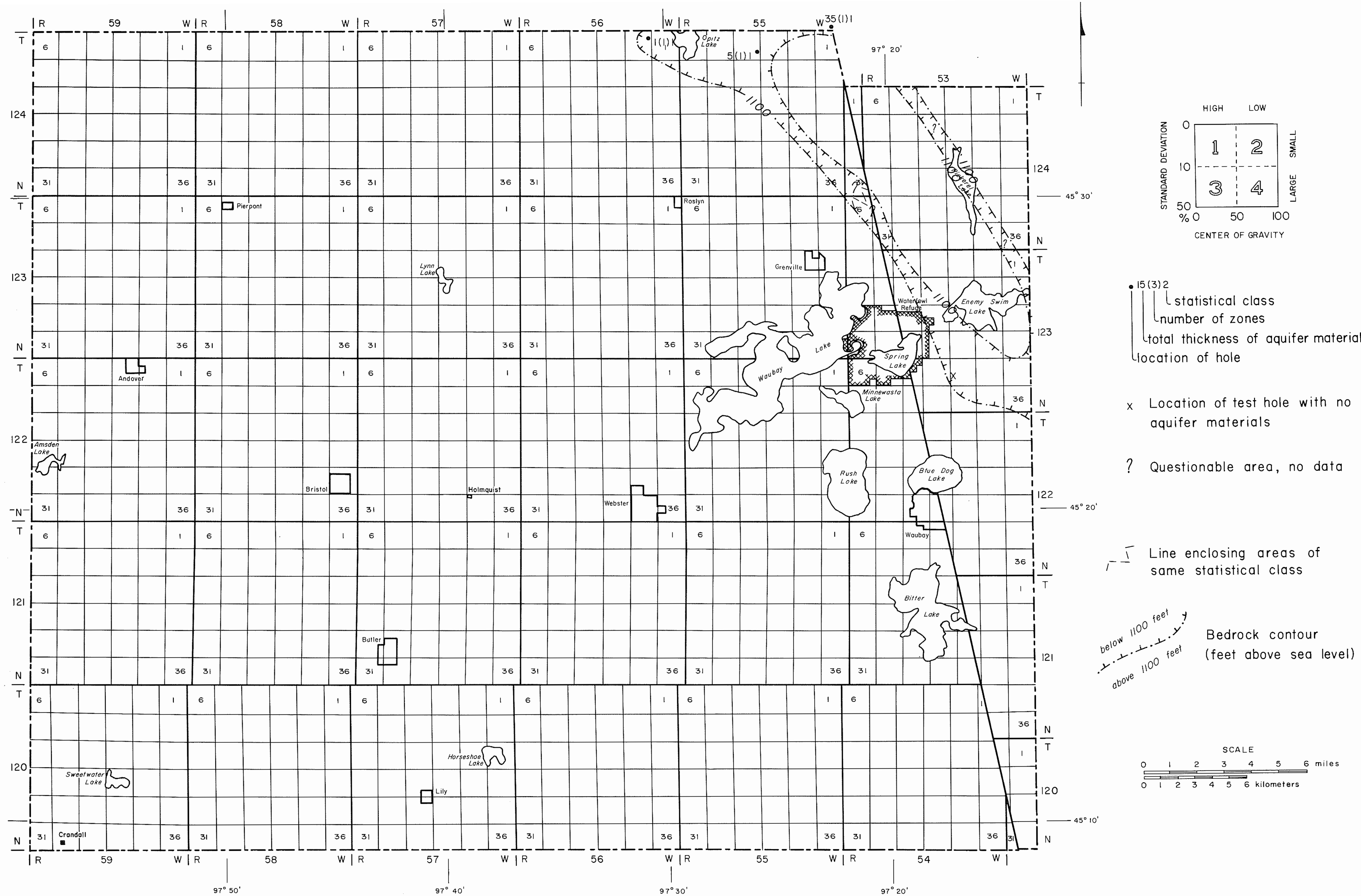


Figure 11. Vertical variability map of drift aquifer materials in Day County, South Dakota. (Elevation interval, 1100 to 1000 feet above mean sea level)

APPENDIX J. Chemical analyses of well waters, Day County, South Dakota

Hardness reported in grains per gallon, specific conductance in micromhos/cm at 25 degrees C. All other analyses with exception of pH in parts per million. Depth reported in feet. General water samples (2 to 134) collected in 1969 were analyzed by the South Dakota Geological Survey. General water samples (140 to 157 collected in 1969 with sodium and potassium analyses were analyzed by the South Dakota State Chemical Laboratory. General water samples (C 1 to C 70) collected in 1970 and 1971 were analyzed by Pennsylvania State University. Water samples (1 1 to W 18) from the Webster City Study, 1971, were analyzed by the South Dakota Geological Survey. See figure 49 for locations of samples.

