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HYDROGEOLOGY AND STRATIGRAPHY OF THE DAKOTA FORMATION IN NORTHWEST IOWA

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Foreword

An assessment of the quantity and quality of water available from the Dakota (Sandstone) Formation in northwest Iowa is presented in this report. The assessment was undertaken to provide quantitative information on the hydrology of the Dakota aquifer system to the Iowa Natural Resources Council for allocation of water for irrigation, largely as a consequence of the 1976-77 drought.

Most area wells for domestic, livestock, and irrigation purposes only partially penetrated the Dakota Formation. Consequently, the long-term effects of significant increases in water withdrawals could not be assessed on the basis of existing wells. Acquisition of new data was based upon a drilling program designed to penetrate the entire sequence of Dakota sediments at key locations, after a thorough inventory and analysis of existing data.

Definition of the distribution, thickness, and lateral and vertical changes in composition of the Dakota Formation has permitted the recognition of two members. Additionally, identification of the rock units that underlie the Dakota Formation has contributed greatly to our knowledge of the regional geology of northwest Iowa and the upper midwest. As with nearly all special studies, many side benefits result from multiple applications and uses of new data.

Comparatively little attention had been given to the geology of northwest Iowa since the turn of the century. Now, when the demands for water are growing, it is appropriate that the water resources of this part of the State receive special consideration. This report will serve as a guide to wise management of those water resources.

Donald. L. Koch
State Geologist and Director
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Acknowledgements

The authors would like to acknowledge the staffs of the Iowa Natural Resources Council, the Iowa Department of Environmental Quality, and the University of Iowa Hygienic Laboratory for their assistance with data collection and processing during the course of this project. The assistance of many of the residents of northwest Iowa is also appreciated. The helpful cooperation of the owners of the irrigation developments mentioned in this study, particularly Mr. R. Hibbing and Mr. and Mrs. L. Hansen, was of great value. Numerous individuals on the staffs of the Iowa and U.S. Geological Surveys also assisted in various parts of the project. We would particularly like to thank Mr. Darwin Evans for his collection of much of the subsurface data used in this report and Dr. George Hallberg for his technical and administrative support of the project. Dr. Michael Burkart provided critical direction to the project and his collaboration during the lengthy process of data collection and analysis has been very helpful. The graphic talents of John Knecht and Pat Lohmann are also appreciated.

Hydrogeology and Stratigraphy of the Dakota Formation in Northwest Iowa

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ABSTRACT

A hydrogeologic investigation of the Dakota aquifer in northwest Iowa utilizing outcrop analysis and over 30,000 feet of research drilling has resulted in the recognition of two members of the Dakota Formation. The lowermost Nishnabotna Member consists predominantly of a medium- to coarse-grained quartz arenite sandstone with interbedded layers of shale, siltstone and lignite. This unit is 200 to 300 feet thick in many of the western and north-central parts of the study area, and provides most of the productive capacity of the Dakota aquifer. The Nishnabotna Member is overlain by the Woodbury Member, which is commonly 100 to 150 feet in thickness and consists of shale interbedded with very fine- to fine-grained sandstone, siltstone and lignite. Individual sandstone beds have limited lateral continuity, but provide low yields to domestic wells in the area. Post-Cretaceous erosion has removed portions of the Dakota Formation in most of the study area.

The Dakota aquifer is confined by Cretaceous-age shales and limestones in the western part of the study area, and by fine-textured glacial drift in nearly all of the study area. The thickness of the drift is commonly 200 to 400 feet.

The Dakota aquifer in Iowa is recharged by downward percolation through the confining units throughout the study area, and also by lateral ground-water inflow from Minnesota. Natural discharge occurs to the lower reaches of most of the major rivers in the area, to several Paleozoic aquifers, and to South Dakota beneath a 30-mile segment of the Big Sioux River.

Comparison of recently collected water-level data with historic records on a regional scale suggests that water levels in the aquifer are neither rising nor lowering at a detectable rate. Several local areas appear to have experienced long-term water-level declines, but the extent and magnitude of these declines are not well known.

Controlled pumping test data from the Dakota aquifer yield an average hydraulic conductivity of 48 feet/day for sandstones in the Nishnabotna Member of the Dakota Formation. Some of the pumping test data appear to have been influenced by heterogeneity in the aquifer. It is suggested that shale or mudstone lenses in the aquifer tend to retard the response of observation wells that are located at relatively large distances from production wells, resulting in low estimates of transmissivity, even where thickness and overall textural properties of the aquifer appear to be relatively uniform.

Water quality in the Dakota aquifer varies from calcium-bicarbonate type to calcium-sulfate type water. The low-sulfate type water (less than 250 mg/l) typically occurs in areas that are inferred to have relatively high recharge rate, mostly in the southwest part of the study area. The high-sulfate type water (greater than 1000 mg/l $SO_4^{=}$) occurs in areas with thick confining units such as in the north, northeast and central parts of the study area.

INTRODUCTION

Northwest Iowa is an agricultural region that depends on natural rainfall for satisfactory crop yields. A regional drought in 1976 and 1977 prompted an increase in interest in irrigation and large numbers of residents sought water for irrigation from the Dakota aquifer, the largest source of groundwater in the region. At that time, however, very little was known about the aquifer, particularly its ability to sustain the large yields that are necessary for irrigation without excessive drawdown. The Iowa Natural Resources Council (INRC) placed a moratorium on issuing new permits for the withdrawal of more water than 200 gallons per minute (gpm) from the Dakota aquifer. At the same time, a four-year cooperative study was undertaken between the Iowa Geological Survey (IGS) and the United States Geological Survey (USGS) to determine the geologic and hydrologic characteristics of the Dakota aquifer and the associated geologic units. This report presents the stratigraphy of the Dakota Formation and adjoining rocks in northwest Iowa, and the extent and characteristics of the Dakota aquifer. This report updates and expands a previous report by Ludvigson and Bunker (1979).

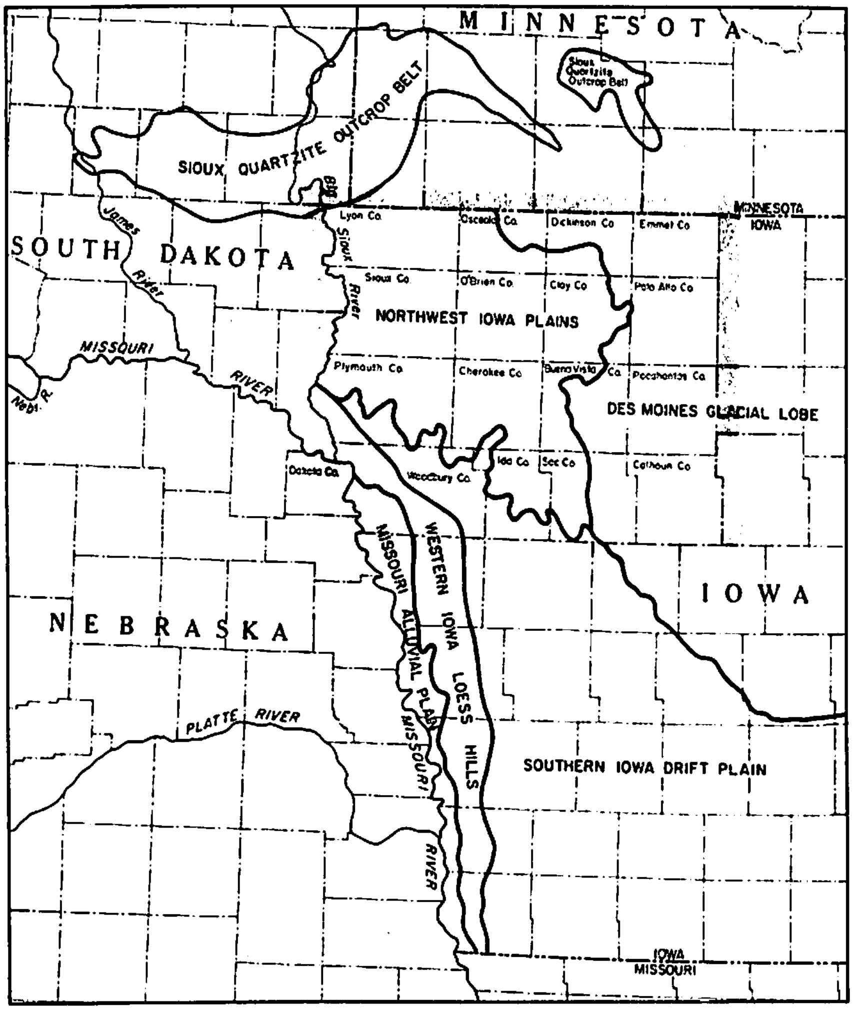

Figure 1. Location of the study area. Physiographic provinces adapted from Prior (1976). Sioux Quartzite outcrop belt after Bunker (1981).

Physiography

The study area is the 16-county region in the northwesternmost corner of Iowa encompassing about 9,270 square miles (figure 1). Physiographically, the area consists mostly of gently rolling upland plains of the Northwest Iowa Plains and Southern Iowa Drift Plain of Prior (1976). The study area also includes the northern part of the relatively high-relief Iowa Loess Hills region (Prior, 1976) near the Big Sioux and Missouri Rivers, and a hummocky region with pot-hole lakes and depressions on the Des Moines Lobe in the eastern part of the study area. The Sioux Quartzite Ridge, a prominent geologic feature, is present immediately north and northwest of the study area.

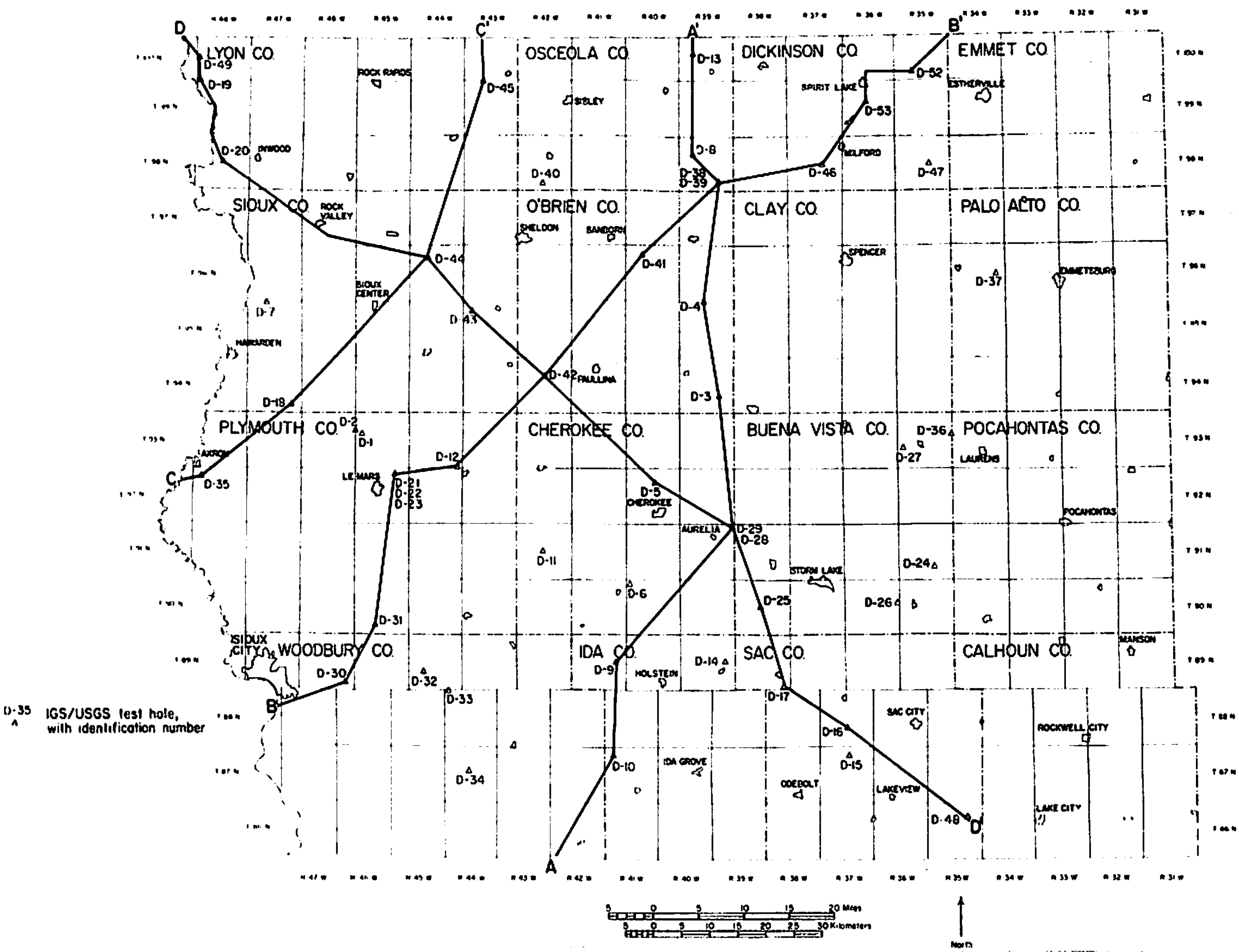

Figure 2. Locations of IGS/USGS test holes.

Methods of Study

Natural exposures of Cretaceous rocks in northwest Iowa are not common and are usually small. Ten of the sixteen counties in the study area have no exposures of rock at all. Although exposures in Iowa and adjacent states were examined in detail as part of this study, the bulk of the geologic data in the study area is from subsurface drill-holes. During the four years of study a total of 53 test holes were drilled and 40 were successfully finished as observation wells. The locations of these test holes are shown in figure 2. The drilling produced cuttings samples for 27,303 feet of rock-bit drill-holes as well as 2,747 feet of rock core for more detailed analysis. Sample cuttings and cores from the test holes were described. Natural gamma radiation logs were obtained for most holes. Electric, caliper, neutron, and gamma-gamma logs were also obtained on some holes. Three nested observation wells were constructed, and the bottoms of 10 piezometers were successfully perforated at higher intervals, providing multiple head and water-quality data at some sites. Water levels were measured monthly from February to August, 1980, and intermittently at other times. Water samples were collected and analyzed for common dissolved minerals, metals, and radiation. Controlled pumping tests were performed at 4 sites to estimate aquifer parameters.

Other data from private drillers in the area were used extensively. These data consist primarily of well cuttings that were voluntarily submitted to IGS and were logged by staff geologists. A selected data set is presented in the Appendix of this report.

PRE-CRETACEOUS STRATIGRAPHY

Cretaceous rocks in northwest Iowa are directly underlain by both Precambrian and Paleozoic-age rocks. The most common Precambrian rock type is the Sioux Quartzite, which occurs in the northwestern part of the study area. Igneous and metamorphic rock types are also present, however (Tvrdik, in prep.; Yaghubpur, 1980). The Paleozoic rocks in northwest Iowa range in age from Cambrian to Pennsylvanian, and dip at about 18 feet/mile to the south-southeast. A succession of these rocks subcrops beneath the Cretaceous rocks (figure 3). The distribution of significant hydrogeologic units in the Paleozoic section is shown in figure 3 and their properties are summarized in Table 1. Details concerning the correlation of these units with better known stratigraphic sequences in adjacent areas can be found in Witzke (1980), Tynan (1980), Klug (1980), Klug and Tynan (1981), McKay (1980), Horick and Steinhilber (1973), and Horick and Steinhilber (1978).

REVIEW OF CRETACEOUS STRATIGRAPHY

The stratigraphic nomenclature of Cretaceous rocks in Iowa used in this report for the Cretaceous section in Iowa is, beginning with the lowermost unit, the Dakota Formation, the Graneros Shale, the Greenhorn Limestone, and the Carlile Shale (Table 2). Two members of the Dakota Formation are recognized in Iowa, the Nishnabotna Member and the Woodbury Member. These names were originally proposed by White (1867, 1870a, b), although he applied lithologic names rather than stratigraphic names (i.e. Nishnabotna Sandstone and Woodbury Sandstones and Shales). White's nomenclature, although never widely adopted, is used in this report because these units are distinct facies assemblages which are recognizable over a wide area, and provide a useful framework for describing the occurrence of the Dakota aquifer in Iowa, and perhaps in adjacent states. The two members of the Dakota Formation are not afforded formational status in northwest Iowa because they can not be precisely mapped in the area with the available data set. A brief review of the development of Cretaceous nomenclature in the Midwest is presented here in order to clarify the nomenclature used in this report. A more comprehensive review is presented in Tester (1931).

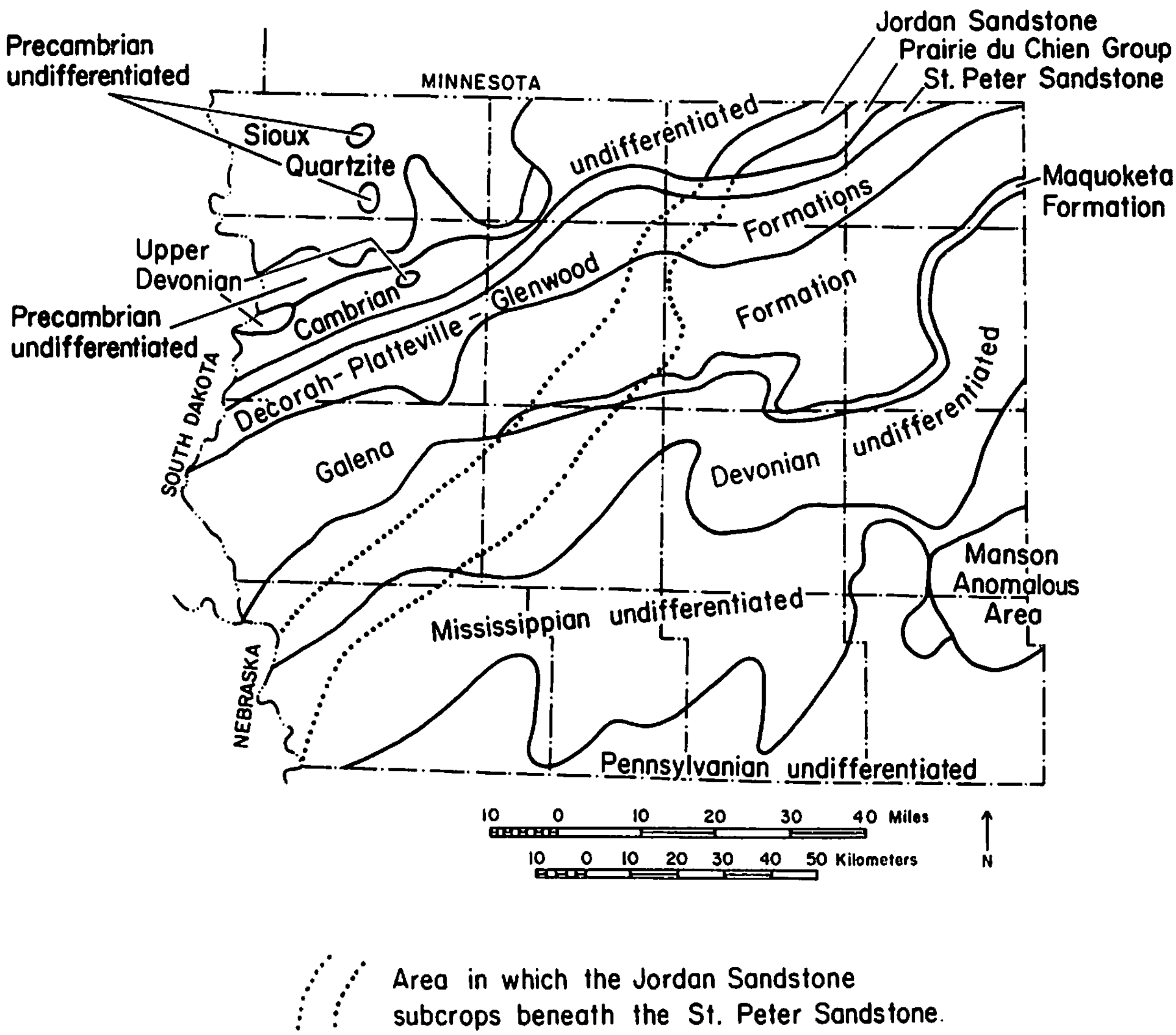

Figure 3. Distribution of Pre-Cretaceous rocks in northwest Iowa.

Meek and Hayden (1862) defined the Dakota Group from the type area of Dakota County, Nebraska (figure 1). This area has been recently revisited (Brenner, et al., 1981), and the section as presently exposed has been described (figure 4). Even though the exposed stratigraphic section is less than 150 feet feet thick, Meek and Hayden (1862) postulated a total thickness of about 400 feet for the Dakota Formation in the type area. This was likely based on well logs in the area (Tester, 1931; Schoon, 1971). The lithology of the lower two to three hundred feet of the formation was not clearly described by Meek and Hayden (1862).

Meek and Hayden's (1862) work encompassed much of the midwest and west, and resulted in the naming of several Cretaceous units above the Dakota Group, including the Fort Benton Group and the Niobrara Division (Table 2). Meek and Hayden referred to these units as "Formations" as well as with the above-mentioned names, and it is apparent that their use of the terms "Group" and "Formation" does not hold the same specific connotation that it does today.

Table 1. Hydrogeologic units in northwest Iowa.