AQUIFER CODES:

B = Basal System
I = Intermediate System
Iu = Intermediate System, undifferentiated
P = Pierre Aquifer
S = Surface System

GENERAL SAMPLES COLLECTED IN 1969

Sample No. (1)	Total dissolved solids (2)	Hardness (3)	Calcium (4)	Magnesium (5)	pH (6)	Chloride (7)	Sulfate (8)	Iron (9)	Manganese (19)	Alkalinity (11)	Nitrate (12)	Depth (13)	Aquifer (14)
2	1130	740	187	67	7.1	8	388	.03	.58	332	3.6	22	---
3	465	400	120	25	7.7	2	88	.08	.63	244	.1	18	Iu
4	830	600	134	65	7.6	6	387	.08	.20	245	3.4	43	Iu
5	1442	210	53	19	7.6	192	705	4.30	.30	308	.5	600	B
6	1130	640	147	67	7.5	12	613	.06	.20	236	5.3	300	Iu
7	1060	660	187	47	7.8	10	620	.03	.13	244	4.6	400	Iu
8	1320	780	254	36	7.6	4	1137	.06	.20	228	.1	355	Iu
9	615	460	127	35	7.8	18	106	.06	.13	296	16.9	14	Iu
10	750	560	167	35	7.9	4	288	.07	.46	272	1.2	287	Iu
11	878	680	207	40	7.5	20	205	.06	.58	245	.1	325	Iu
12	1230	900	267	57	7.7	20	400	.10	.51	232	.1	200	Iu
13	1052	680	200	44	7.6	24	260	.13	.13	222	.2	---	---
14	1393	1180	321	98	7.5	56	500	.13	.09	260	.2	60	Iu
15	1043	800	227	57	7.3	6	300	2.62	.25	300	.2	200	Iu
16	863	620	187	32	7.4	6	200	2.60	2.10	292	.2	441	Iu
17	1021	700	200	50	7.9	14	300	.03	.20	180	.1	160	I 5
18	1102	970	221	149	7.5	6	335	.33	.09	312	.1	40	Iu

General Samples collected in 1969 -- continued.

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(19)	(11)	(12)	(13)	(14)
19	1100	960	260	76	7.7	6	360	3.20	1.32	400	.1	---	---
20	1170	1006	254	91	7.7	8	140	.31	.35	232	13.2	80	Iu
21	2190	1780	401	217	7.6	47	220	.98	.09	228	10.1	120	---
22	1248	940	334	26	7.6	20	550	.03	1.25	244	8.6	---	---
34	782	460	128	35	7.3	4	225	.06	.63	200	.5	200	Iu
35	993	600	160	50	7.5	4	338	.03	.35	220	.5	168	Iu
36	2233	1850	409	202	7.6	77	1313	.08	.68	320	16.4	25	Iu
37	1353	640	168	54	7.4	14	450	.06	2.10	180	16.6	220	Iu
38	842	580	152	50	7.5	16	275	.06	.51	320	6.0	115	Iu
39	3332	2350	417	320	7.6	243	670	.06	.01	330	6.0	32	Iu
40	887	1120	108	71	7.5	4	263	13.95	.51	260	2.2	180	Iu
41	1062	740	185	69	7.4	8	363	.06	1.33	340	.8	140	Iu
42	2100	1240	253	149	7.5	120	750	.03	.40	220	16.6	150	Iu
43	1172	800	216	64	7.5	10	500	.94	1.22	320	.8	---	---
44	750	420	89	48	7.8	4	125	.03	.51	260	6.3	140	I 1
45	2216	600	161	50	7.0	159	650	.03	.35	265	16.6	---	---
46	828	700	160	73	7.1	6	325	.03	1.40	200	5.8	165	Iu
47	1789	1300	361	98	7.0	149	450	.08	.13	380	16.4	70	Iu
48	766	400	200	20	7.5	4	288	.16	1.40	240	1.9	85	I 2
49	2100	1600	320	196	7.1	194	425	.06	.13	220	16.6	50	Iu
50	4658	3700	1042	502	7.4	228	1750	.06	.01	220	16.6	153	Iu
51	1022	700	160	73	7.6	44	288	.03	.01	280	16.2	21	Iu
52	600	400	120	25	7.6	10	63	.16	.01	320	5.3	48	I 20
53	383	200	80	3	7.7	2	63	.06	.01	240	5.0	---	---
54	898	700	160	74	7.6	8	350	.03	.01	300	9.9	24	Iu
55	974	1100	374	74	7.8	20	463	.01	.80	352	3.4	108	Iu
56	1199	650	246	86	7.7	81	325	.01	.01	332	16.6	14	Iu
57	1500	1100	247	147	7.5	75	888	.01	1.68	312	11.0	60	Iu
58	1800	108	80	10	7.6	85	420	.01	.80	316	16.4	87	Iu
60	750	550	180	25	7.5	81	40	.03	.00	264	16.4	---	---
61	800	550	140	49	7.7	54	35	.01	.00	288	16.2	40	Iu
62	1150	950	220	98	7.5	95	85	.01	.00	321	16.4	42	Iu
63	650	450	160	13	7.6	6	160	.01	.35	268	1.3	70	Iu
64	1200	500	140	38	7.8	34	135	1.15	.58	300	9.2	35	Iu
65	1245	900	220	86	7.3	16	200	.06	.00	396	16.2	30	Iu
66	675	450	100	50	7.9	16	113	.06	.00	300	16.2	25	Iu
67	1184	1050	240	110	7.5	8	563	37.50	1.48	244	5.8	140	Iu
68	1653	1200	360	74	7.6	19	1075	.06	.00	376	16.2	58	Iu
69	1170	700	180	61	7.5	54	200	.05	.25	380	14.2	12	Iu
70	375	300	100	18	7.8	8	44	.10	.01	200	13.4	25	Iu
71	850	300	165	30	7.7	57	75	.01	.01	344	16.2	27	i u
72	893	550	165	34	7.8	78	63	.01	.01	380	16.0	---	---
73	735	550	140	70	7.8	8	81	.01	.58	448	4.5	---	---
74	1373	800	220	70	7.7	60	81	.01	.01	340	15.4	80	Iu
76	1200	860	192	93	7.6	9	178	.03	.00	280	14.4	84	Iu
77	2120	900	248	370	7.4	268	455	.06	.00	360	14.6	20	Iu
78	881	480	120	44	7.5	74	185	1.38	.00	516	13.0	154	Iu
79	1050	400	73	53	7.7	14	625	.03	.00	240	16.2	45	Iu
80	303	200	56	15	7.8	2	13	.06	.01	192	12.4	56	Iu

General Samples collected in 1969 -- continued.