Era	System	Formation	Description	Hydrostratigraphic unit
Cenozoic	Quaternary	undifferentiated	sand and gravel near streams	alluvial aquifers
			loess, wind blown silt mantling uplands and terraces	minor aquifers grading to leaky confining unit
			till, poorly sorted fine-textured glacial sediment	regional confining unit commonly 200-400 feet thick
			sand or sand and gravel within or between tills or beneath tills in bedrock valleys.	intertill or buried channel aquifers, locally highly productive.
Mesozoic	Cretaceous	Carlile	calcareous black marine shale	regional confining beds, where present. Weathered Greenhorn may yield small amounts of water.
		Greenhorn	chalky limestone, shaly	
		Graneros	calcareous marine shale	
		Dakota: Woodbury Member	interbedded shale, sandstone and lignite. Thickness and extent variable	Dakota aquifer: minor aquifer grading to confining unit. Low to moderate yields to wells
		Dakota: Nishnabotna Member	Massive sandstone, medium to coarse grained, with shale interbeds. Commonly over 200 feet thick.	Dakota aquifer: major aquifer in much of northwest Iowa.
Paleozoic	Pennsylvanian	undifferentiated	mostly shale, with some sandstone, limestone and coal	confining unit not extensive in northwest Iowa.
	Mississippian	undifferentiated	limestone and dolostone	low to moderate yields to wells, significant aquifer only where near land surface.
	Devonian	undifferentiated	dolostone, shaly near top	
	Ordovician	Maquoketa	dolostone	
		Galena	dolostone	
		Decorah	shale	regional confining unit
		Platteville	shale and shaly dolostone	
		Glenwood	shale and oolitic ironstone	
		St. Peter	sandstone, fine-grained and shaly.	Major regionally extensive aquifer
		Prairie du Chien Group	dolostone and shale	
	Cambrian	Jordan	sandstone, medium-grained, dolomitic	
		St. Lawrence	dolostone	No major aquifers
		Davis	shale, some sandstone and dolostone	
		Bonneterre	dolostone, silty	
		Mt. Simon	sandstone	
Precambrian		Sioux	quartzite and argillite, commonly weathered at top, low yields to wells	effective base of ground-water systems
		undifferentiated	igneous and metamorphic rocks, very low water-bearing capacity.	

Table 2. Stratigraphic nomenclature of Cretaceous rocks in and near Iowa.

<table>
<tr><th>Meek and Hayden (1862)</th><th>White (1870a,b)</th><th>Gilbert (1897)</th><th colspan="2">Plummer and Romary (1942) and Moore et al. (1951)</th><th colspan="2">Iowa Geological Survey 1981, (this report)</th></tr>
<tr><td rowspan="2">Niobrara Division</td><td></td><td>Carlile Shale</td><td colspan="2">Carlile Shale</td><td colspan="2">Carlile Shale</td></tr>
<tr><td>Inoceramus beds</td><td>Greenhorn Limestone</td><td colspan="2">Greenhorn Limestone</td><td colspan="2">Greenhorn Limestone</td></tr>
<tr><td>Fort Benton Group</td><td rowspan="2">Woodbury Sandstones and Shales</td><td>Graneros Shale</td><td colspan="2">Graneros Shale</td><td colspan="2">Graneros Shale</td></tr>
<tr><td rowspan="2">Dakota Group</td><td rowspan="2">Dakota Sandstone</td><td rowspan="2">Dakota Formation</td><td>Janssen Member</td><td rowspan="2">Dakota Formation</td><td>Woodbury Member</td></tr>
<tr><td>Nishnabotany Sandstones</td><td>Terra Cotta Member</td><td>Nishnabotna Member</td></tr>
</table>

The Dakota Group is currently recognized in the western United States where it is composed of several well-defined formations. Near the Big Sioux River, however, mappable subdivisions of the Dakota have never been described. For this reason, the Dakota is assigned formational status in South Dakota (Schoon, 1971) and Iowa.

White (1867, 1870a,b) apparently recognized that Meek and Hayden's (1862) nomenclature was too general to describe Cretaceous rocks in Iowa. He recognized a unit extensively developed in southwestern Iowa and described it as "a coarse-grained, friable, ferruginous sandstone, to which I have given the provisional name of Nishnabotany [sic] sandstones (White, 1867, p. 27)." Furthermore, he states that this unit "is suspected to be a part of the Dakota group of the Cretaceous rocks (White, 1867, p. 28)." White (1870a,b) also provided a general description of the unit, including the paleontology, geographical extent, and specific section descriptions and sketches. The general lithologic description is reproduced here:

> "Lithologically, this formation is almost entirely a rather coarse grained, friable, more or less ferruginous sandstone; but in a few instances, thin, irregular layers of clayey material are found in it. Sometimes the grains of sand of which it is composed, are so lightly coherent that a spade may be thrust into it by a strong man. Occasionally, layers of gravel occur intercalated with the sand, which would thus form conglomerate if the pebbles were firmly cemented together. At Lewis, in Cass County, the sandstone contains so much brown oxyd [sic] of iron that it has a uniform dark-brown color. In some other places the iron acts as a firm cementing material for the grains of sand, forming hard, brown, irregular layers and concretions in the softer and lighter colored portions of the rock (White, 1870a, p. 290)."

This unit does not outcrop in northwest Iowa.

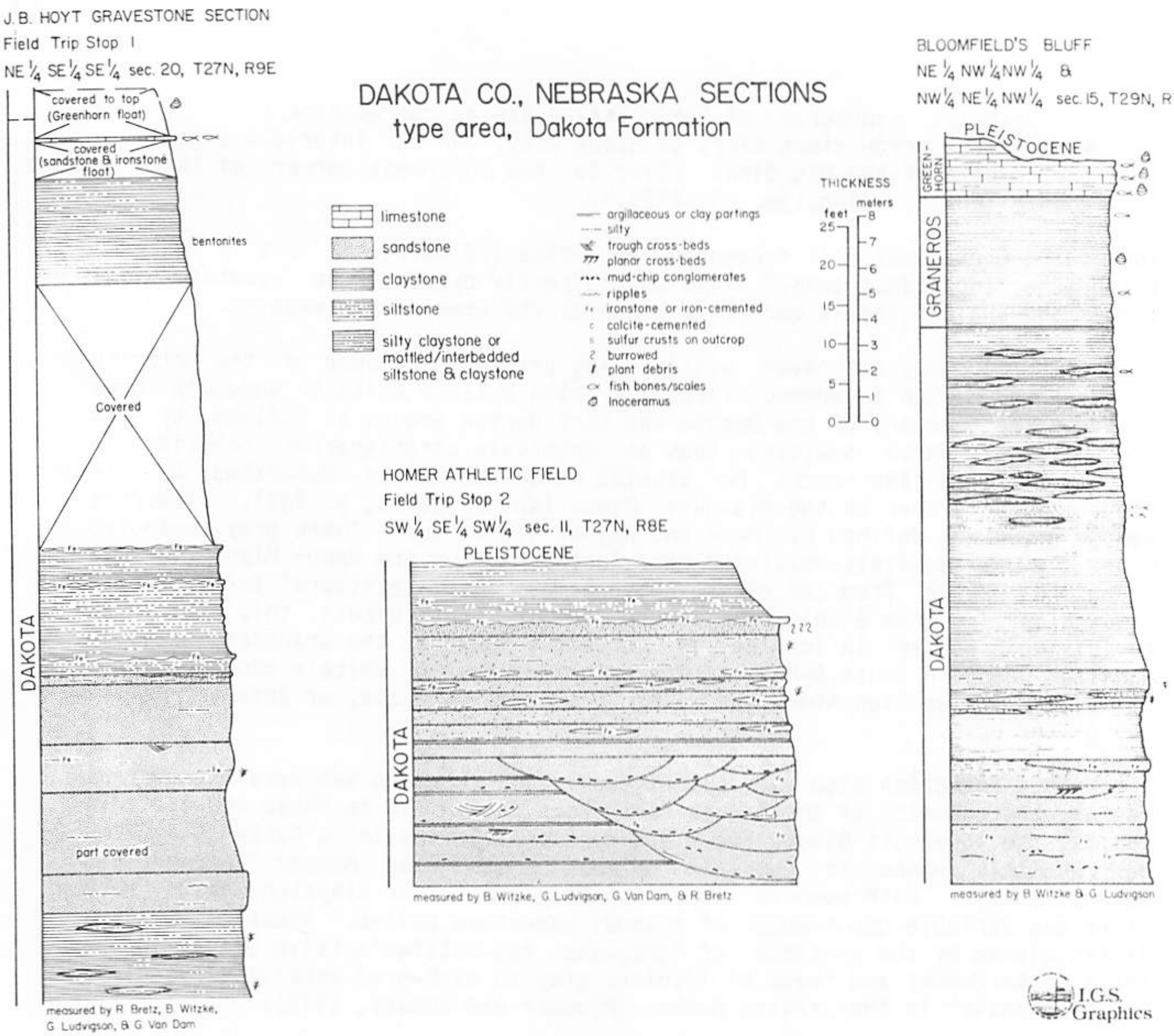

Figure 4. Measured stratigraphic sections of the Dakota, Graneros, and Greenhorn Formations (from Witzke and Ludvigson in Brenner, et al., 1981, p. 154-157).

White, (1980a,b) also introduced the Woodbury Sandstones and Shales, and his general description is also reproduced:

> "These strata, as their name implies, are composed of alternating sandstones and shales, the latter being sometimes sandy, and sometimes clayey, with more or less calcareous material intermixed. They follow next in order, and rest upon the Nishnabotany [sic] sandstone. They have not yet been observed outside the limits of Woodbury County which give them their name, but they are found there to reach a maximum thickness of about one hundred and fifty feet.

The principal exposures of these strata are at Sergeant's Bluff's, seven miles below Sioux City, at Sioux City, and at intervals along the bluffs of the Big Sioux river to the northwest corner of the county (White, 1870a, pp. 291-292)."

The third Cretaceous unit recognized by White (1870a,b) in Iowa is what he termed the "Inoceramus beds." This unit directly overlies the "Woodbury Sandstones and Shales" and is currently known as the Greenhorn Limestone.

White's terminology was never widely used, primarily because of the priority of Meek and Hayden's nomenclature, but also because White's Woodbury rocks straddle the boundary of the Dakota and Fort Benton Groups as defined by Meek and Hayden. White admitted that an uncertain stratigraphic relationship existed between the rocks he studied and the rocks described by his predecessors further up the Missouri River (White, 1870a, p. 288). The Fort Benton group was defined by Meek and Hayden (1862) as: "Dark grey laminated clays . . . extensively developed near Fort Benton on the Upper Missouri; also along the latter from ten miles above James River (eastward) to (the) Big Sioux River." From a thickness of 800 feet in South Dakota, this unit thins to less than 50 feet in Iowa and is currently known as the Graneros Shale in Iowa and eastern South Dakota. The upper contact of White's Woodbury Sandstones and Shales lies somewhere within the Graneros Shale, or possibly at the top of the unit.

The Dakota Formation also outcrops extensively in eastern Nebraska and central Kansas, and subunits of the Dakota have been recognized in these states. In Kansas, the lowermost Dakota rocks are contained in the Terra Cotta Clay Member and this member is overlain by the Janssen Clay Member (Plummer and Romary, 1942). Both members are dominantly kaolinitic claystone units with minor and variable occurrences of channel sandstone bodies. These members are distinguished by the presence of "gray-and red-mottled massive clay" in the Terra Cotta Member and "beds of lignite, grey to dark-grey massive clay, silt, and some shale" in the Janssen Member (Plummer and Romary, 1942).

A three-fold division of the Dakota in eastern Nebraska was proposed by Condra and Reed (1943, 1959). These units were not found to be useful by recent workers (Bowe, 1972; Karl, 1976) who used the nomenclature of the Kansas Geological Survey in their studies of the Dakota Formation in eastern Nebraska. Numerous previous workers have commented on the difficulty of correlating individual sandstones units in the Dakota Formation, even over short distances (Gould, 1901; Condra, 1908; Tester, 1931; and Plummer and Romary, 1942).

QUATERNARY STRATIGRAPHY

The Quaternary geology of northwest Iowa is relevant to this study because the Quaternary deposits constitute both the major confining unit of the Dakota aquifer, but also contain major aquifers that hydraulically interact with flow systems in the Dakota aquifer. The thickness and lithology of these units are highly variable because of the configuration of the pre-Quaternary surface, the complexity of erosion and deposition during multiple periods of Quaternary glaciation, and post-glacial erosional and depositional features in major stream valleys. Table 1 summarizes some of the properties of the major Quaternary hydrostratigraphic units in northwest Iowa.

The surficial distribution of major Quaternary stratigraphic units in northwest Iowa is presented in figure 5. The Pre-Illinoian deposits (formerly known as Kansan and/or Nebraskan; see Hallberg, 1980; Hallberg and Boellstorff, 1978) are a result of the oldest known glaciations in the area and represent several separate periods of glacial ice advance and interglacial periods.

The Wisconsinan deposits in Iowa have been separated into the Tazewell till and the Cary till (Ruhe, 1969). The Tazewell till is late middle-Wisconsinan in age and is overlain by thin deposits of late Wisconsinan loess. The Cary till is late Wisconsinan in age, forms the prominant physiographic region known as the Des Moines Lobe, and is not overlain by loess. The Des Moines Lobe deposits are relatively young (deposited about 12,000-14,000 years before present), and are characterized by poorly developed drainage networks, knob and kettle topography, a variety of morainal features, and valley-type outwash systems. Nearly all of Iowa's natural lakes are on the Des Moines Lobe.

Loess deposits reach a maximum thickness in the study area of approximately 100 feet near their major source area, the Missouri River Valley. The Loess Hills region is the area of thickest loess deposition. The deep incision of modern-day streams has resulted in a fairly high-relief area. The loess thins rapidly in a northeasterly direction (figure 5) in the study area.

Nearly all of the larger streams in northwest Iowa carried drainage from Pleistocene glacial meltwaters. The sand and gravel deposited in these valleys form the major alluvial aquifers in the region (figure 5). The Little Sioux River Valley is particularly noteworthy because it drained a major glacial lake, and consequently is deeply incised into the Quaternary glacial deposits (Hoyer, 1980). This deep valley has a significant influence on the Dakota aquifer flow system. Details of the Floyd River alluvial aquifer can be found in Wahl, and others, (1982).

DESCRIPTION OF CRETACEOUS ROCKS IN NORTHWEST IOWA

Dakota Formation

The following descriptions of the Dakota Formation rely on previously published descriptions and on additional information obtained through the course of this study. It should be noted that the Woodbury Member, as used herein, differs from the original description of White (1870a) in that the upper boundary of the member coincides with the contact between the Dakota and the Graneros Formations, rather than with the base of White's (1870a,b) "Inoceramus beds" (Greenhorn Limestone). Also, the spelling of White's "Nishnabotany" term is modified to reflect the current spelling of the river for which the rocks were named, Nishnabotna.

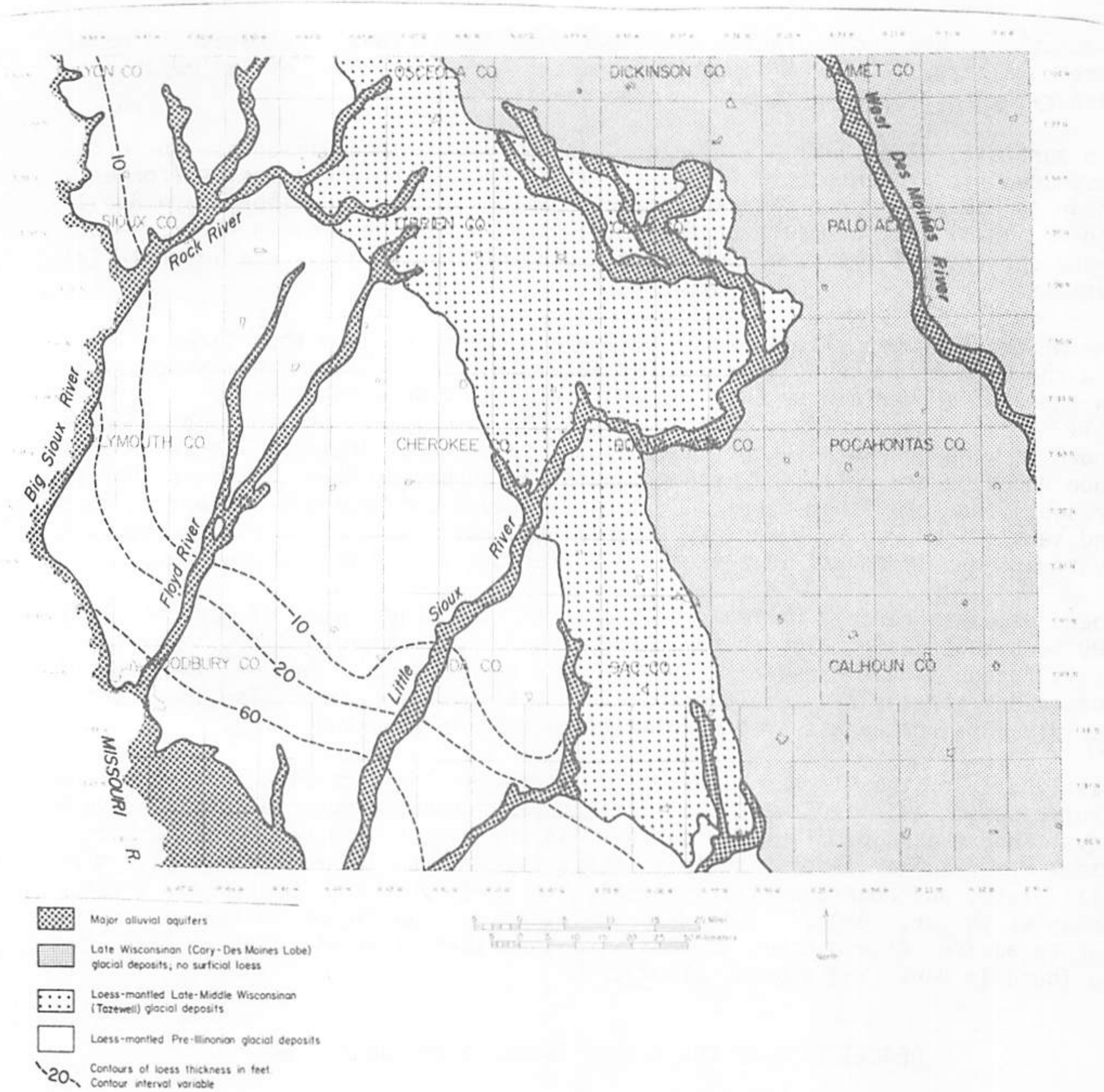

Figure 5. Surficial geologic map of Quaternary deposits of northwest Iowa.

<u>Nishnabotna Member</u>

The Nishnabotna Member, the lowermost member of the Dakota Formation, is dominantly sandstone, a medium-to coarse-grained friable quartz arenite to sublitharenite (terminology after Folk, 1968) composed of mono-and polycrystalline quartz grains with rare crystalline rock fragments. Nishnabotna sandstones are commonly micaceous. The Nishnabotna Member also contains some shale, claystone, fine-grained sandstone and conglomerate interbeds. Rare lignites are present, generally no more than one or two feet in thickness. Pyrite and iron oxide and/or hydroxide cementation is locally present. In the sandstone intervals, both coarsening-upward and fining-upward sequences are observed. The fine-grained sequences observed in cores commonly consist of white to red mottled, nonlaminated, noncalcareous clay-rich units with root casts. Light- to dark-grey shales are also present. Thick clay sequences with limestone and chert clasts, which are inferred to be weathered residues of Paleozoic rocks, are commonly found at the base of the Nishnabotna, resulting in difficulty in precisely defining the base of the Cretaceous System at some localities. Where the Cretaceous rocks are directly underlain by Paleozoic carbonate rocks, solution cavities are often encountered. This is inferred from the common loss of large volumes of drilling fluid upon penetration of the Paleozoic carbonate rocks.

The sedimentary structures and textures in the Nishnabotna Member suggest that braided stream systems (Bowe, 1972) and/or coarse-grained meandering stream systems (Whitley, 1980) are the dominant depositional environments. These types of depositional environments are characterized by the winnowing of most of the silt-and clay-sized material, and by the deposition of mostly sand-sized material. Sand bodies in the Nishnabotna Member are relatively thick and widespread, and are generally well interconnected with one another. This results in an aquifer of regional extent that has a significant potential for development.

The contact of the Nishnabotna Member with the overlying Woodbury Member is not known to be exposed anywhere in Iowa. Also, wherever the Nishnabotna Member has been observed, it is never directly overlain by the Graneros Shale. Complete Nishnabotna sequences, with both upper (Woodbury) and lower contacts preserved, were penetrated in 16 IGS/USGS test holes (see Appendix). The thickness of the Nishnabotna varied from 63 to 365 feet in these holes. Analysis of these data shows that the average sandstone content in vertical sequences of the Nishnabotna Member is 83%.

Woodbury Member

The Woodbury Member of the Dakota Formation overlies the Nishnabotna Member and outcrops extensively in Woodbury County, Iowa, in surrounding areas in Nebraska, and also in Plymouth and Sac Counties in Iowa. It is not known whether or not this unit is present in west-central or southwest Iowa. The most complete descriptive inventory of the known outcrops is contained in Tester (1931). More recent descriptions of some of the same outcrops are found in Whitley (1980), and Brenner and others (1981). The Woodbury Member consists of a complex interbedded assemblage of very fine-to medium-grained, friable, calcite-, goethite-, or limonite-cemented, or non-cemented sandstone, commonly micaceous, and noncalcareous, dark-grey, or yellow- to red-mottled shale or mudstone with interbedded lignite and siltstone. Most of these thinly interbedded lithologies have maximum thicknesses of a few tenths of a foot to a few feet. Pyrite and siderite nodules are common, as are gypsum crystals, plant fragments, and root casts. The sandstones commonly exhibit trough and tabular cross bedding, ripplemarks and occasional burrowed fabrics. Tester

(1931) reported the presence of glauconite in many sections, but this has not been confirmed by recent workers. Marine fossils have been noted in the upper parts of the Woodbury Member (Tester, 1931; Hattin, 1965).

The depositional environment of the Woodbury Member is interpreted to be a fine-grained meander-belt system (Whitley, 1980) or a fluvial-deltaic complex (Bowe, 1972) resulting from encroachment of the Cretaceous sea from the west. Because of this transgression, stream gradients declined, average sediment grain size decreased, and floodplains aggraded and probably widened.

This type of deposition results in little lateral continuity of individual beds within the Woodbury Member. Tester (1931, p. 254) concluded that "two sections at the same level only a few hundred feet apart, but concealed in the interval, will show distinctly different types of rocks." This conclusion has been substantiated by the present study. As a result of this depositional environment, the hydraulic connection between sandstone bodies in the Woodbury Member is poor, and the productive capacity of wells completed in those sandstones is limited.

The contact between the Woodbury Member and the underlying Nishnabotna Member varies from sharp to gradational. Criteria used to distinguish these units are:

1) Differences in lithologic unit thickness. Thicknesses of sandstone and mudstone units in the Woodbury Member are typically a few tenths of a foot to a few feet, whereas in the Nishnabotna Member, the units are typically a few tens of feet thick.

2) Differences in grain size distribution of the sandstones. Well-sorted very fine-to fine-grained sandstones are characteristic of the Woodbury Member, whereas the Nishnabotna Member is distinguished by more poorly-sorted very coarse-to fine-grained sandstones.

Precise delineation of the contact may require the application of one or both of these criteria, and may be somewhat subjective because of the gradational nature of the contact at some localities. At most places, the contact may be defined as the top of the first relatively thick (>20 feet) sandstone beneath the Greenhorn Limestone.

Given the gradational nature of this contact it must be recognized that the Woodbury and Nishnabotna Members may grade laterally into each other, over relatively short distances, within their "zone" of contact. This is best seen at a locality in Osceola County where 4 Dakota wells are located within a small area. A geologic cross section (figure 6) illustrates the lithologic variation at the site. Each well has a distinctive contact separating the Woodbury from the Nishnabotna Members. If a structure contour map were prepared on this surface at this locality, the relief of the surface would be greater than 100 feet. This is interpreted to be a result of the deposition of the upper parts of the Nishnabotna contemporaneously with, and adjacent to, deposition of the lower parts of the Woodbury. In other words, lateral facies changes occur over distances of a few hundreds of feet. This is consistent

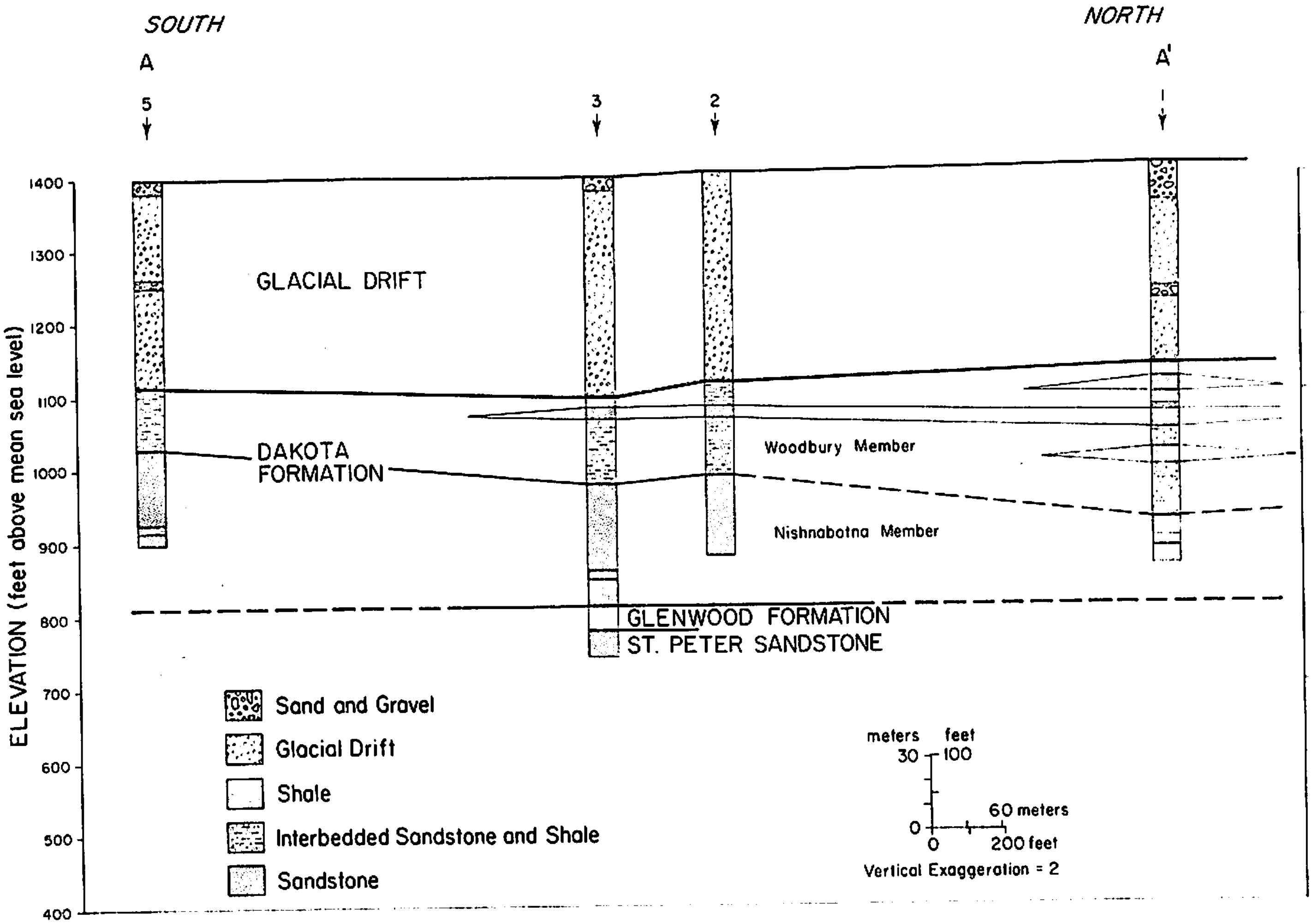

Figure 6. Geologic cross section at the Hibbing irrigation site.

with the concept of a gradational contact separating the two members. However, the value of distinguishing between the two members is that the lithologic assemblages of each unit are widely recognizable, and that the stratigraphic position of each member is consistent throughout the study area.

The conformable upper contact of the Woodbury Member with the overlying Graneros Shale is commonly difficult to recognize. White (1870a,b) apparently recognized the difficulty in drawing lithologic distinctions in the gradational sequence of rocks and identified only one formation in this area beneath the "Inoceramus beds." Tester (1931, p. 275) also recognized the problem: "The Dakota stage . . . is conformable with the overlying calcareous marine shales and sandstones of the Graneros Formation. Not only is it impossible to find any break in the section, but it is very difficult to place any arbitrary boundary between the two stratigraphic units." Nevertheless, several criteria have been used. Hattin (1965) and Schoon (1971) used the top of the first major sandstone below the Greenhorn. Many sections, however, are dominantly shale or interbedded sandstone and shale deep within the Dakota. In these situations, Hattin (1965) used the top of "clay-ironstone" horizons that contained, at various localities, siderite concretions, pyrite nodules, or distinctive limonitic zones. Witzke (1981, p. 112) noted that calcareous shales can be called Graneros Shale and that noncalcareous shales can be called Dakota shales. This criteria is most commonly used if the distinction between the two must be based only on subsurface samples.

Fortunately, the analysis of subsurface samples can be augmented with geophysical logs to more accurately delineate lithologic units. Natural gamma radiation logs show that the Graneros has more natural radiation and that the radiation is less variable than in the Dakota Formation. Gamma logs are also useful for distinguishing sandstone from shale or mudstone, which is necessary for identifying the Woodbury and Nishnabotna Members in the subsurface.

The Woodbury Member has been identified in the subsurface at 25 locations where the Graneros Shale is also present (see Appendix). The average thickness of the Woodbury in these holes is 121 feet with a standard deviation of 41 feet. The thickness of the Woodbury ranges from 45 feet to 215 feet in these wells. Twenty three other wells have been identified in which the Woodbury Member is the uppermost Cretaceous unit present and was fully penetrated. Even though part of the Woodbury is erosionally removed, the average thickness of the Woodbury Member is 147 feet. Although the thickness of the Woodbury is variable, it appears that a regionally averaged thickness of 100 to 150 feet is reasonable. The determination of a regionally averaged thickness for the Woodbury Member was necessary for mapping the regional extent and thickness of the Dakota aquifer. Eleven wells were identified where the Nishnabotna Member is the uppermost Cretaceous unit present, and where the Woodbury Member has been erosionally removed.

Graneros Shale

The Graneros Shale directly overlies the Dakota Formation and consists of thinly laminated, dark-grey, dominantly calcareous clay shale with some silty and sandy interbeds. The unit varies in thickness from 18 to 65 feet, where complete sections are present. Fossils within the Graneros include pelecypods, ammonites, fish fragments, and plant debris. The dominant clay mineral in the Graneros is illite (Bowe, 1972) with lesser amounts of kaolinite and smectite (Hattin, 1965).

Greenhorn Limestone

The Greenhorn Limestone conformably overlies the Graneros Shale and consists of thin-to medium-bedded, fossiliferous, shaly, chalky limestone. The unit is medium grey and weathers to a light yellowish-brown. The Greenhorn has a maximum thickness of about 30 feet in Iowa. Specimens of the bivalve *Inoceramus* are abundant.

Carlile Shale

Overlying the Greenhorn Limestone is the Carlile Shale, a dark-grey, calcareous, thinly laminated marine shale. The full stratigraphic thickness of the unit in Iowa is not known because the upper contact is erosional, but thicknesses of up to eighty feet are known (IGS/USGS test well D-19). Thicknesses of over 200 feet have been observed in southeastern South Dakota (Iles, pers. communication, 1981). The geographic extent of the Carlile, Greenhorn, and Graneros Formations is mostly restricted to the western half of the study area because of post-Cretaceous erosion.

STRUCTURE OF THE CRETACEOUS ROCKS IN IOWA

To fully describe the thickness and the extent of the Dakota aquifer, it is necessary to analyze the structure of the Cretaceous rocks. A structure contour map was constructed on the base of the Graneros Shale (figure 7). The principal data for this map consist of outcrops and drillholes which penetrate the Graneros Shale-Dakota Formation contact. Numerous other data points used in the map consist of geologic logs which only note the occurrence of sandstones in the Dakota Formation. These points can be used to infer minimum elevations for the base of the Graneros Shale, which provide guidelines for interpretation in areas where the Graneros is absent.

The regional dip of Cretaceous rocks in the study area is to the northwest at approximately 4 feet per mile. Locally, features with much greater relief are superimposed on this regional trend. Anomalies shown in Dickinson, Ida, and Sioux Counties are based on subsurface data, and the anomaly in Sac County is based on closely spaced outcrops of Greenhorn Limestone, Dakota sandstone and two drill holes, one of which was cored (core hole D-48E, see Appendix). This core exhibits a bedding-plane dip of approximately 25° in the Cretaceous strata. Subsurface data only 135 feet apart shows approximately 50 feet of local structural relief in the area. The Sac County data demonstrate at least 150 feet of structural relief within an area of 0.25 square miles (160 acres). Whether faulting, folding or other structural elements are involved is not fully known. The presence of significant local post-Cretaceous tectonism is consistent with recent studies of the Cretaceous deposits in Minnesota (Shurr, 1980).

The largest structural anomaly in the region is the Manson anomalous area in the southeast part of the study area (figure 3). A detailed stratigraphic analysis was not done within the boundaries of this area because of the complexity of the region.

The Manson anomalous area refers to a circular-shaped region of structurally disturbed rocks approximately 20 miles in diameter in Calhoun, Pocahontas, Humboldt, and Webster Counties. The structure was first reported by Hale (1955, p. 35), who referred to it as the "Manson Volcanic Basin." The structural configuration of the anomalous area was defined by Hoppin and Dryden

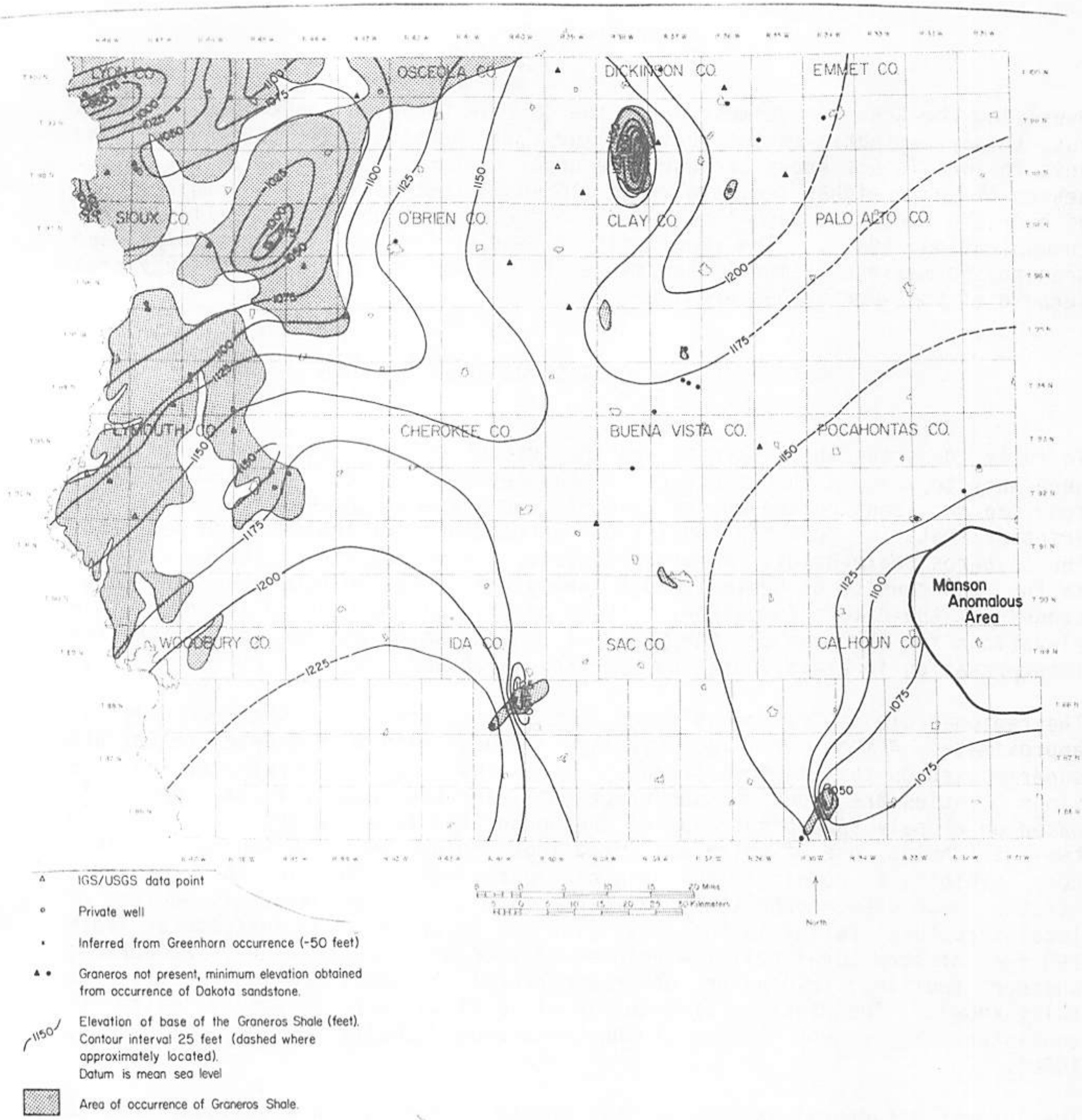

Figure 7. Elevation of the base of the Graneros Shale in northwest Iowa.

(1958), who described a central area of uplifted, brecciated, igneous and metamorphic Precambrian rocks surrounded by a structurally depressed area of deformed Cretaceous and Paleozoic rocks. A detailed gravity mapping study by Holtzman (1970) showed that, in addition to the central peak of uplifted crystalline Precambrian rocks, the peripheral areas are characterized by arcuate faults with an outer ring graben.

The origin of the feature is not firmly established. Hoppin and Dryden (1958) referred to the Manson structure as a "cryptovolcanic" feature, similar to other small areas of intensely deformed rocks in the midcontinent region. Holtzman (1970, p. 6) suggested a meteor impact origin for the Manson structure, based on the general structural configuration, the similarity of the area's gravity expression to documented impact sites, and personal communications with NASA workers who were investigating the petrology of the crystalline rocks. Bunch (1968) reported on the petrology of deformed Precambrian rocks from Manson and other possible impact sites. The presence of kink bands in feldspars and micas, and deformation lamellae in quartz were cited as microstructural evidence of shock metamorphism. The absence of shock-formed glasses and high pressure silica polymorphs, however, led Bunch (1968, p. 431) to withhold positive identification of the Manson area as a meteor impact site.

DESCRIPTION OF THE DAKOTA AQUIFER

The term Dakota aquifer, as used in this report, refers to sandstone beds within the Dakota Formation that yield significant quantities of water to wells. Wells drilled only into the Woodbury Member are significantly less productive than wells completed in the Nishnabotna Member because of the limited vertical and lateral extent of the sandstone deposits within the Woodbury. Wells penetrating a significant thickness of the Nishnabotna Member, commonly have very high yields (800-1000 gpm) because of the thick and extensive nature of the sandstone units. The objective of the following section is to present a series of geologic maps that delineate the occurrence of the Dakota aquifer in the study area.

Thickness and Extent of the Dakota Aquifer

To delineate the Dakota aquifer, it is necessary to produce maps for several important geologic horizons. One such horizon is the surface formed by the unconformity at the base of the Cretaceous system, or, where Cretaceous rocks are absent, the base of the Quaternary system (figure 8). Paleocurrent data (Bowe, 1972) support the interpretation of this surface as a drainage or stream-dissected surface with net transport of Dakota-age sediment to the southwest. In the construction of the drainage network on this map, post-Cretaceous tectonic activity is assumed to be negligible.

A second significant unconformity is present at the base of the Quaternary system (Plate 1). This map is also interpreted to be a drainage surface, but the large data density allows for considerably more detail and less uncertainty than is present in figure 8.

Figure 8 and Plate 1 represent the bounding surfaces of the Cretaceous deposits in Iowa, and it is readily apparent that each surface is highly irregular. The high relief of each surface results in a highly variable thickness of Cretaceous rocks within the study area. Using the maps of these surfaces,

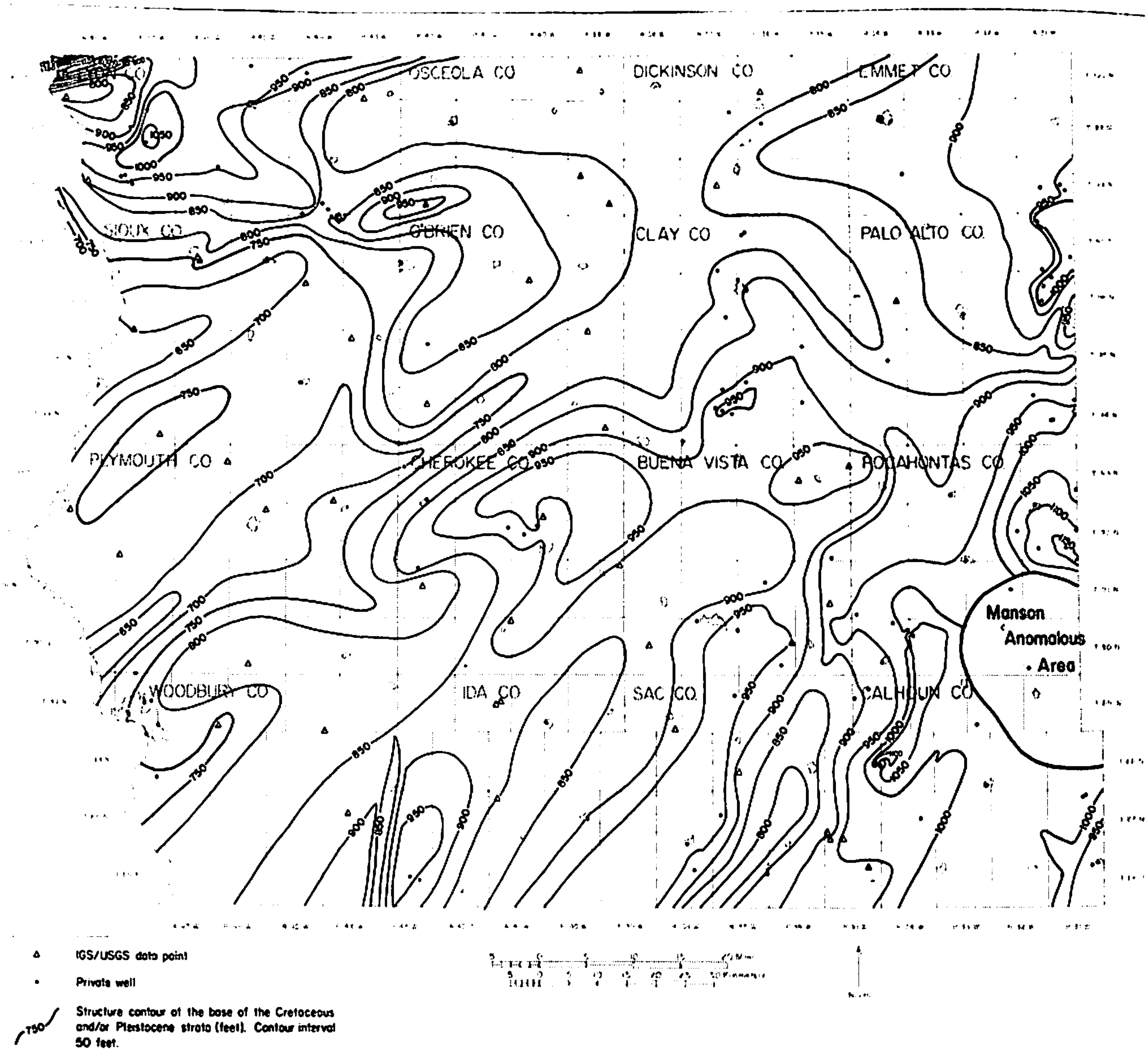

Figure 8. Elevation at the base of the Cretaceous system (or base of the Pleistocene where Cretaceous rocks are absent) in northwest Iowa.

the structure contour map in figure 7, and all available geologic data, a sub-Pleistocene geologic map was constructed (figure 9). The approximate distribution of the Woodbury and Nishnabotna Members of the Dakota Formation was delineated by assuming a uniform thickness of 150 feet for the Woodbury Member (derived from the average thickness of the member). The portion of the geologic map (figure 9) showing the subcrop belt of the two members of the Dakota Formation is intended to be a generalized indicator of the distribution of these members. The accuracy of this map can be evaluated by comparing the locations of the 37 IGS/USGS data points (see Appendix) that penetrate either the Nishnabotna or Woodbury Members as the uppermost Cretaceous unit with the mapped units on figure 9. The majority of these points (32 out of 37) are consistent with the map, indicating that the mapping techniques are generally