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(19)	(11)	(12)	(13)	(14)
81	706	460	88	59	7.7	14	45	.08	.01	324	3.6	12	Iu
83	525	320	80	30	7.6	6	18	2.79	.51	360	6.1	125	Iu
84	473	300	72	30	7.8	8	25	.08	.01	296	14.2	40	Iu
85	680	460	60	40	7.7	2	100	.06	.63	388	1.8	---	---
86	564	268	56	31	7.6	10	50	.00	.00	288	15.6	---	---
87	716	440	80	60	7.7	14	68	.01	.00	224	16.4	35	Iu
88	675	260	68	20	7.5	12	40	.01	.00	210	11.8	14	Iu
89	588	480	64	80	7.7	4	160	.20	.00	364	1.6	---	---
90	563	350	96	27	7.8	2	105	.03	.30	316	.5	25	Iu
91	542	350	96	20	7.8	2	105	.08	.46	344	1.9	18	Iu
92	700	320	104	25	7.7	71	128	.03	.00	308	16.4	60	Iu
93	678	360	108	25	7.5	2	103	.06	.00	380	3.4	---	---
94	842	420	92	47	7.9	87	100	.06	.00	232	16.4	---	---
95	600	350	140	20	8.0	30	98	.03	.01	352	14.4	40	I 48
96	1442	830	260	41	8.1	48	100	.06	.01	348	16.4	54	---
97	525	360	100	27	7.9	2	70	.03	.01	320	.7	---	---
98	1155	650	104	99	8.0	2	600	4.25	.85	560	5.3	---	---
99	984	600	104	95	7.9	25	388	.03	.01	364	15.6	---	---
100	545	260	64	24	8.2	6	75	.08	.01	332	6.1	---	---
101	1008	790	160	96	8.1	4	405	.08	.01	408	1.0	---	---
102	1050	850	116	137	8.2	38	90	.12	.40	664	16.4	28	Iu
103	1433	950	168	130	8.2	143	246	.08	.01	512	16.6	24	Iu
104	764	490	96	61	8.3	48	190	.13	.01	264	16.0	---	---
105	395	270	72	21	8.4	14	33	.08	.01	252	7.5	36	Iu
106	474	350	92	30	8.2	12	95	.40	.63	248	.5	25	Iu
107	1375	1040	204	105	7.9	83	390	.06	.01	392	16.6	25	Iu
108	345	270	68	20	8.0	6	50	.08	.01	200	9.9	50	Iu
109	420	270	68	21	8.1	8	65	.08	.01	232	15.2	20	Iu
110	1413	970	164	137	7.6	125	150	.24	.40	584	16.4	20	Iu
111	1530	900	232	80	7.7	10	1450	.06	2.75	332	3.5	---	---
112	750	510	128	47	8.4	28	85	.48	.01	408	16.2	---	---
113	487	320	76	32	8.5	4	50	.06	.30	664	.5	162	Iu
114	693	370	96	32	8.1	46	65	.06	.01	276	16.3	14	Iu
115	1836	1180	148	198	8.2	268	95	.12	.01	300	16.4	50	Iu
116	525	350	76	40	8.2	6	75	.03	.72	348	.3	80	Iu
117	357	240	60	20	8.2	10	125	.06	.00	236	11.4	25	Iu
118	1385	780	112	123	8.3	137	108	.12	.35	504	16.4	25	Iu
119	2088	1280	120	234	7.8	105	130	.06	.01	632	16.5	---	---
120	714	400	84	47	8.3	26	33	.12	.01	344	16.2	36	Iu
121	1923	1290	104	256	8.1	349	115	.08	.01	400	16.4	---	---
122	823	320	96	42	8.0	58	185	.03	1.05	328	2.7	164	Iu
123	527	340	80	36	8.4	30	55	.03	.01	296	15.6	200	I 29
124	383	320	60	42	7.9	6	58	.06	.01	256	8.6	---	---
125	1610	1025	192	133	8.0	107	300	.03	.01	412	16.4	---	---
126	579	470	88	61	8.0	6	155	.03	.01	344	.5	---	---
127	1136	550	116	64	7.8	12	590	5.26	1.05	352	.5	64	Iu
128	690	450	72	66	8.2	46	180	.06	.58	320	9.9	---	---
129	1554	590	160	47	7.7	46	255	4.71	1.82	292	3.4	70	Iu
130	2320	1700	353	200	7.9	26	112	.48	1.75	380	7.5	90	Iu

GENERAL SAMPLES COLLECTED IN 1970 AND 1971

Sample No. (1)	Specific Conductance (2)	Calcium (3)	Magnesium (4)	Sodium (5)	Bicarbonate (6)	Chloride (7)	Depth (8)	Aquifer (9)
C 1	1656	118	77	118	380	16.5	---	---
C 2	1760	60	29	273	229	16.5	334	Iu
C 3	550	37	29	26	283	18.0	---	---
C 4	1528	169	84	105	266	29.0	380	B
C 5	626	171	86	105	221	29.3	365	B
C 6	1251	98	74	75	276	21.8	300	Iu
C 7	3106	178	108	300	377	34.0	373	B
C 8	2409	183	106	288	104	19.0	189	I 17
C 9	864	85	76	96	217	12.5	330	B
C 10	1650	202	47	135	329	18.3	240	I 38
C 11	1667	206	65	97	245	15.7	360	B
C 12	1812	183	102	100	120	8.4	383	B
C 13	1699	114	95	148	105	16.0	347	I 11
C 14	1672	108	97	156	232	15.2	---	---
C 15	1068	123	45	55	322	---	341	I 6
C 16	1247	102	73	79	166	---	325	I 13
C 17	1180	117	34	95	314	---	202	Iu
C 18	1869	108	54	254	---	---	318	I 34
C 19	3182	206	126	378	354	---	279	Iu
C 20	1161	114	39	78	151	9.7	184	I 17
C 21	1527	144	84	50	141	7.4	292	I 9
C 22	1833	125	97	156	298	25.0	300	Iu
C 23	1656	127	102	105	283	16.8	260	I 13
C 24	1428	171	53	68	237	18.2	220	I 17
C 25	1463	106	75	129	152	18.5	280	I 34
C 26	1510	106	41	118	211	11.5	190	I 17
C 27	1202	133	55	30	318	---	158	Iu
C 28	820	80	46	14	188	18.0	18	Iu
C 29	1592	108	52	172	245	60.0	218	B
C 30	1812	182	96	60	116	5.6	355	Iu
C 31	831	44	40	48	193	5.9	195	I 23
C 32	1294	152	44	83	335	14.0	164	I 5
C 33	2538	70	18	576	486	---	200	B
C 34	2297	64	20	413	450	---	210	Iu
C 35	1333	132	43	90	272	25.0	290	I 30
C 36	1608	5	1	384	349	39.3	256	Iu
C 37	1501	85	83	125	192	22.0	360	B
C 38	1263	95	32	172	200	7.3	174	I 17
C 39	1355	123	30	121	231	63.0	398	B

General Samples Collected in 1970 and 1971 -- continued.