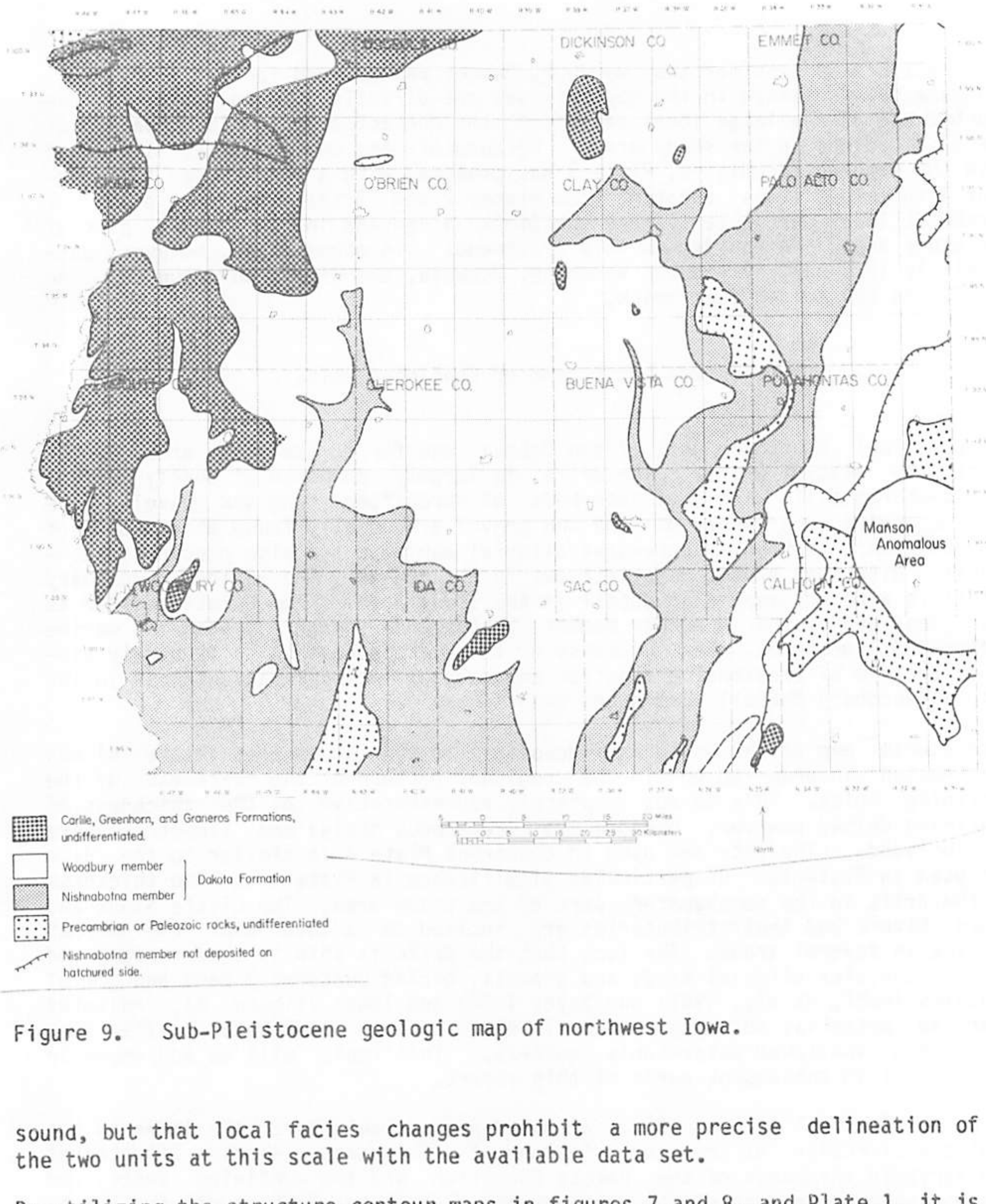

Figure 9. Sub-Pleistocene geologic map of northwest Iowa.

sound, but that local facies changes prohibit a more precise delineation of the two units at this scale with the available data set.

By utilizing the structure contour maps in figures 7 and 8, and Plate 1, it is possible to construct an isopach map of the Dakota Formation (Plate 2). This map gives a good indication of the distribution of the formation in northwest Iowa. A still more useful description of the Dakota aquifer can be provided by an isopach map of the Nishnabotna Member. By using an idealized structure contour map of the Woodbury/Nishnabotna contact in conjunction with the structure contour maps in figure 8 and Plate 1, it is possible to construct an isopach of the Nishnabotna Member (Plate 3). As for the geologic map, a uniform thickness of 150 feet for the Woodbury Member was assumed for this analysis. The data set presented in the Appendix was not directly used to construct the map because of the large local relief of the contact and the wide spacing of the data points in the study area. Because of the uncertainties associated with the mapping techniques, Plate 3 was prepared with a one hundred foot contour interval. It is apparent from Plates 2 and 3 that in large areas of northwest Iowa, particularly near the Sioux Ridge and in the eastern part of the study area, the aquifer is thin or absent. In other areas, however, particularly in Sioux, Plymouth, Woodbury, Osceola, and Dickinson counties, the aquifer is 200 to 300 feet thick.

Thickness and Extent of Confining Units

The principal confining unit of the Dakota aquifer in the study area is the Quaternary glacial drift. The drift is largely composed of poorly sorted fine-textured tills with some interbeds of stratified sand and gravel. The most extensive occurrences of sand and gravel are usually found at the base of the Quaternary section. Extensive alluvial aquifers are also present in conjunction with most of the major streams in the region. The various Quaternary materials were not mapped in detail in the study area. The Dakota aquifer is also confined by the Woodbury Member Shales and younger Cretaceous marine shales and limestones. The thickness of these Cretaceous units is highly variable because of erosional dissection and complex facies relationships in the Dakota (Woodbury Member) shales and sandstones.

A thickness map of the Quaternary deposits in the study area (Plate 4) was constructed in order to obtain the regional pattern of the thickness of the confining units. This is not completely representative of the thickness of confining units, however, because the Cretaceous shales and limestones were not included. The data set used to construct Plate 4 is similar to the data set used in Plate 1. Of particular significance in Plate 4 is the thickness of the drift in the southwestern part of the study area. The Little Sioux and Floyd Rivers and their tributaries are incised to a level near the bedrock surface in several areas. The fact that the drift is thin in these areas, and that it contains alluvial sands and gravels, buried Quaternary sand and gravel deposits (Wahl, et al., 1981; and Saye, 1980) and loess (figure 4), indicates that the potential for interaction is high between the Dakota aquifer flow system and shallower water-table aquifers. This topic will be addressed in more detail in subsequent parts of this report.

Cross Section D-D' (figure 10) is oriented perpendicularly to the inferred net drainage direction of Cretaceous "streams." This cross section illustrates the variable thickness of the Dakota Formation and the confining units, and the variable occurrence of the Woodbury and Nishnabotna Members of the Dakota Formation. It should be noted that the Nishnabotna Member is relatively thick and consistently present in the western portion of the study area, except near the Sioux Ridge.

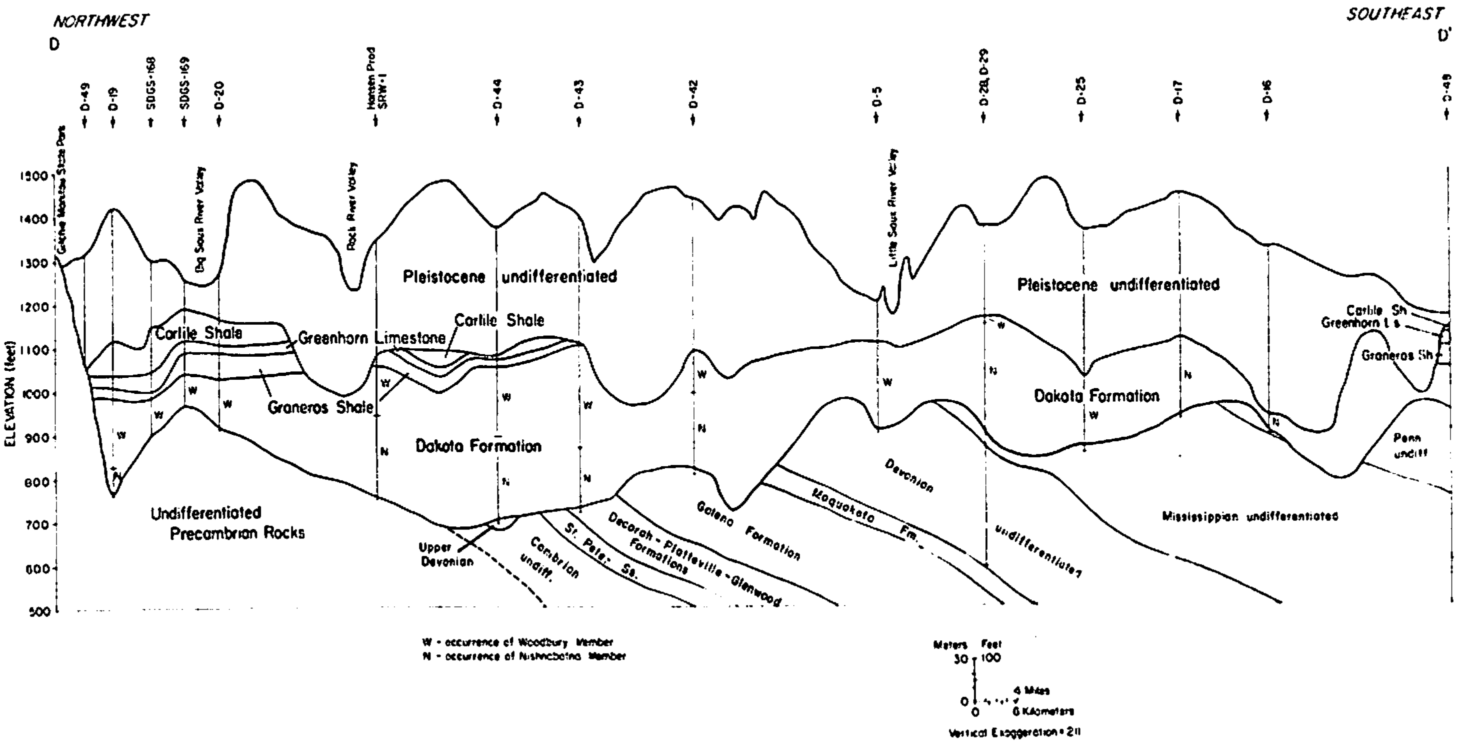

Figure 10. Geologic cross section D-D'. Location of the line of section is illustrated in Plate 5.

Ground-Water Flow Systems in the Dakota Aquifer

Water-level data collected from IGS/USGS observation wells and from selected private wells in the Dakota aquifer between October, 1979, and October, 1980, were used to construct a map of the potentiometric surface for the Dakota aquifer (Plate 5). Elevations of measuring points were taken from 7.5 minute USGS topographic quadrangle maps. In areas where these data points were sparse, water levels on file at IGS (submitted by drillers), but not remeasured during the study, were also used. The accuracy of using data from drillers is illustrated by a comparison of 58 water-level measurements submitted by drillers at the time of well construction (mostly between 1957 and 1965), with water-level measurements by IGS and USGS personnel in the same wells in 1979-80. The recent water-level measurements made as part of this study averaged 1.2 feet higher (standard deviation of 9.4 feet) than those reported by the drillers. Three water levels submitted by drillers were 30 feet or more below the 1979 levels. If measurements in these three wells are omitted, then water levels measured in 1979-1980 are an average of 0.45 feet lower than previously submitted water levels, with a standard deviation of 6.1 feet. This indicates that, on the average, data submitted by drillers are relatively accurate, and are acceptable for use in areas of sparse data.

The potentiometric surface illustrates the presence of a regional ground-water divide trending north-south through the study area. East of the divide, corresponding to the area in which the Dakota is thin and discontinuous, local flow systems dominate. Ground water flows through a combination of Quaternary sands and gravels, Dakota sandstones, and Paleozoic carbonate rocks to discharge points along the Des Moines River and its tributaries. Some discharge also occurs to the Jordan aquifer, which underlies the Dakota Formation and has a lower potentiometric surface (Horick and Steinhilber, 1978).

West of the major ground-water divide, a regional flow system is present in the Dakota aquifer. Recharge occurs in all the upland areas, in the upper reaches of major streams and rivers in the area, and as lateral inflow from Minnesota. Significant recharge is likely to be occurring in the West Branch Floyd River Valley and in the Floyd River Valley north of central Plymouth County because the heads in the alluvial aquifer are higher than the heads in the Dakota aquifer, and because the river valleys are incised through most of the till and into some of the Cretaceous marine confining units surrounding the valley. Low-sulfate water has been found in this area, possibly indicating a proximate recharge area, and a sand and gravel deposit above and within the till section has been described (Saye, 1980). Saye (1980) described a local ground-water flow system with recharge at the surface and discharge into an elongate sand and gravel body within the till section. The ultimate discharge point for this ground water is unknown, but must either be the Dakota aquifer or the alluvium of the West Branch Floyd River Valley, because of the local head relationships. The quantification of recharge rates to the Dakota aquifer throughout the study area requires further work and is beyond the scope of this report.

Water in the Dakota aquifer in the western half of the study area flows generally in a southwesterly direction, and discharges to the Missouri River alluvial aquifer and to the alluvial aquifers of the Big Sioux River south from southern Sioux County, the Floyd River south from southern Plymouth County, and the Little Sioux River south from northeastern Cherokee County. The average slope of the potentiometric surface of the Dakota aquifer in the western part of the study area is about 2 feet/mile.

An interesting feature of the Dakota aquifer flow system is that ground water in the Dakota aquifer flows from Iowa into South Dakota. This is in contrast to previously published maps of the Dakota aquifer in South Dakota, summarized by Schoon (1971), showing discharge from South Dakota either to the Big Sioux River or to Iowa. Water-level data from South Dakota (D. L. Iles, pers. communication, 1981) and in this report show that ground water flows beneath a segment of the Big Sioux River from central Lyon County (about one mile south of well D-19) to southern Sioux County. The slope of the potentiometric surface is to the southwest in this area, and it is at a lower elevation than the elevation of the Big Sioux River (Plate 5). If this is coupled with the fact that the Dakota Formation extends into South Dakota in this area (Schoon, 1971), then the movement of ground water into South Dakota appears to be the only reasonable conclusion.

The possibility that the present-day flow system has been affected by withdrawals of ground water in the area is remote because of the lack of major pumping centers, flowing wells, or large numbers of Dakota irrigation wells in the area. One of the major contributing factors to the configuration of the flow system appears to be a major valley that was cut into the Sioux Quartzite fringing the northwestern corner of Sioux County and subsequently filled with sand-dominated Dakota sediments (D. L. Iles, pers. communication, 1981; and figure 8, this report).

Vertical components of flow are integral parts of the description of the Dakota aquifer flow system. Nested well data identifying vertical flow are available at thirteen locations in the study area. The regional generalizations that can be made are that gradients are downward from the Woodbury Member to the Nishnabotna Member (observation wells D-38-39) and also from the Dakota aquifer into the Paleozoic or Precambrian rock units (in observation wells D-10, D-11, D-18, D-25, D-28-29, D-30, D-34, D-38-39, and D-40). No consistent vertical gradients were observed at observation well D-13. Upward gradients were measured near the Big Sioux River (observation wells D-19, D-35) and near Le Mars (observation wells D-21-22). Gradients in wells D-19 and D-35 are consistent with the interpretation of discharge to portions of the Big Sioux River, where upward components of flow should be present. The upward ground-water gradients observed at Le Mars could be a result of withdrawals from the Dakota aquifer in the Le Mars area, although historic water level data are lacking.

Cross-section C-C' (figure 11) illustrates both areal and vertical aspects of the regional Dakota aquifer flow system in Iowa. In the northern part of the study area, near the Sioux Quartzite Ridge, the Dakota Formation is thin, and the potentiometric surface has a relatively steep slope of 4-10 feet/mile. Immediately south of the area where Precambrian rocks subcrop beneath the Dakota Formation, the formation thickens dramatically and the potentiometric slope decreases about 0.5-1 feet/mile. Further to the southwest, where the confining units thin and the aquifer maintains its thickness, the potentiometric slope increases to approximately 2 feet/mile. If it is assumed that the hydraulic conductivity of the aquifer does not change significantly where the potentiometric slope increases, then an increase in recharge to the aquifer provides the most likely explanation for the observed changes in the potentiometric slope. This is consistent with the area where confining units are thinnest, such as in southwestern Sioux and western Plymouth and Woodbury Counties, and provides further support to the concept that recharge rates are somewhat higher in this area.

Cross-section B-B' (figure 12) illustrates relationships similar to those described above for cross-section C-C'. Cross-section A-A' (figure 13) illustrates the flow system of the Dakota aquifer in the central portion of the study area. The depth of the incision of the Little Sioux River Valley and its tributaries is noteworthy, as well as the fact that the gradients are downward from the river to the Dakota aquifer at this line of section (Plate 5). In addition, the water level in well D-3 is unusually low for this area (see enclosed 1180 contour, Plate 5). The most reasonable interpretation of these relationships is that water from the Dakota aquifer recharges the Paleozoic aquifers in this area, resulting in a depression of the potentiometric surface of the Dakota aquifer.

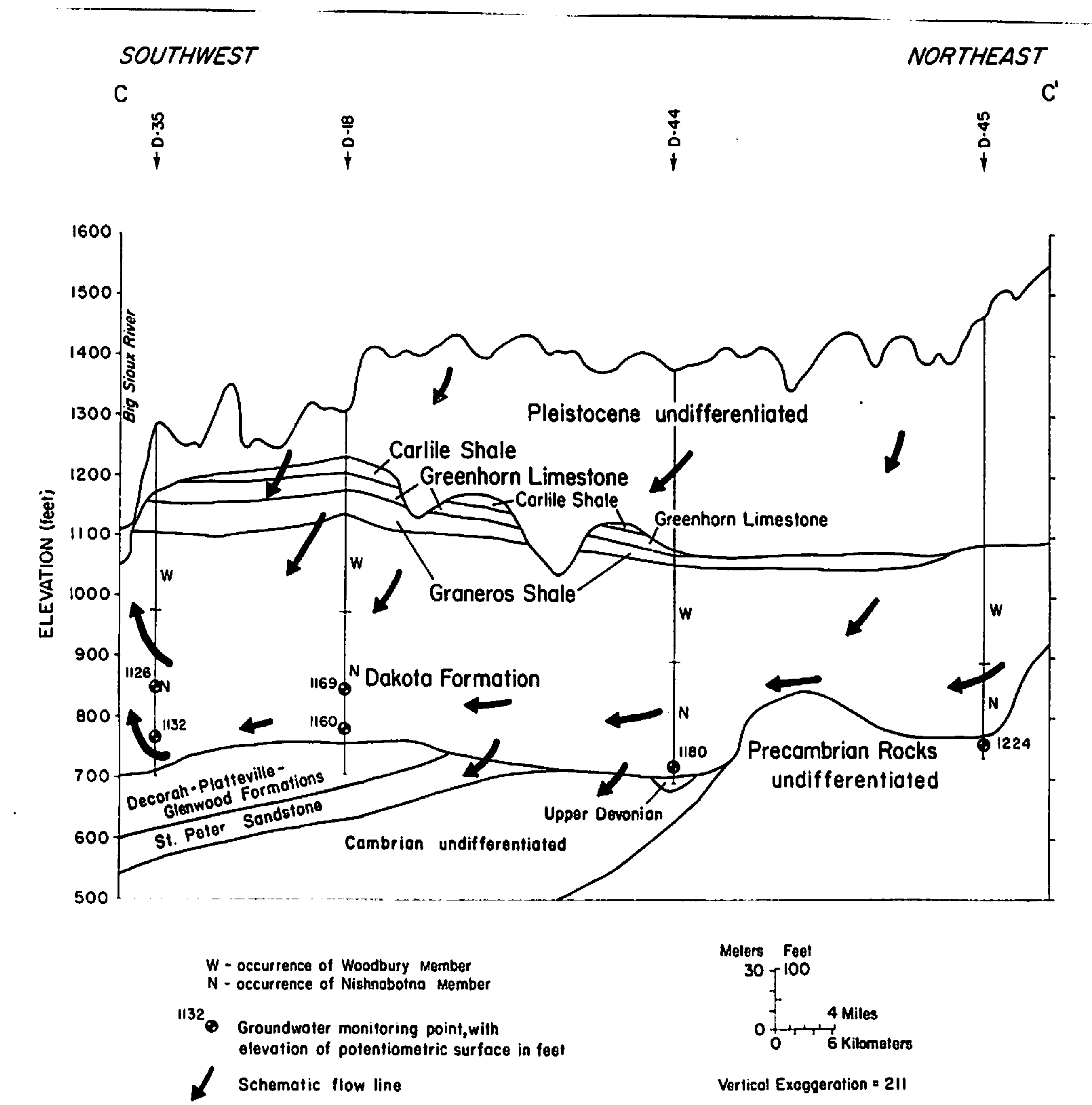

Figure 11. Hydrogeologic cross section C-C'. Location of the line of cross section is illustrated in Plate 5.

POTENTIAL FOR DEVELOPMENT OF THE DAKOTA AQUIFER

Estimates of Aquifer Parameters

Several controlled pumping tests were conducted during the course of this investigation to estimate the hydraulic parameters transmissivity (T) and storativity (or storage coefficient, S) of the Dakota aquifer at specific localities. These hydraulic parameters can be used to describe the ability of the aquifer to supply water to a well and to estimate future declines in water levels on a local scale caused by ground-water withdrawals. Estimates of these parameters throughout the region would also be required to estimate regional changes in water levels caused by pumping.

The results of four IGS-supervised aquifer tests are presented in Table 3. Table 3 also summarizes the results of a test conducted by the southern Sioux County Rural Water System, Inc. (SSCRWS, 1979). Each of the production wells was completed in the Nishnabotna Member, and the thickness of sandstones in this member was estimated at each site from analyses of drilling logs, geophysical logs, and samples. Estimates of hydraulic conductivity (K) in Table 3 were obtained by dividing the transmissivity by the net thickness of sandstone in the Nishnabotna Member. Thin sandstones of the Woodbury Member were not included in this analysis because they were either effectively isolated from the larger part of the aquifer by shales or yielded only negligible quantities of water. The average value of K at the test sites is 48 feet per day (ft/day), with a range from 33 ft/day to 77 ft/day.

In order to illustrate the potential for development and the hydraulic complexity of the Dakota aquifer, the details of a test performed at the Hibbing site in Osceola County are presented. The location and geology of the site are presented in figure 6. The production well, although not shown on the cross section, is 565 feet deep with 120 feet of 8 inch diameter screen at the bottom. Observation wells in the Nishnabotna Member were constructed at radii (r) of 710 feet (well #2) and 1750 feet (well #5, IGS/USGS test hole D-39) from the production well (see Appendix). Well #2 was screened at a depth interval of 440 feet to 490 feet, and well #5 was perforated from 490 to 500 feet. These depths correlate closely with the center of the screened interval in the production well, thus minimizing the possibility that the partial penetration of the aquifer by the observation wells significantly affected the test results.

A nested piezometer (IGS/USGS test hole D-38) was constructed 605 feet from the production well with one well open to a sandstone bed in the Woodbury Member and another well open to the St. Peter Sandstone (a Paleozoic aquifer). Well #1, northeast of the production well, was not a functional observation well. The altitude of the tops of all observation wells was determined by instrument leveling so that water-level data could be compared.

A center-pivot irrigation system was used to discharge water on flat terrain for the duration of the test. An in-line flow-rate meter with a total-gallon water meter indicated that the average discharge for the continuous 67-hour pumping period was 1000 gpm. Drawdown data were corrected for barometric fluctuations, which were recorded by a continous recording barograph at the site.

Drawdown data from wells #2 and #5 (figure 14) were analyzed by the type-curve method (Theis, 1935). The data from well #5 did not fit the type curve as well as the data from well #2. The central portion of the data set from well #5 was used to match the type curve so that a time-averaged estimate of transmissivity could be obtained, rather than an estimate based only on the early data. The late data deviate from the type curve suggesting that a

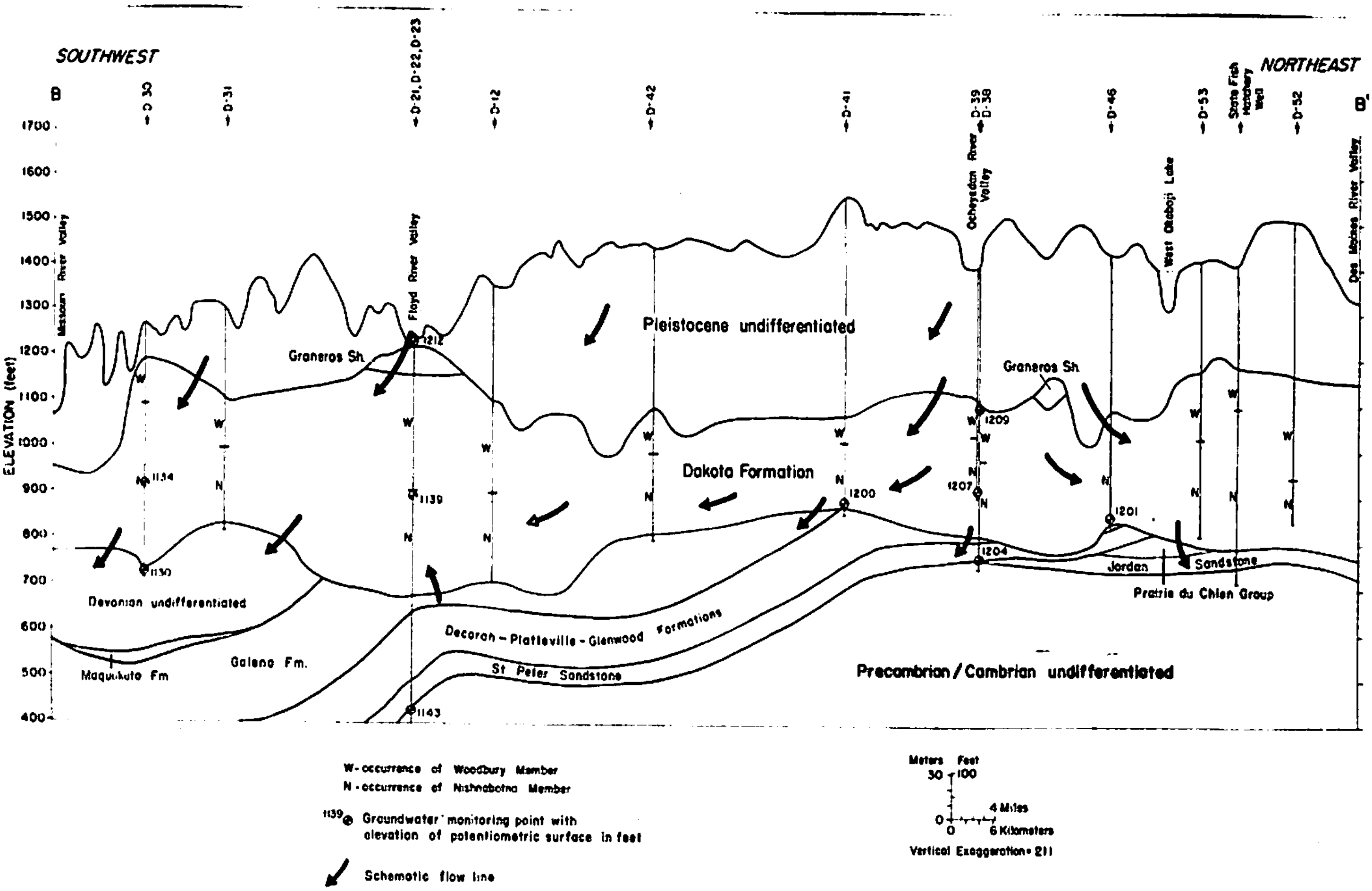

Figure 12. Hydrogeologic cross section B-B'. The location of the line of cross section is illustrated in Plate 5.

recharge boundary was encountered. Both sets of drawdown data are presented in figure 14 to illustrate the fact that significantly different sets of aquifer coefficients were calculated from the data set from each well. If the aquifer coefficients obtained from each well were the same, then the data should have plotted along a single smooth curve. Although the data from well #5 can be fit to the type curve in a number of different ways, it is clear that the resulting aquifer coefficients will invariably be different than the ones determined from the data from well #2. Two possible explanations for the results of the aquifer test are presented.

First, the transmissivity of the aquifer may actually be lower in the vicinity of well #5, or in the area between the production well and well #5. This could result from textural or cementation variations in the Nishnabotna Member, or from changes in the thickness of the unit. No indications of these conditions were observed, however, that can readily account for the different transmissivity values that were determined. Although well #5 does not penetrate Paleozoic rocks, the Nishnabotna Member is penetrated at a higher altitude in this well than in surrounding wells. This indicates that the aquifer is more likely thicker near well #5 than thinner.

Another problem with the hypothesis of a reduced transmissivity in the aquifer near well #5 is that the data from well #2 was not affected by any such irregularity. The Theis solution assumes the presence of a homogeneous aquifer of

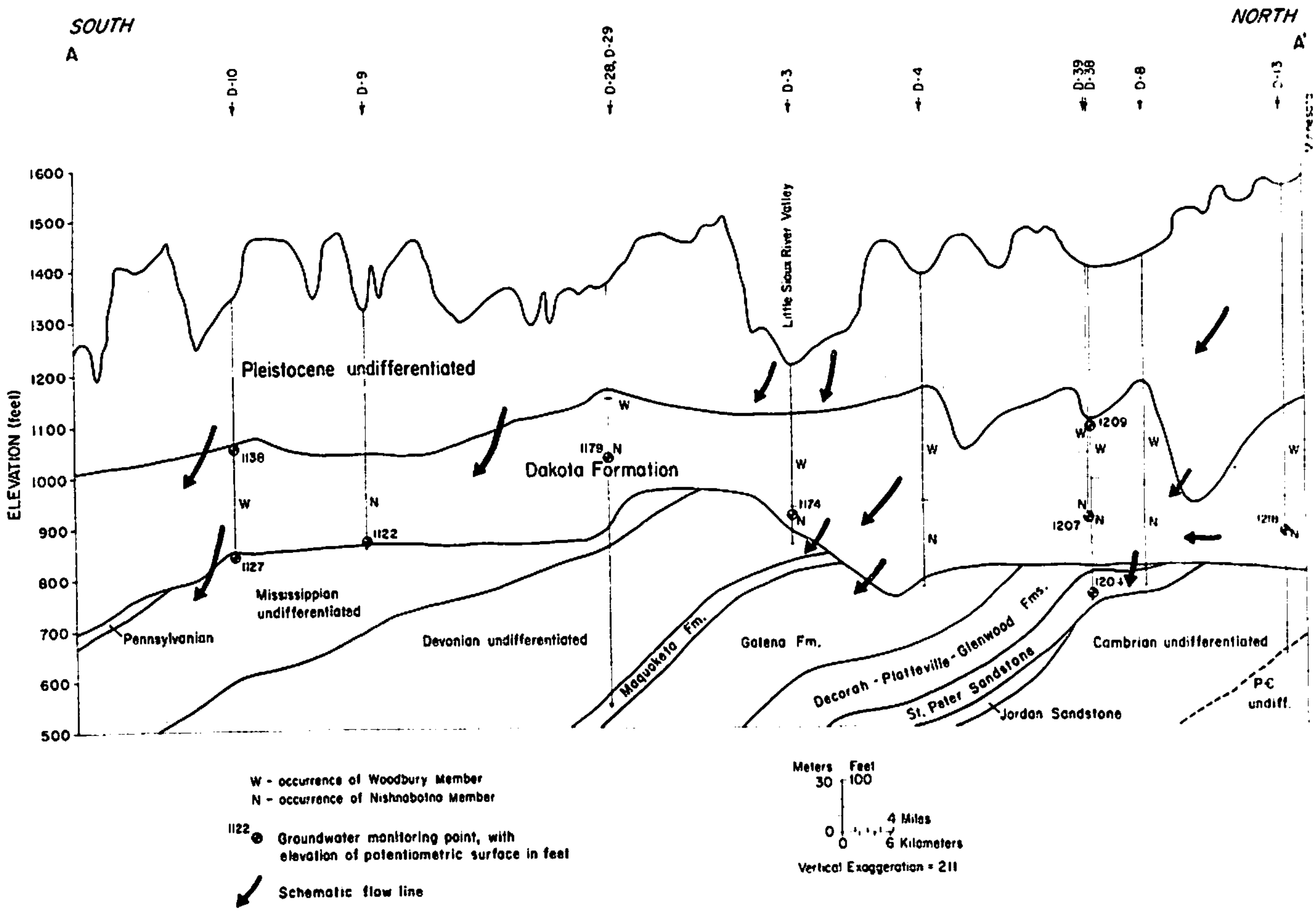

Figure 13. Hydrogeologic cross section A-A'. The location of the line of cross section is illustrated in Plate 5.

large lateral extent, and this assumption would be seriously compromised if the transmissivity of the aquifer were reduced by more than 50% in the local area of the Hibbing observation and production wells. Because the data from observation well #2 did not deviate significantly from the type curve, and because the geology does not support a change in transmissivity of more than two-fold, an alternative hypothesis is proposed.

As previously indicated, the Theis solution presumes a homogeneous aquifer. From geologic evidence, it is known that the Dakota aquifer is not homogeneous. The presence of heterogeneity in the Dakota aquifer may be responsible for the difference in observed transmissivities between well #2 and well #5, and, in general, heterogeneity in the Dakota aquifer may have a significant influence on drawdowns that occur in observation wells relatively distant from pumping wells. This concept is premised on the presence of irregularly shaped lenses or layers of shale or mudstone within the aquifer that would tend to retard the response of an observation well which may appear to be completed in the same sandstone unit. One of the implications of this concept is that the aquifer may be heterogeneous, yet may have a fairly uniform transmissivity in a large area.

The hypothesis that heterogeneity is responsible for the difference in calculated transmissivity values at the Hibbing site is supported by the data in figure 15 in four ways. First, the data from well #5 show less drawdown than

Table 3. Pumping test data from the Dakota aquifer in Iowa.

Site No.	Site Name	Distance from the production well to the observation well (feet)	Thickness of sandstone in the Nishnabotna member (feet)	Hydraulic Conductivity (feet/day)	Transmissivity (gpd/ft²)	Storativity
1.	Hansen	2500	80	48	29,000	6×10^{-4}
2.	Hosteng	4000	125	36	34,000	8×10^{-4}
3.	Ritz	1100	140	54	57,000	3.5×10^{-5}
4a.	Hibbing (Well #2)	710	162	74	90,000	2×10^{-4}
4b.	Hibbing (Well #5)	1750	162	33	40,000	2×10^{-3}
5a.	Southern Sioux County Rural Water System, Inc. (SSCRWS) (Well 79-1)	100	155	47	55,000	8×10^{-4}
5b.	SSCRWS (Well 79-2)	2400	155	38	44,000	3×10^{-4}

do comparable data from well #2 at any point in time, even after correcting for the difference in radii. This is what would be expected to result if interference from shale beds in the aquifer is significant. Secondly, the value of storativity determined from the data from well #5 is an order of magnitude larger than the value determined from the data from well #2, and is larger than all of the other storativity values listed in Table 3. Also, the value of storativity from well #2 is near the center of the range of values of storativity normally obtained from aquifers of this type (Freeze and Cherry, 1979, p. 60). The high value of storativity determined from the data from well #5 suggests that both the transmissivity and storativity values determined from the data may be misleading.

Figure 14 also illustrates that the data collected near the end of the aquifer test deviated from the type curve, suggesting the presence of a recharge boundary. This would not be an unusual response from a heterogeneous aquifer if portions of the aquifer are initially shielded from the aquifer by shale beds and are intercepted as pumping continues. These portions of the aquifer provide a mechanism that may explain the source of the "recharge" water and the observed stabilization of water levels in well #5.

The fourth observation concerns the possibility that the two sets of data in figure 14 would have converged if the aquifer test had been continued for a longer period of time. This would have resulted in a single set of aquifer parameters (T and S) for the site. This suggests that heterogeneity may have a substantial influence on short-term (i.e. 2-3 day) pumping tests, but that the effects may tend to become smaller as a larger area is tested and different parts of the aquifer trend toward hydraulic equilibrium. In other words,

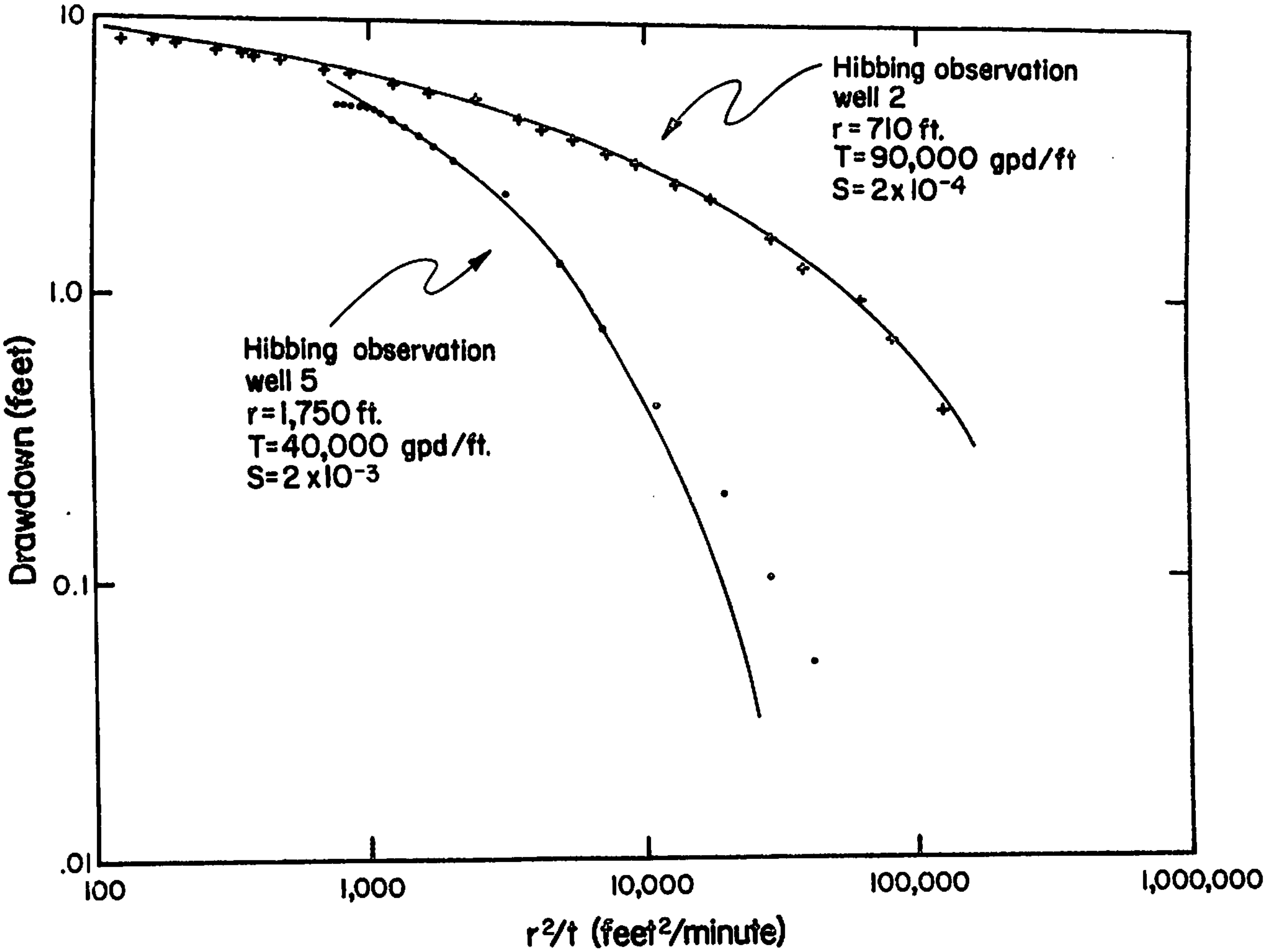

Figure 14. Drawdown data from the Hibbing pumping test. Locations of the wells are shown on Figure 6.

an aquifer that is heterogeneous in a smaller area during short periods of hydraulic stress may be relatively homogeneous over a larger area with hydraulic gradients approaching steady state conditions.

Examination of the data in Table 3 reveals the degree to which heterogeneity in the Dakota aquifer affects pumping-test results throughout the study area. The only other pumping test for which data are available is from two observation wells in the SSCRWS site (Table 3). As at the Hibbing site, the near observation well yielded a value of transmissivity that was higher than the value that was obtained from the more distant observation well. Although the difference in transmissivities is not large, this test is independent of the Hibbing test and does not, at least, contradict the hypothesis that transmissivity values determined from distant observation wells are generally less than the values determined from close observation wells because of aquifer heterogeneity.

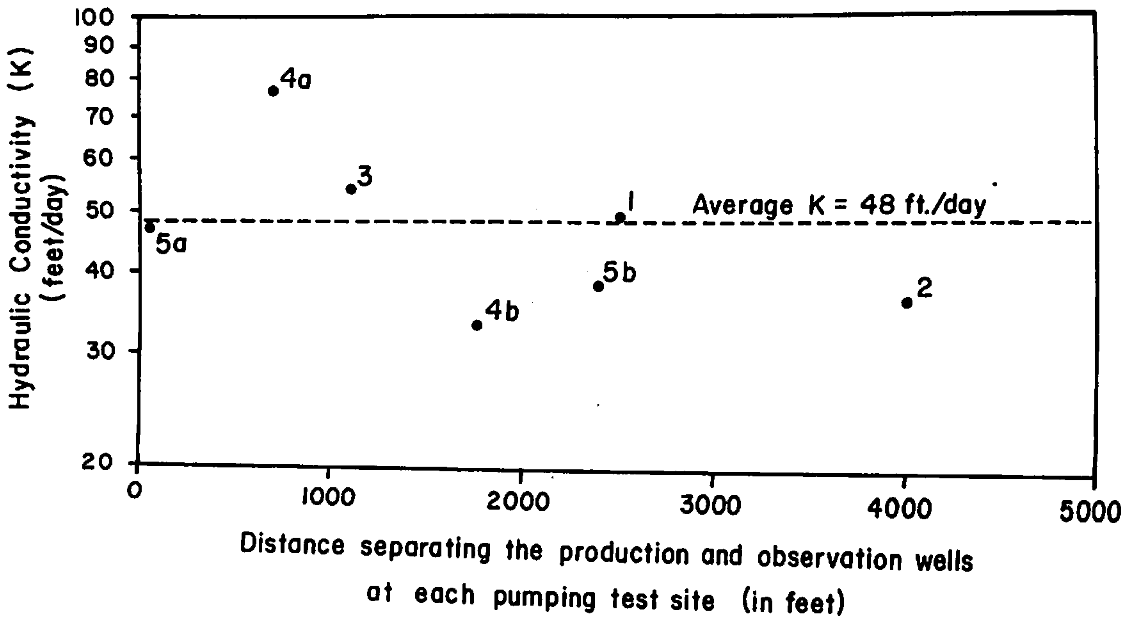

Figure 15. Graph showing the relationship between hydraulic conductivity and the distance between the production well and the observation well at each site. Data points are indexed to Table 3.

Figure 15 is a graph of the hydraulic conductivity values in Table 3 plotted on logarithmic paper as a function of distance (D) separating the observation and production wells at each site. K is plotted rather than transmissivity so that the effects of different aquifer thicknesses from site to site are eliminated. A random scattering of points about the line representing the average hydraulic conductivity of 48 ft/day would indicate that the location of the observation well has an insignificant effect on the value of K that is determined. Apart from the Hibbing and SSCRWS sites, each of the three remaining sites show successively smaller values of hydraulic conductivity with increasing values of D. This limited data set cannot be used to define a quantitative relationship between K and D, but the inference of the existence of a relationship is entirely reasonable.

A discussion of the heterogeneity of the Dakota aquifer and its influence on pumping test results is presented in this report for several reasons. First, it is supported by a variety of geologic and hydrologic information including the geologic characteristics of the Dakota Formation, the geology and the hydraulic response of the Dakota aquifer at the Hibbing site, and the small body of pumping test data from the Dakota aquifer in Iowa. Secondly, the relationships discussed in this report are consistent with the extensive body of well and aquifer hydraulic theory that has been developed. The Dakota aquifer should be considered to be an example of an aquifer that does not precisely fit all of the assumptions upon which most aquifer testing is done. A quote from Freeze and Cherry (1979, p. 349) helps to illustrate this point:

> "The fact that a theoretical curve can be matched by pumping test data in no way proves that the aquifer fits the assumptions on which the curve is based."