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
C 40	768	59	46	43	115	3.4	138	I 7
C 41	1441	158	82	55	113	3.4	324	I 16
C 42	725	54	46	20	237	4.2	343	I 16
C 43	559	54	29	22	361	3.5	338	I 16
C 44	3430	370	178	78	128	---	366	B
C 45	3106	325	165	64	127	---	---	---
C 46	893	86	47	95	320	11.5	120	Iu
C 47	2588	387	152	64	134	12.7	145	I 7
C 48	1574	210	70	46	177	7.9	254	Iu
C 49	1090	51	39	79	173	13.9	138	I 7
C 50	2630	262	118	192	131	---	147	I 7
C 51	1935	221	68	150	190	9.0	153	Iu
C 52	1896	176	67	200	222	38.2	261	Iu
C 53	1377	132	33	122	281	24.0	211	Iu
C 54	4153	406	318	276	115	---	215	Iu
C 55	1349	127	87	28	144	7.9	160	I 7
C 56	895	89	49	37	271	6.2	176	I 27
C 57	1190	129	52	42	188	13.2	115	I 24
C 58	1863	174	100	144	196	17.0	285	I 10
C 59	1435	120	40	160	271	9.4	113	Iu
C 60	1283	133	68	92	229	13.8	285	I 32
C 61	1014	112	41	50	---	---	186	Iu
C 62	863	71	41	43	298	8.0	160	Iu
C 63	1774	132	98	139	200	16.4	376	I 11
C 64	621	47	43	17	199	5.5	230	S
C 65	1774	222	77	72	244	11.2	230	I 17
C 66	1531	198	55	78	373	11.2	274	I 16
C 67	1549	118	73	127	298	26.0	341	B
C 68	841	56	48	42	207	5.4	164	I 27
C 69	1662	35	31	38	271	11.6	---	I
C 70	626	138	110	99	243	6.7	328	Iu

SAMPLES FROM WEBSTER CITY STUDY, 1971

Sample No. (1)	Total dissolved solids (2)	Hardness (3)	Calcium (4)	Magnesium (5)	pH (6)	Chloride (7)	Sulfate (8)	Iron (9)	Manganese (10)	Nitrate (11)	Depth (12)	Aquifer (13)
W 1	1590	900	210	92	---	6	1200	.0	.90	1.9	240	Iu
W 2	1252	805	265	35	8.0	1	1100	.06	.90	.9	210	I 17
W 3	1500	830	140	120	8.1	20	1075	.0	1.52	.4	37	Iu
W 4	1092	770	110	120	8.9	60	500	.0	.25	2.7	200	I 17
W 5	1415	750	210	55	---	3	665	.16	.0	1.7	30	Iu
W 6	1685	935	230	90	---	12	775	.12	.68	8.0	45	Iu
W 7	1435	750	210	55	---	8	1200	.10	.85	.9	188	I 17
W 8	1125	710	340	u	---	11	390	.0	.0	.4	190	I 17
W 9	3830	1950	415	224	---	90	2275	.0	.0	111.0	33	Iu
W 10	1235	685	160	70	---	35	925	.0	.68	.8	210	Iu
W 11	1970	1090	185	154	---	135	800	.0	.0	115.0	80	Iu
W 12	1385	847	235	64	7.4	9	650	.13	.72	6.1	83	I 18
W 13	1425	830	204	73	7.2	18	796	.80	.80	.0	187	I 17
W 14	1120	720	195	60	---	8	590	.08	.0	1.2	200	I 17
W 15	658	490	70	75	8.4	40	185	.0	.09	18.5	23	Iu
W 16	1226	725	120	105	8.4	12	925	.0	3.22	13.2	190	I 17
W 17	2570	775	195	70	---	---	875	.06	.80	4.4	11	Iu
W 18	810	300	105	9	---	8	200	.0	.0	19.5	200	Iu