Thirdly, practical considerations may require the use of short-term pumping-test data from distant observation wells for projections of long-term impacts of aquifer development. A recognition that some data may not be suitable for this purpose would be of value in this analysis. A factor of safety is likely to be included in long-term projections because the projections of drawdowns, based on aquifer coefficients from data from distant observation wells, are likely to be conservative.

A fourth consideration is that the location of observation wells for future pumping tests may have an influence on the test results. This should be taken into consideration during the design phase of the aquifer test so that the objectives of the test would more likely be achieved.

Transmissivity Map

A ground-water flow model of the Dakota aquifer could be used to estimate natural recharge and discharge rates to and from the aquifer, as well as regional changes in water levels caused by artificial stress on the aquifer. One of the items required for such a simulation, however, is a transmissivity map of the aquifer. A transmissivity map can also be used to estimate the potential for developing high-capacity wells in the aquifer. The information needed for the preparation of a transmissivity map are:

1. The isopach map of the Nishnabotna Member of the Dakota Formation;

2. the estimate that 83% of the Nishnabotna Member consists of sandstone; and

3. the estimate that the average hydraulic conductivity of sandstones in the Dakota aquifer is 48 ft/day.

Additionally, the assumption is made that where only the Woodbury Member of the Dakota Formation is present, the transmissivity of the Dakota aquifer is less than 5000 gallons per day per foot (gpd/ft). This value is somewhat arbitrary because few data are available, and because of the variability of the thickness and composition of the Dakota Formation in these areas. A transmissivity value of 5000 gpd/ft is representative of the transmissivity of a continuous 14-foot thick sandstone bed in the Woodbury Member with a hydraulic conductivity of 48 ft/day. It is also assumed for the transmissivity map that the Woodbury Member contributes insignificantly to the transmissivity of the Dakota aquifer where both members of the Dakota Formation are present.

The contours of the transmissivity map (Plate 6) were generalized somewhat from the contours of the thickness map of the Nishnabotna Member (Plate 3). The values of the contours on the transmissivity map were determined by multiplying the values of the contour interval in Plate 3 by 83% and by 48 ft/day. For example, where 100 feet of Nishnabotna Member is present, approximately 83 feet of sandstone is present and the transmissivity is approximately 4000 square feet per day (ft^2/day), or 30,000 gpd/ft.

One application of the transmissivity map is to delineate areas where it should be possible to develop an 800-1000 gpm well from the Dakota aquifer. As a general approximation, this type of well could be developed wherever the transmissivity is greater than 30,000 gpd/ft (Plate 6). This is based on the fact that yields of 800 to 1000 gpm were obtained from all of the irrigation wells listed in Table 3, and because the limited precision of the transmissivity map prohibits a more quantitative evaluation.

In areas where the transmissivity of the Dakota aquifer is between zero and 30,000 gpd/ft, the productivity of the aquifer is difficult to assess because the relief on both the bedrock surface (Plate 1) and the Pre-Cretaceous surface (figure 8) is large enough to result in a great deal of variability in the thickness of the Dakota Formation. As a regional guide, however, well yields in excess of several hundred gallons per minute should not be expected without test drilling. The presence of significant thicknesses of Pleistocene sands and gravels in many of the areas where the Dakota Formation is thin may provide an alternative for the development of ground-water supplies, however.

Water-Level Trends

As previously indicated, water levels in private wells throughout the study area were measured in the fall of 1979. These data were found to be generally consistent with data from the same wells previously submitted by drillers, and no significant trends of changing water levels were noted. This indicates that the aquifer is not likely to be undergoing a regional decline in water levels with time. Of major concern, however, is the local and long-term impact of high-capacity wells on water levels in the aquifer. The longest and most complete record of water-level data near an irrigation system in the Dakota aquifer in Iowa has been collected at the Hansen site (figure 16). A pre-development water level of 126.0 feet was measured on June 6, 1978, in an observation well 2500 feet from the production well. The production well pumped approximately 20 million gallons during the irrigation seasons of 1978 and 1979, and about 40 million gallons in 1980. The observation well does not show evidence of a long-term water-level decline, although the period is too brief to be definitive. A longer period of record at the Hansen well, combined with long-term data from IGS/USGS test wells in the area, would be useful for detecting changes in water levels caused by irrigation pumping.

Four long-term (i.e. 20-40 year) Dakota observation wells have been maintained by the U.S. Geological Survey. Three of these wells (in Emmett, Lyon, and Sac Counties) show long-term water-level declines of about 0.3 feet/year. The cause of these declines is unknown. A fourth observation well (at Sioux City) has not shown any significant long-term changes, possibly because the aquifer is near the land surface and is readily recharged.

GROUND-WATER QUALITY IN THE DAKOTA AQUIFER

A discussion of the regional variations in water-quality types is included in this report because of the relevance to the ground-water flow systems that are

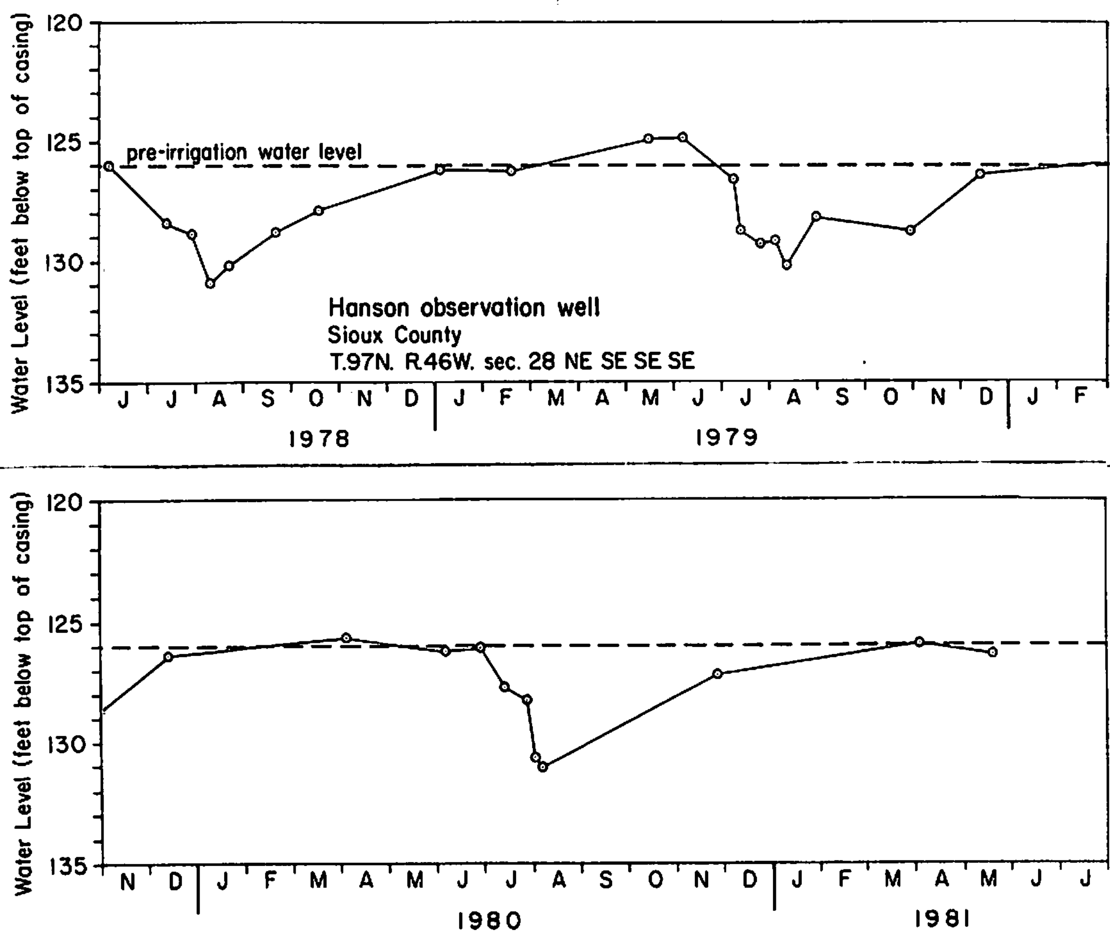

Figure 16. Hydrograph of the Hanson observation well. Data points are water levels measured at non-pumping times (note overlap on time scale).

present in the Dakota aquifer. A Piper diagram (Piper, 1944) showing analyses of water from IGS/USGS test wells is presented in figure 17. The distribution of dissolved sulfate in the aquifer and pertinent data point locations are shown in figure 18. Two distinctly different water-quality types are present in the study area.

In the majority of the samples (solid circles, figure 17) the dominant water type is a calcium-sulfate type, with significant and subequal amounts of magnesium and sodium. Bicarbonate is the secondary anion, with low chloride concentrations. This water type is interpreted to be the result of the dissolution of common minerals, particularly calcite, dolomite, gypsum and anhydrite, as the water percolates downward through a thick sequence of Pleistocene glacial deposits.

Another major group of water analyses (solid squares, figure 17) can be classified as calcium-bicarbonate water types, with low sodium and very low chloride concentrations. This water type is located in the southwestern part

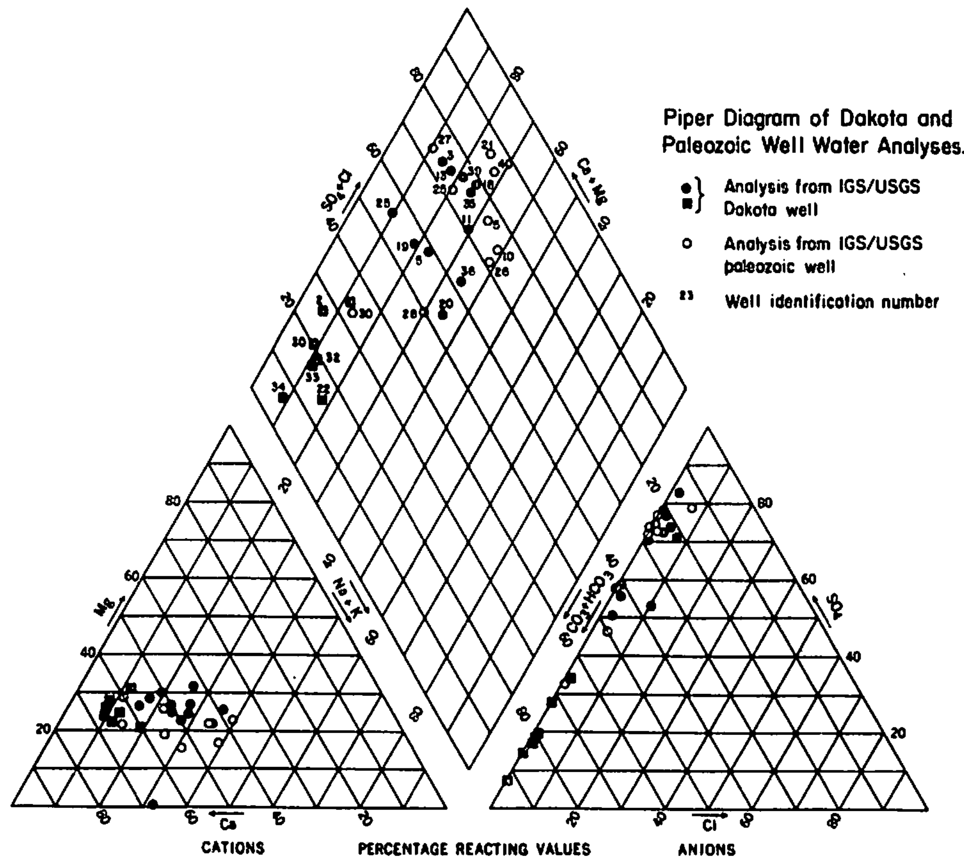

Figure 17. Piper diagram of selected water analyses from the Dakota and Paleozoic aquifers. Locations of data points are shown in Figure 18.

of the study area, which is an area of low-sulfate water (figure 18). One explanation for the source of the low-sulfate water is that it is the product of sulfate-reducing reactions taking place in the aquifer as the water travels from recharge areas in the north and north-central parts of the study area to the discharge areas in the southwest. Although sulfate-reducing reactions may be occurring in the Dakota aquifer, a preferred explanation for the large area of low-sulfate water in the southwest portion of the study area is that it is the result of a greater rate of recharge by relatively unmineralized surface water for the area. This is supported by the geology, by the hydraulic head relationships in the Dakota aquifer and by the water-quality data.

The confining units in the southwestern part of the study area are significantly thinner than they are in much of the remaining study area (Plate 4, figures 11 and 12). The Carlile, Greenhorn and Graneros Formations are absent in most of this area (figure 9), and a portion of the confining unit included in the map in Plate 4 is loess, which is more permeable than the tills in the region. Sand and gravel bodies within the till section (e.g. see Saye, 1980) and beneath the till section provide possible pathways for the movement of water into the Dakota aquifer.

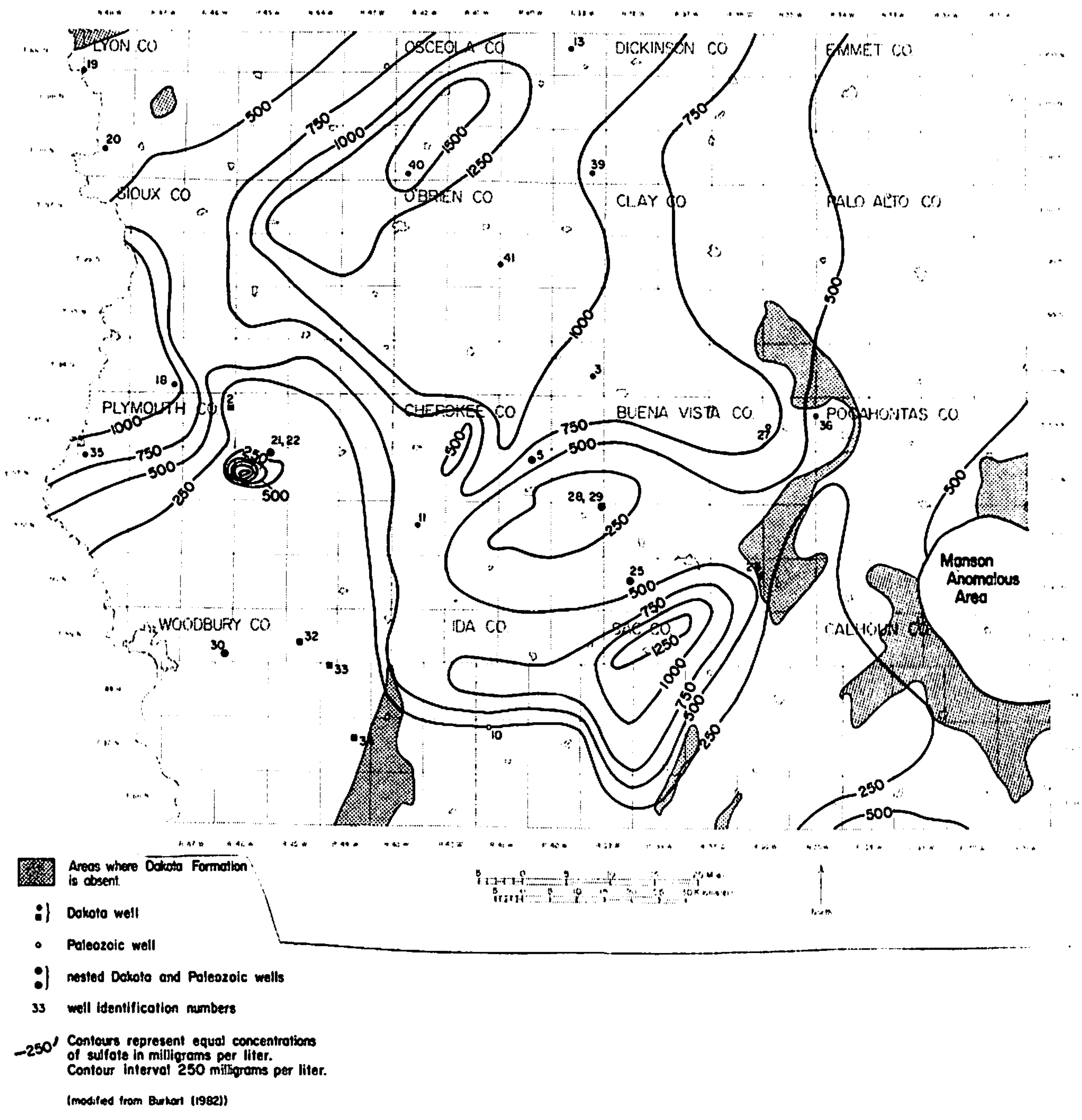

Figure 18. Distribution of dissolved sulfate in ground-water in the Dakota aquifer.

The potentiometric surface of the Dakota aquifer (Plate 5) also supports the interpretation of the presence of higher rates of recharge in northern Woodbury and western Plymouth Counties. The surface exhibits relatively flat areas or slight mounds that are adjacent to more steeply sloping portions of the surface to the southwest. These areas are not coincident with areas in which the transmissivity of the aquifer is known to change significantly (Plate 6), thus indicating that local recharge is the most likely cause for the changes in slope.

The water-quality data also indicate the presence of local sources of recharge. Both the sodium and chloride ion concentrations in the low-sulfate analyses (solid squares, figure 17) are typically lower than they are in the high-sulfate analyses (solid circles, figure 17). This is opposite of what would be expected if the bulk of the low-sulfate water is derived from the high-sulfate water to the northeast. Numerous workers, including Chebotarev (1955) and Thorstenson and others (1979) have helped to establish the concept that sodium and chloride ions in ground water commonly increase in concentration along ground-water flow paths. The lack of a likely mechanism whereby the concentration of sodium and chloride ions can be decreased from the high-sulfate water to the low-sulfate water suggests that dilution by relatively unmineralized local recharge water is the most likely explanation of the origin of the low-sulfate water.

Analyses of water samples from the Paleozoic aquifers are also plotted on figure 17. These analyses typically contain concentrations of common dissolved minerals that are similar to the majority of Dakota water samples and do not constitute a distinctive water type. This supports the interpretation that water from the Dakota aquifer recharges the Paleozoic aquifers throughout most of the study area.

SUMMARY AND CONCLUSIONS

The Dakota Formation in Iowa is a complex interbedded assemblage of largely fluvial sandstones, siltstones, shales, and lignites that directly overlie rocks ranging in age from Pennsylvanian to Precambrian with angular unconformity. Two members of the Dakota Formation are recognized in Iowa. The lowermost Nishnabotna Member is composed of approximately 83 percent sandstone, and is over 300 feet thick in places. The Woodbury Member overlies the Nishnabotna Member and is commonly about 100 to 150 feet in thickness. The Woodbury Member is composed of thin-to medium-scale interbeds of shales, sandstones, siltstones, and lignites. The Dakota aquifer consists of both members of the Dakota Formation and is most productive in the west-central and north-central parts of the study area where thick (i.e. 200 to 300 foot) sections of Nishnabotna sandstones are present. The Dakota aquifer is thin or absent in much of the northwestern and eastern parts of the study area. The aquifer is confined in most of the area by 200 to 400 feet of fine-textured glacial till and Cretaceous-age shales and limestones of the Dakota, Graneros, Greenhorn, and Carlile Formations.

The Dakota aquifer is recharged throughout the study area by downward percolation through the confining units, and by lateral inflow from southern Minnesota. The aquifer discharges to the lower reaches of the major rivers in the area and to the underlying Paleozoic and Precambrian rocks. The Dakota aquifer in Iowa also discharges to the Dakota aquifer in South Dakota beneath a segment of the Big Sioux River.

Pumping-test data from the Dakota aquifer at five localities are available. From these data an average hydraulic conductivity for sandstones in the Nishnabotna Member of the Dakota Formation of 48 ft/day with a range of 33 ft/day to 77 ft/day was calculated. This value was used with a map showing the thickness of the Nishnabotna Member to construct a transmissivity map for the Dakota aquifer. It is interpreted from the transmissivity map that the potential exists for the development of large capacity (800-1000 gpm) wells throughout much of the western and north-central portions of the study area.

The aquifer-test data also suggest that heterogeneity in the Dakota aquifer has an influence on the results of pumping tests in which the observation well is located at a relatively distant position from the production well. This effect is considered to be the result of shales or mudstones within the Dakota Formation that retard the response of the observation well to pumping, even though the production and observation wells may appear to be completed in the same sandstone unit. The retarded response of the observation well results in a poor fit of the data to published type curves and in lower estimates of transmissivity, even though the thickness and textural properties of the aquifer may not appear to vary significantly in the area. The influence of heterogeneity on pumping-test data is discussed to facilitate a recognition of the limitations of existing pumping-test data, and to suggest that the locations of observation wells may influence the results of future aquifer tests and should be considered during the design phase of any such test.

Comparison of recent measurements of water levels in 58 wells in the Dakota aquifer with historic records, has shown that the water levels in the Dakota aquifer are not likely to be declining significantly with time on a regional scale. Long-term records from three U.S.G.S. observation wells, however, have shown average declines of about 0.3 feet per year. An observation well with a 3-year period of record near an irrigation development has shown that water levels recover to pre-irrigation levels or higher, prior to the onset of irrigation the following season. The establishment of a comprehensive monitoring system would be useful for identifying significant trends in water levels in the Dakota aquifer.

The quality of water in the Dakota aquifer varies from a calcium-sulfate type to a calcium-bicarbonate type. The calcium-sulfate type water occurs where the confining units are fairly thick and is characterized by higher sodium and chloride concentrations than the calcium-bicarbonate type water. The calcium-sulfate type water is interpreted to be a result of the dissolution of common minerals as the water percolates downward through the confining units. The calcium-bicarbonate type water is interpreted to result from relatively rapid recharge to the Dakota aquifer in areas where the confining units are thin, notably in the southwestern part of the study area.

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APPENDIX

Summary of IGS/USGS Subsurface Data and Selected Private Well Data

Footnotes for the Appendix

[1]Elevations relative to the National Geodetic Vertical Datum (NGVD) of 1929.

[2]Geophysical logs as follows:
- N.G. = natural gamma radiation log
- S.P. + R. = spontaneous potential and resitivity logs
- C. = caliper log
- G.-G. = gamma-gamma radiation log
- N. = neutron radiation log

[3]Indicates that the lower interval was cemented off and the higher interval was subsequently perforated.

[4]Borehole collapsed or plugged and abandoned, no observation well constructed.

[5]Poor Data, water-levels not consistent.

[6]Unit not penetrated.

[7]Abbreviations for geologic units:

Penn.	-- Pennsylvanian rocks, undifferentiated
Miss.	-- Mississippian rocks, undifferentiated
Dev.	-- Devonian rocks, undifferentiated
Galena	-- Galena Formation
D-P-G	-- Decorah, Platteville, and Glenwood Formations, undifferentiated
Camb.	-- Cambrian rocks, undifferentiated
Sioux Qtzt	-- Sioux Quartzite

Well Identifier	Location	Land surface elevation[1]	Geophysical logs[2] N.G.	S.P.+ R.	C.	G-G.	N.	Sample Interval Cuttings	Core	Elevations of formation tops[1] Carlile Shale	Greenhorn Limestone	Graneros Shale	Dakota Formation Wdby. Mem.	Nish. Mem.	Pre-Cretaceous Geologic Unit Unit[7]	elev.[1]	Elevation screened or perforated interval[1]	Elevation of ground-water potential or head[1]	Date of water-level measurement	Comment
D-1 W-24555	Plymouth Co. T 93N, R 45W Sec. 18, NW NE NW	1240						3-255												C & A[4]
D-2 W-24556	Plymouth Co. T 93N, R 46W Sec. 12, SE SE SE SE	1280	X	X	X			0-570			1250	1222	1172	1090	Galena	725	920-925	1160	8/6/80	
D-3 W-24557	O'Brien Co. T 94N, R 39W Sec. 26, NW SE NE NW	1210	X	X	X	X	X	0-352					1118	930	Dev.	881	915-919	1174	8/6/80	
D-4 W-24558	O'Brien Co. T 95N, R 39W Sec. 4, NW SW NW NE	1390	X	X	X	X	X	5-620					1123	940	Galena	785	none			C & A[4]
D-5 W-24569	Cherokee Co. T 92N, R 40W Sec. 10, SW SW SW NE	1209	X	X	X	X	X	0-301					1112	none	Dev.	905	1091-105	1180	8/6/80	
D-6 W-25521	Cherokee Co. T 90N, R 40W Sec. 6, SE SW SE NW	1182	X	X	X	X	X	0-293						1063	Dev.	904	927-930	1147	8/6/80	
D-7 W-26008	Sioux Co. T 95N, R 47W Sec. 5, NE NE NE NE	1292	X	R		X	X	0-73	78-664	1219	1154	1127	1067	937	Dev.	651	720-722	1160	8/5/80	
D-8 W-24734	Osceola Co. T 98N, R 39W Sec. 8, SE SE SE SW	1420						0-580					1155	?	D-P-G	811	none			C & A[4]
D-9 W-24735	Ida Co. T 89N, R 41W Sec. 13, SE SW SW SW	1320	X					0-469						1042	Miss.	861	848-851	1122	3/6/80	Cemen-ted 4/81.
D-10 W-24736	Ida Co. T 87N, R 41W Sec. 5, SW SW SW SW	1344	X					0-510					1064	none	Miss.	850	834-854 c&p[9] 1040-1043	1127 1138	3/6/80 8/7/80	

D-11 W-25114	Cherokee Co. T 91N, R 42W Sec. 16, SE SE SE SE	1320	X		0- 576					1059	980	Dev.	770	744-759 c&p[3] 930-934	1165 1165	2/27/80 8/6/80	
D-12 W-24963	Plymouth Co. T 93N, R 44W Sec. 36, SW SW SW	1350			8- 642					1101	900	Galena	709				C & A[4]
D-13 W-25108	Osceola Co. T 100N, R 39W Sec. 17, NW SW SW SE	1560	X	X X	3- 449, 513- 770	475- 513, 770- 923				1099	940	Camb.	799	637-790 c&p[3] 860-880	1218 1218	4/10/80 7/10/80	
D-14 W-25317	Ida Co. T 89N, R 39W Sec. 14, SE SE SE SE	1300			0- 375					~1093	?	N.P.[6]					C & A[4]
D-15 W-25318	Sac Co. T 87N, R 37W Sec. 3, SW SW SW				0- 240							N.P.[6]					C & A[4]
D-16 W-25319	Sac Co. T 88N, R 37W Sec. 22, SE SW SW SW	1320	X	X X	0- 435						930	Penn.	892	885-903	1155	8/4/81	
D-17 W-25320	Sac Co. T 89N, R 38W Sec. 36, SW SW NW SW	1445	X	X	0- 521						1111	Miss.	933	1005-1015	1154	8/4/81	
D-18 W-25321	Sioux Co. T 94N, R 47W Sec. 35, NW NE NE NE	1305	X	X X	0- 601		1230	1203	1177	1135	973	D-P-G	755	765-785 c&p[3] 851-855	1160 1169	2/28/80 8/6/80	
D-19 W-25313	Lyon Co. T 100N, R 48W Sec. 31, SW SW SW SW	1417	X	X X	0- 657		1115	1033	1009	982	827	Sioux Qtzt.	764	747-767 c&p[3] 962-967	1262 1261	2/29/80 8/5/80	
D-20 W-25523	Lyon Co. T 98N, R 48W Sec. 16, SE NE SE SE	1268	X		0- 358		1163	1203	1088	1023	none	Sioux Qtzt.	915	913-933	1174	8/5/80	

Well Identifier	Location	Land surface elevation[1]	Geophysical logs[2]: N.G.	S.P. + R.	C.	G-G.	N.	Sample Interval: Cuttings	Core	Elevations of formation tops[1]: Carlile Shale	Greenhorn Limestone	Graneros Shale	Dakota Formation: Wdby. Mem.	Nish. Mem.	Pre-Cretaceous Geologic Unit: Unit[7]	elev.[1]	Elevation screened or perforated interval[1]	Elevation of ground-water potential or head[1]	Date of water-level measurement	Comment
D-21 W-25498	Plymouth Co. T 92N, R 45W Sec. 2, NW SW NW SW	1245	X	R				0-568	573-595, 596-1089			1218	1155	905	Galena	677	156-672	1143	8/6/80	
D-22 no W number	Plymouth Co. T 92N, R 45W Sec. 2, NW SW NW SW	1244.8						none							N.P.[6]		880-898	1139	8/6/80	
D-23 W-25524	Plymouth Co. T 92N, R 45W Sec. 2, NW NE NW SW	1220						0-22							N.P.[6]		1198-1208	1212	8/6/80	
D-24 W-25525	Buena Vista Co. T 91N, R 35W Sec. 26, SW SW SW NW	1291	X					0-357						956	Miss.	944	944-953	1266	8/5/80	
D-25 W-25526	Buena Vista Co. T 90N, R 38W Sec. 16, SE SE SE SE	1365	X					0-517					1041	none	Miss.	865	848-866 c&p[3] 1015-1019	1174 1176	2/27/80 8/4/80	
D-26 W-25527	Buena Vista Co. T 90N, R 36W Sec. 13, NE SE SE NE	1281	X					0-338							Miss.	950	1043-1058	1179	8/5/80	
D-27 W-25528	Buena Vista Co. T 93N, R 35W Sec. 19, NW NW SW SE	1322	X										1079	none	Dev.	981	954-969	1195	8/5/80	
D-28 W-25529	Cherokee Co. T 91N, R 39W Sec. 1, SE NE SE SE	1370	X			X	X	0-253	253-1545					1145	Miss.	895	-179-+244	1176	8/6/80	
D-29 no W number	Cherokee Co. T 91N, R 39W Sec. 1, SE NE SE SE	1370						none						1145	N.P.[6]		1030-1035	1179	8/6/80	

D-30 W-25591	Woodbury Co. T 89N, R 46W Sec. 36, SW SE NW NW	1268	X	0- 557			1188	1093	Dev.	733	711-729 c&p[3] 906-910	1130 1134	2/28/80 8/7/80	
D-31 W-25592	Plymouth Co. T 90N, R 45W Sec. 28, SE SW SW	1300		0- 487			1107	995	Dev.	820				C & A[4]
D-32 W-25593	Woodbury Co. T 89N, R 44W Sec. 20, SW SE SW SE	1160	X	0- 220				1050	N.P.[6]		939-954	1134	8/6/80	
D-33 W-25594	Woodbury Co. T 88N, R 44W Sec. 6, NW NE NE NW	1340	X	0- 521				1040	Miss.	825	1003-1008	1139	8/7/80	
D-34 W-25735	Woodbury Co. T 87N, R 44W Sec. 15, NW NW NW SW	1165	X	0- 281				1045	Miss.	890	884-894 c&p[3] 976-980	1100 1104	2/28/80 8/7/80	
D-35 W-25736	Plymouth Co. T 92N, R 48W Sec. 6, NE SE SE SE	1282	X	0- 581	1173	1154	1102	977	D-P-G	707	767-772 c&p[3] 848-852	1132 1126	3/27/80 5/5/80	
D-36 W-25737	Buena Vista Co. T 93N, R 35W Sec. 13, NE NE SE NE	1330	X	0- 381				987	Dev.	970	970-980	1196	8/4/80	
D-37 W-25773	Palo Alto Co. T 96N, R 34W Sec. 24, NW NW NW NW	1315	X	0- 501				965	Galena	817	none			
D-38 W-25898	Osceola Co. T 98N, R 39W Sec. 26, SE NE SE SW	1401.98	X X	0- 661			1095	977	D-P-G	810	1057-1097 742-782	1209 1204	6/17/80 6/17/80	nested well
D-39 W-25899	Osceola Co. T 98N, R 39W Sec. 26, SW SW SE SW	1397.69	X	0- 500			1113	1030	N.P.[6]		898-908	1207	6/17/80	
D-40 W-25900	Osceola Co. T 98N, R 42W Sec. 33, NE NE NW NW	1440	X	0- 481			1081	none	Sioux Qtzt.	975	958-964 c&p[3] 1040-1044	1192 1199	8/5/80 11/26/80	

Well Iden-tifier	Location	Land surface elevation[1]	Geophysical logs[2] N.G.	S.P. + R.	C.	G-G.	N.	Sample Interval Cuttings	Core	Elevations of formation tops[1] Carlile Shale	Greenhorn Limestone	Graneros Shale	Dakota Formation Wdby. Mem.	Nish. Mem.	Pre-Cretaceous Geologic Unit Unit[7]	elev.[1]	Elevation screened or perforated interval[1]	Elevation of ground-water potential or head[1]	Date of water-level measurement	Comment
D-41 W-25963	O'Brien Co. T 94N, R 42W Sec. 5, NE SE SE SE	1560	X	X				0- 701					1073	1016	D-P-G	872	859-899	1200	9/10/80	
D-42 W-25964	O'Brien Co. T 94N, R 42W Sec. 9, SE SE SE SE	1440	X										1088	990	Galena	814	904-924	P.D.[5]		
D-43 W-25965	Sioux Co. T 95N, R 43W Sec. 7, NE NE NE NE	1398	X					0- 681					1103	868	D-P-G	728	717-757	1183	8/6/80	
D-44 W-25941	Sioux Co. T 96N, R 44W Sec. 8, SE NE SE NE	1373	X	X				0- 682			1077	1070	1052	891	Dev.	703	706-726	1180	8/6/80	
D-45 W-25966	Lyon Co. T 100N, R 43W Sec. 33, SE SW SW SW	1465	X					0- 732					1086	860	Sioux Qtzt.	770	733-753	1224	8/5/80	
D-46 W-26009	Dickinson Co. T 98N, R 37W Sec. 15, SE SE SE SE	1430	X					0- 600						1086	D-G-P	842	830-850	1201	8/80	
D-47 W-26041	Dickinson Co. T 98N, R 35W Sec. 15, NE SE SE SE	1417						0- 380					1130	1116	N.P.[6]					C & A[4]
D-48 W-26042	Sac Co. T 89N, R 35W Sec. 11, SW SE SW SE	1160	X	X				5- 261		1130	1070	1042	989	none	Penn.	928				C & A[4]
D-48E W-26170	Sac Co. T 89N, R 35W Sec. 11, SW SE SW SE	1160	X					90- 150, 250- 260	30- 83, 183- 233	1130	1118	1090	1040	none	Penn.	942	953-970	1106	12/16/80	

D-49 W-26168	Lyon Co. T 100N, R 48W Sec. 19, SW SW SW NW	1315		0- 252						Sioux Qtzt.	1063			C & A[4]
D-50	Plymouth Co. T 92N, R 48W Sec. 6, NE SE SE SE	1282		0- 49	49- 135	1173	N.P.[6]							C & A[4]
D-51	Sioux Co. T 96N, R 44W Sec. 8, SE NE SE NE	1373			94-95 110-116 130-131									C & A[4]
D-52 W-26169	Dickinson Co. T 100N, R 35W Sec. 29, NE SE SE SE	1505	X	0- 657				1167	965	N.P.[6]		848-858	P.D.[5]	
D-53 W-26219	Dickinson Co. T 99N, R 36W Sec. 16, NE NE NE NE	1418	X	0- 600				1170	1028	N.P.[6]				C & A[4]

			Geophysical logs[2]					Sample Interval		Elevations of formation tops[1]						
													Dakota Formation		Pre-Cretaceous Geologic Unit	
Well Identifier	Location	Land Surface elevation	N.G.	S.P.+ R.	C.	G-G.	N.	Cuttings	Core	Carlile Shale	Greenhorn Limestone	Graneros Shale	Wdby. Mem.	Nish. Mem.	Unit[7]	elev.[1]
Hanson Production Well W-24520	Sioux Co. T 97N, R 46W Sec. 28 SE NE NW SE	1345	X	X	X			0-596				1080	1053	940	Rhyolite	755
Hanson observation well W-24559	Sioux Co. T 97N, R 46W Sec. 28, NE SE SE SE	1302	X	X	X			20-520				1102	1072	948	Rhyolite	787
Hosteng observation well W-24560	Sac Co. T 87N, R 35W Sec. 30, SE SE SE SE	1242	X	X	X			0-360						1092	Penn.	905
Ritz production well W-25186	Plymouth Co. T 92N, R 47W Sec. 31, SW SE SW SE	1300	X					0-377			1230	1210	1160	955	N.P.[6]	
Ritz observation well W-25140	Plymouth Co. T 92N, R 47W Sec. 31, NE SW SE SW	1320	X					0-595			1220	1190	1135	920	Galena	728
Hibbing observation well #1	Osceola Co. T 98N, R 39W Sec. 26, SW NW NW SE	1416	X					none					1136	924	N.P.[6]	
Hibbing observation well #2	Osceola Co. T 98N, R 39W Sec. 26, SW NW SW SE	1407.66	X					none					1118	990	N.P.[6]	
Spirit Lake State Fish Hatchery W-24842	Dickinson Co. T 100N, R 36W Sec. 28, SE SW SE SE	1410	X					0-695					1200	1095	Jordan	790
Holman Estates	Dickinson Co. T 99N, R 37W Sec. 32, NE NW NW NW	1484	X					none					1166	979	N.P.[6]	

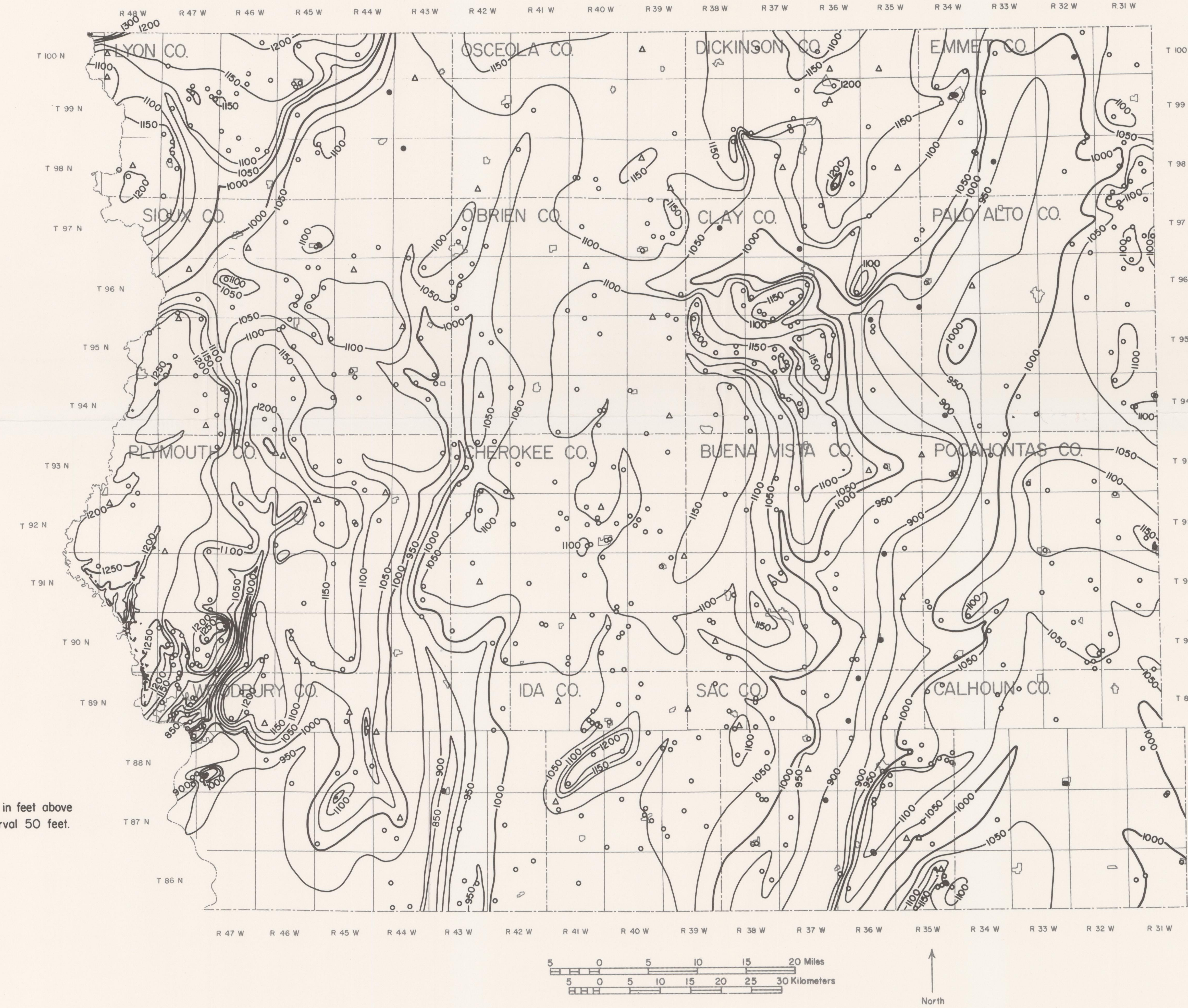
Well Identifier	Location	Land Surface elevation	Geophysical logs[2] N.G.	S.P.+ R.	C.	G-G.	N.	Sample Interval Cuttings	Core	Elevations of formation tops[1] Carlile Shale	Greenhorn Limestone	Graneros Shale	Dakota Formation Wdby. Mem.	Nish. Mem.	Pre-Cretaceous Geologic Unit Unit[7]	elev.[1]
Inwood town well	Lyon Co. T 98N, R 47W Sec. 7, SW SW SW SW	1430	X					none		1165	1125	1100	1050	none	Sioux Qtzt.	965
So. Sioux Co. Rural Water System 79-1 W-25487	Sioux Co. T 93N, R 45W Sec. 4, SW SW SW NW	1269	X	X				0-448					~1169	979	Galena	824
SDGS-168 (So. Dakota Geol. Survey)	Lincoln Co, So. Dakota T 99N, R 48W Sec. 16, SW SW SW SW	1300						none		1137	1042	997	984	none	Sioux Qtzt.	898
SDGS-169 (So. Dakota Geol. Survey)	Lincoln Co, So. Dakota	1254						none		1189	1112	1074	1038	none	Sioux Qtzt.	965
J. Gravengoed W-24568	Sioux Co. T 96N, R 47W Sec. 10, SW NW NW NW	1217	X					0-320		974			982	N.P.[6]	N.P.[6]	
Ill. Central RR #1	O'Brien Co. T 94N, R 40W Sec. 22, NE SE	1432						none		1200	1194	1177	1137	1032	N.P.[6]	
Inwood City Well #1 W-1344	Lyon Co. T 98N, R 47W Sec. 18, NW SE NW	1463						0-518		1153	1123	1093	1043	none	Sioux Qtzt.	963
Rock Rapids #3 W-7421	Lyon Co. T 99N, R 45W Sec. 5, NW NE	1368						0-375			1168	1148	~1098	none	Sioux Qtzt.	1003

Well Identifier	Location	Land Surface elevation	Geophysical logs[2] N.G.	S.P.+R.	C.	G-G.	N.	Sample Interval Cuttings	Core	Elevations of formation tops[1] Carlile Shale	Greenhorn Limestone	Graneros Shale	Dakota Formation Wdby. Mem.	Nish. Mem.	Pre-Cretaceous Geologic Unit Unit[7]	elev.[1]
Rock Rapids #2 W-7418	Lyon Co. T 99N, R 45W Sec. 5, NE NE SE	1423						0-549				1128	~1078	none	Sioux Qtzt.	933
Larchwood #1 W-0409	Lyon Co. T 100N, R 47W Sec. 30, NE SW	1475						0-562		1151	1050	1025	975	none	Sioux Qtzt.	915
Ireton town well W-2310	Sioux Co. T 94N, R 46W Sec. 7, SE NE SE	1435						0-543		1220	1180	1125	1085	940	N.P.[6]	
H. Koopman W-13003	Sioux Co. T 94N, R 46W Sec. 18, NE NE SE NE	1456						0-507		1206	1186	1156	1106	N.P.[6]	N.P.[6]	
J.C. Toenjes W-8634	Sioux Co. T 94N, R 46W Sec. 36, SE SE SE NE	1426						0-424		1236	1226	1186	1126	1026	N.P.[6]	
J. Rehder W-1543	Sioux Co. T 96N, R 47W Sec. 32, NE SE	1330						0-425		1205	1145	1105	1055	960	N.P.[6]	
Hull City Well #4 W-10434	Sioux Co. T 97N, R 45W Sec. 26, NE SE NW SW	1415						0-665		1120	1065	1015	965	915	N.P.[6]	
W. Phillips W-11476	Plymouth Co. T 92N, R 48W Sec. 10, SE NE NW	1358						0-400			1213	1193	1138	1008	N.P.[6]	

Well Identifier	Location	Land Surface elevation	Geophysical logs[2] N.G.	S.P.+ R.	C.	G-G.	N.	Sample Interval Cuttings	Core	Elevations of formation tops[1] Carlile Shale	Greenhorn Limestone	Graneros Shale	Dakota Formation Wdby. Mem.	Nish. Mem.	Pre-Cretaceous Geologic Unit Unit[7]	elev.[1]
L. Langel W-19423	Plymouth Co. T 92N, R 45W Sec. 14, NE SE SW SW	1375						0- 367			1202	1205	1165	1025	N.P.[6]	
N. Brunken W-18006	Plymouth CO. T 92N, R 44W Sec. 6, SW SE SW SW	1383						0- 276			1248	1238	1178	1133	N.P.[6]	

PLATE I.

ELEVATION OF THE BEDROCK SURFACE (BASE OF THE PLEISTOCENE) IN NORTHWEST IOWA



1000 — Elevation of bedrock surface in feet above mean sea level. Contour interval 50 feet.

△ IGS/USGS data point

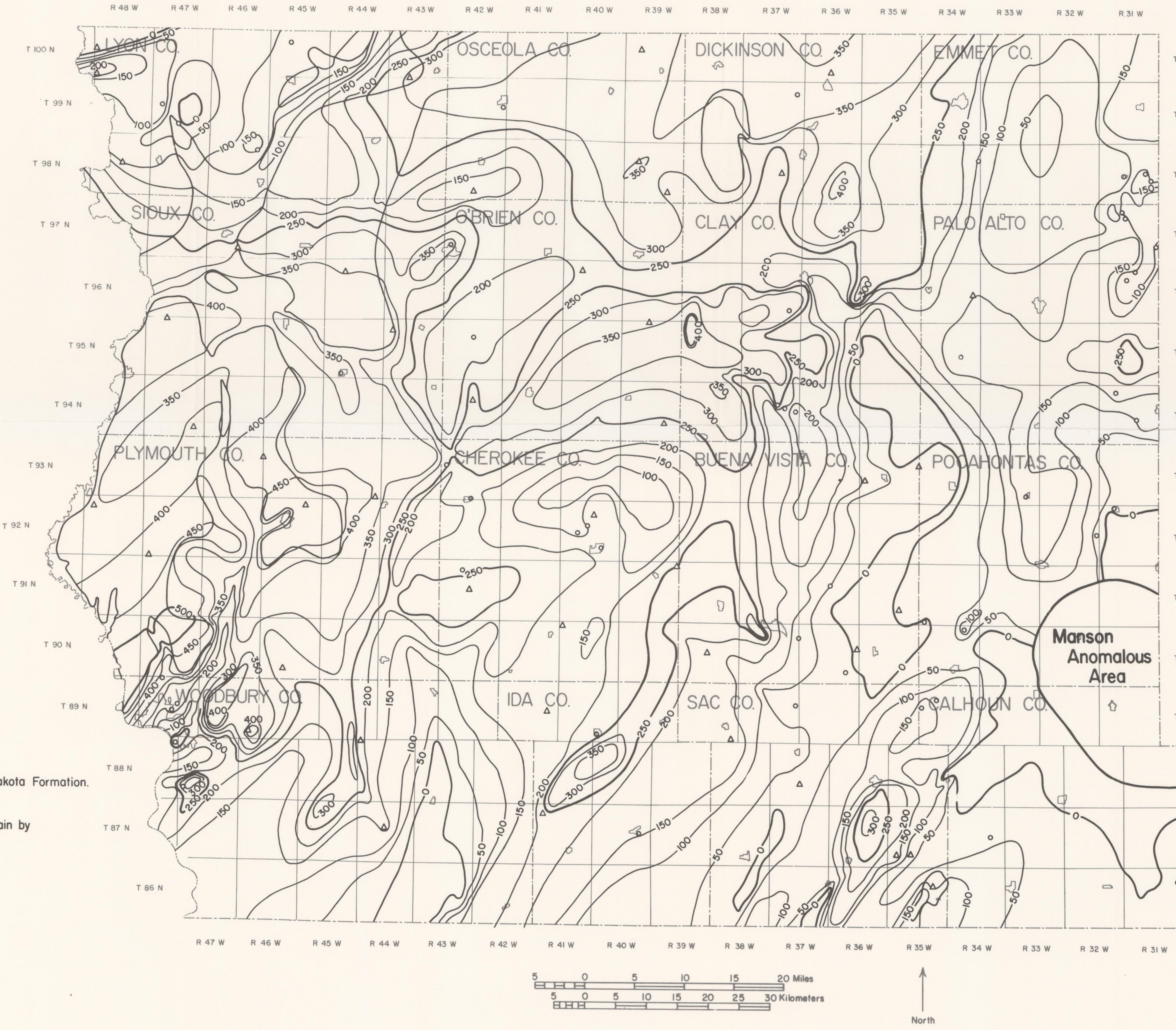
○ Private well

Bedrock exposure

● Deep Pleistocene well

PLATE 2.

THICKNESS OF THE DAKOTA FORMATION IN NORTHWEST IOWA



—100— Line of equal thickness of the Dakota Formation. Contour interval 50 feet.

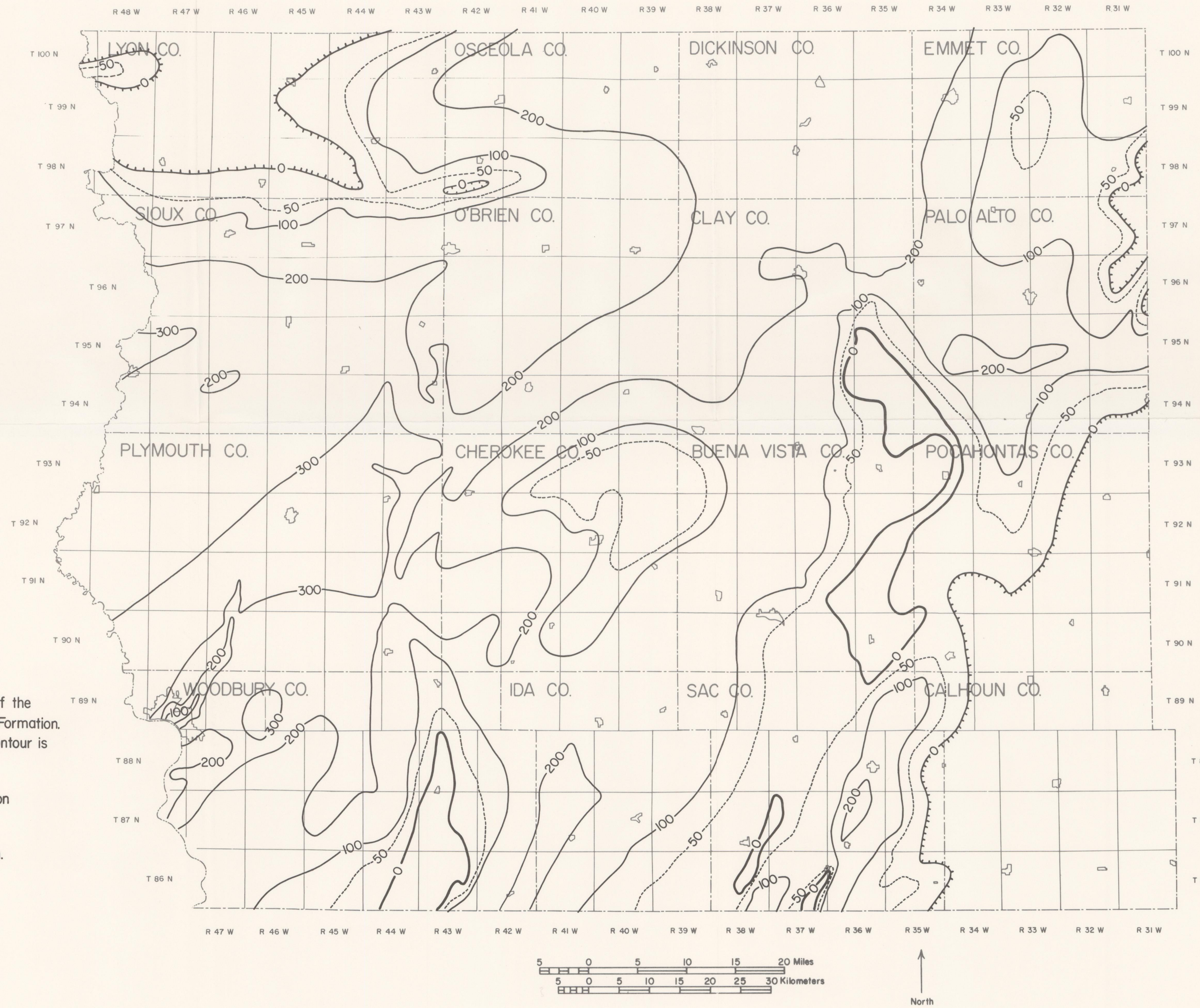
▭ Areas where the Dakota is overlain by younger rocks.

△ IGS/USGS data point.

○ Private well

PLATE 3.

THICKNESS OF THE NISHNABOTNA MEMBER OF THE DAKOTA FORMATION IN NORTHWEST IOWA



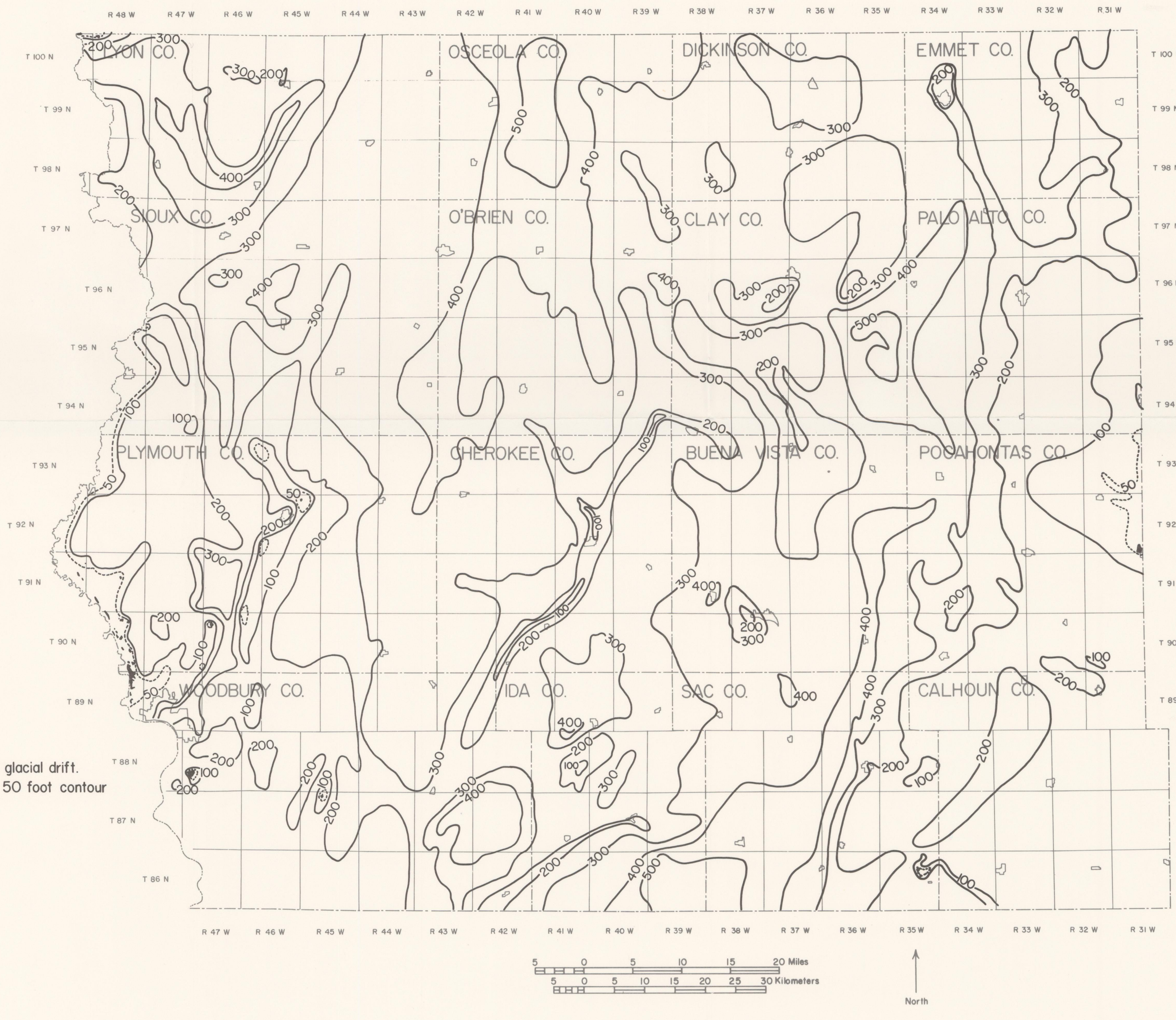
—100— Approximate line of equal thickness of the Nishnabotna member of the Dakota Formation. Contour interval 100 feet, 50 foot contour is dashed.

—0— Nishnabotna member not deposited on hatchured side.

Dakota Formation removed by erosion.

PLATE 4.

THICKNESS OF THE GLACIAL DRIFT (DEPTH TO BEDROCK) IN NORTHWEST IOWA

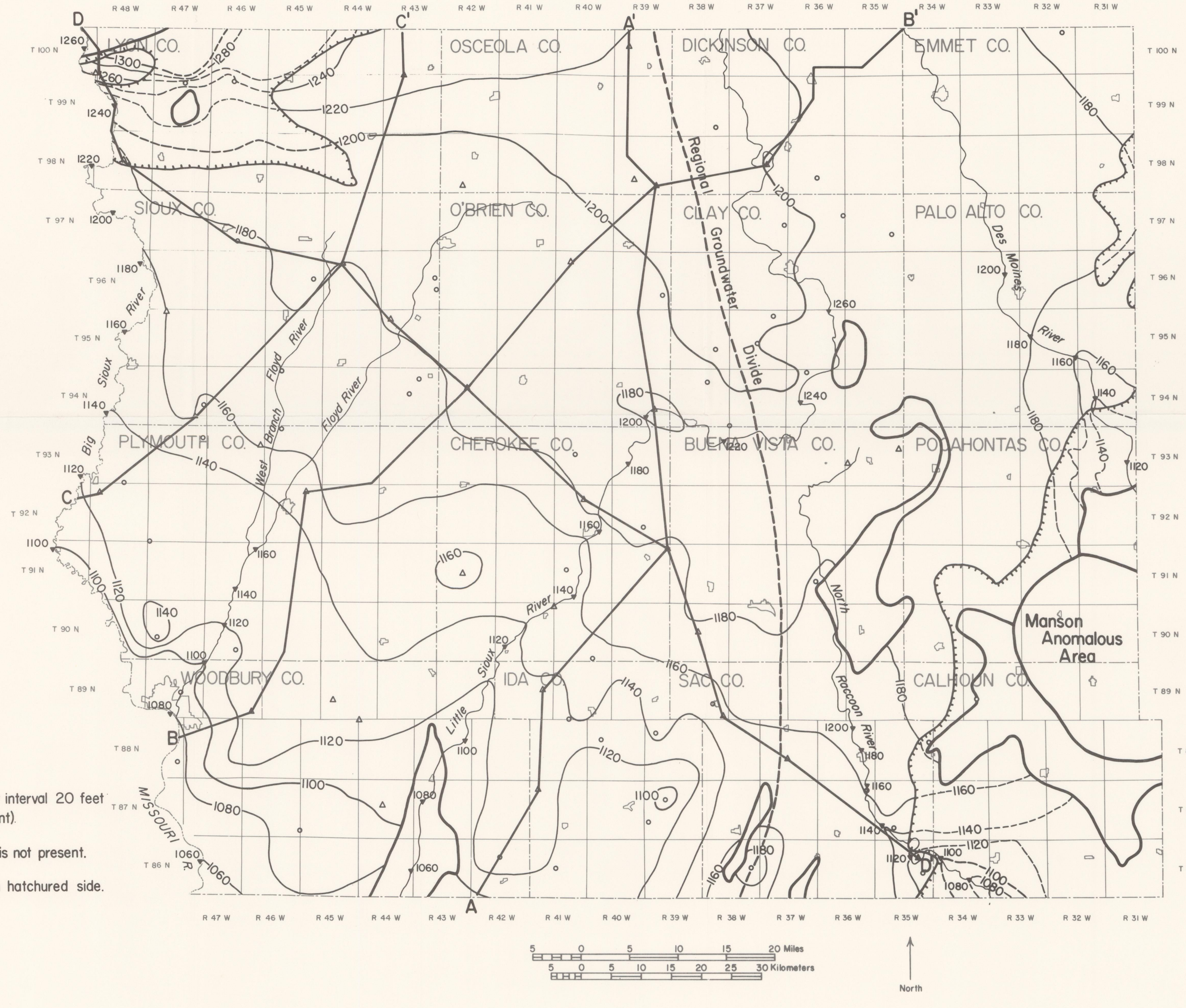


Line of equal thickness of glacial drift. Contour interval 100 feet, 50 foot contour is dashed.

Bedrock exposure

PLATE 5.

POTENTIOMETRIC SURFACE OF THE DAKOTA AQUIFER IN NORTHWEST IOWA



△ IGS/USGS data point

○ Private well

1080▾ River elevation (feet)

Potentiometric contour (feet). Contour interval 20 feet (dashed where Nishnabotna not present).

Areas where the Dakota Formation is not present.

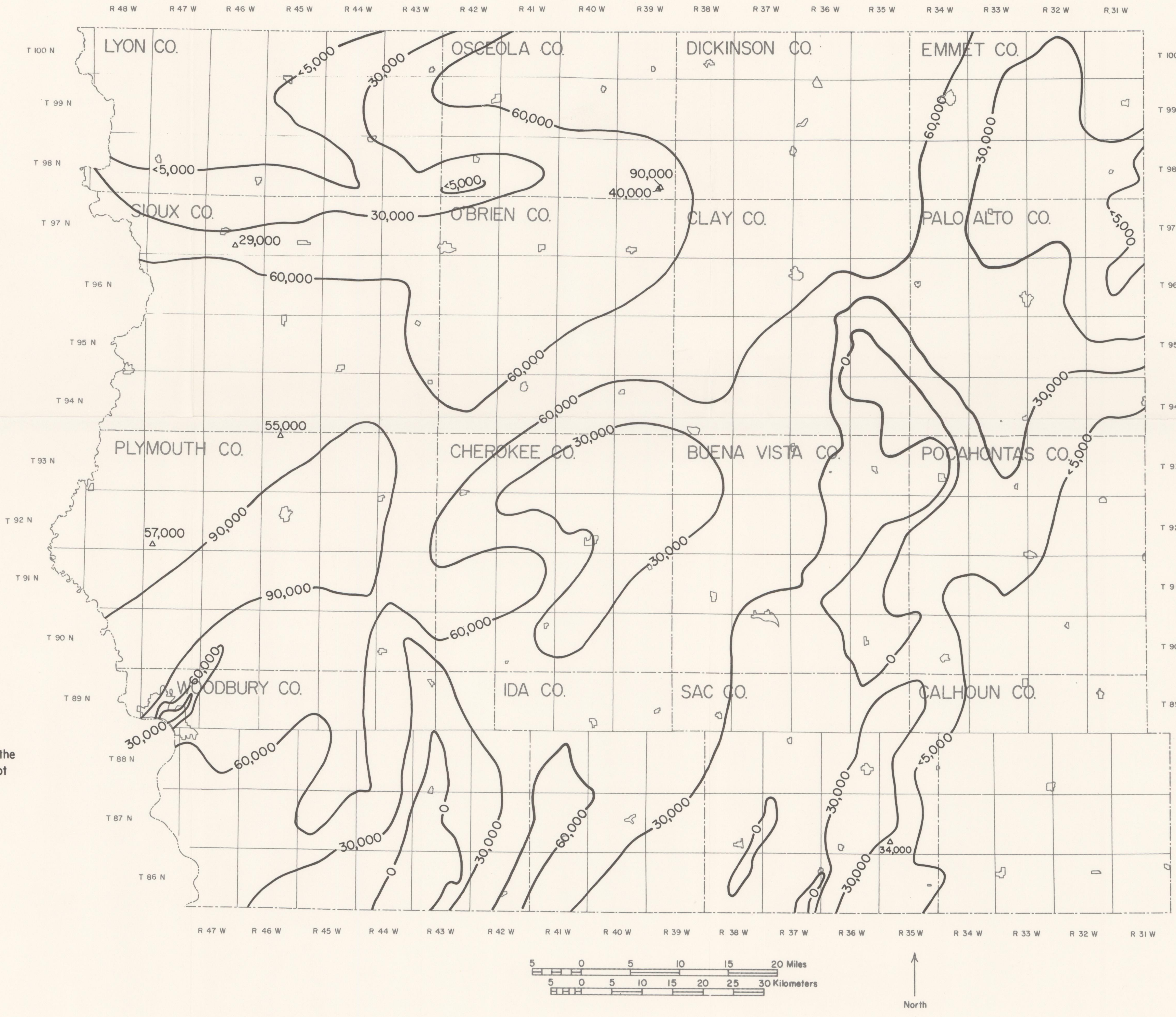
Nishnabotna member not present on hatchured side.

Cross-section lines

Datum is mean sea level.

PLATE 6.

TRANSMISSIVITY OF THE DAKOTA AQUIFER IN NORTHWEST IOWA



—60,000— Lines of equal transmissivity of the Dakota aquifer in gallons/day/foot

57,000 △ Pumping test site, with value of transmissivity in gallons/day/foot

5 0 5 10 15 20 Miles

5 0 5 10 15 20 25 30 Kilometers