The hydrogeology of the Skunk River regolith aquifer supplying Ames, Iowa

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THE HYDROGEOLOGY OF THE SKUNK RIVER REGOLITH AQUIFER
SUPPLYING AMES, IOWA

by

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Signatures have been redacted for privacy

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INTRODUCTION

This study presents the results of a hydrogeologic investigation conducted for the City of Ames, Iowa. It is the second in a series of studies sponsored by the Department of Earth Science, Iowa State University, and the City of Ames for the purpose of evaluating the sand and gravel regolith* aquifer which is the source of the City water supply.

The first study (Backsen, 1963) encompassed an area of 55 square miles which included the City of Ames. In that study, Backsen established the existence of the regolith aquifer in this area, and furnished hydrologic and geologic information pertinent to the evaluation of its water bearing potential.

Purpose of Study

The purpose of this investigation was to extend the study of the aquifer initiated by Backsen to the north. This included the determination of: a) the textural, dimensional, and spatial characteristics of the aquifer unit; and b) the relationship of the aquifer unit to the bedrock surface and to other regolith deposits.

Area of Study

Backsen showed that the aquifer is limited to the confines of a pre-glacial (?) bedrock channel which he and others (Zimmerman, 1952; Twenter and Coble, 1965) show to separate into two branches north of Ames. The

* The term regolith refers to the unconsolidated material above the bedrock surface.
buried channels underlie for the most part the modern Skunk River and Squaw Creek, and hereafter will be referred to as the Skunk channel and the Squaw channel. Because the Skunk channel segment appeared to be the smaller of the two channels and because of its relationship to a potentially large surface recharge area, the Story City flat, it was chosen for this study. The study area covers approximately 100 square miles in northwest Story County and southeast Hamilton County, and is shown in Figure 1. The area is directly north of Backsen's area of study, overlapping the northernmost two tiers of sections included in his work.
Figure 1. Index map of Story County showing area investigated.
LITERATURE REVIEW

Geology

Introduction
The area of study is mantled almost entirely by deposits of glacial or glaciofluvial origin (Wallace, 1961). Portions of these deposits have been assigned by Beyer (1898) to (in descending order) the Wisconsin stage, the Iowan substage, and the Kansan substage of the Pleistocene epoch.

Underlying the Pleistocene deposits, the bedrock (first indurated rock below the regolith) surface, which is locally exposed by stream dissection and quarry operations, consists of rocks belonging to the Pennsylvanian and Mississippian systems. A thorough discussion of the bedrock geology of the study area is found in Bedrock Geology of Western Story County, Iowa by Zimmerman (1952).

Modern bedrock physiography

Modern physiography The study area is drained by the Skunk River and its chief tributary, Squaw Creek. The Skunk River and its local tributaries, Keigley Creek on the west, Long Dick and Bear Creeks on the east, drain the eastern four-fifths of the area, and Squaw Creek drains the southwest one-fifth of the area. Squaw Creek and Keigley Creek flow southeast, as do most of the streams in central and eastern Iowa. The Skunk River flows south through the northern two-thirds of the area, southwest in the southern one-third, and southeast paralleling the regional stream trend, south of the present study area. The southeast trend of the Skunk River
and the trend of Bear Creek (Figure 1) probably reflect the Ames-Roland anticlinal structure (Zimmerman, 1952; Huedepohl, 1956). Bear Creek and the lower part of Skunk River in the study area lie on the northwest flank of the anticline, as outlined by Zimmerman.

The surface of the area consists for the most part of the gently undulating swell and swale topography described by Gwynne (1942). Maximum relief in the area is 50 feet, except in the vicinity of the major streams, where relief approaches 100 feet.

The swell and swale topography is conspicuously absent between Skunk River and Keigley Creek. This area, known locally as the "Story City Flat," has a relief of 20 feet or less. Poorly developed natural drainage has made extensive field tiling necessary to make the land usable for farming.

Gwynne (1942) was the first to point out that the swells and swales are arranged in distinct arcuate patterns. Because of their low relief (five to 10 feet), these features are not readily seen on the topographic map of the area (Figure 1), although they do exert considerable influence on the minor drainage pattern (Wallace, 1961). They are easily distinguished on air photos (see Figure 2), on which the lighter color of the tops of the ridges contrasts with the darker color of the depressions. Generally, the orientation of these features is southwest-northeast, although pronounced variations from this trend can be seen in the vicinity of Squaw Creek, where the ridges appear to bend upstream. No such relationship exists between the ridges and either Skunk River or Keigley Creek. In fact, the ridges seem to be closely aligned on either side of the
Figure 2. Uncontrolled aerial mosaic of area investigated
TYPICAL ARCUATE PATTERNS
featureless Story City Flat, as if the swell and swale topography had once been continuous over that area, and had been subsequently covered by younger deposits or removed by erosion.

A major end moraine system, the Altamont system, lies just to the northwest of the study area. Leverett defined the limits of the Altamont moraine (Leverett, 1932) and included in that system a linear high located on the south side of Keigley Creek (Figure 1). Originally assigned to the Gary moraine complex by Chamberlain (1883), the feature extends southeast from the western border of Story County to Section 12, T 84 N, R 24 W, where it is incised by the Skunk River. On the east side of the river it is present in Sections 17 through 19, T 84 N, R 23 W.

In recent publications Ruhe and others (e.g., Wright and Ruhe, 1965) have classified this feature as ground moraine. Reasons for this latest change in classification are (Ruhe)* the lack of sufficient relief across the feature and its lack of alignment with the southwest-northeast trend of the prominent Altamont ridges in Boone and Hamilton counties. Gwynne (1942) has suggested that the feature consist primarily of relief on the pre-Wisconsin drift surface, which has been overlain by a veneer of Wisconsin drift.

Pre-Pleistocene (?) physiography Two previous studies (Zimmerman, 1952; Twenter and Coble, 1965) presented generalized bedrock topographic maps which include the area covered in this investigation. The former work encompassed the western half of Story County, and the latter covered a

ten-county area in central Iowa. Backsen (1963), covering a smaller area in more detail, studied the bedrock topography directly south of the present study area. Although all three studies show a bedrock channel underlying Ames and separating into two branches, the Skunk and Squaw channels, some disagreement exists with regard to the extent and depth of the channels. For example, Zimmerman showed the Skunk channel occurring north of Story County. Twenter and Coble indicated that the channel is absent just north of Story City. According to Zimmerman and Twenter and Coble, the bottom elevations of each of the two bedrock channels near the point of confluence at Ames is 800 feet above sea level, whereas Backsen indicates that the Squaw channel is 80 feet deeper at the same point.

Twenter and Coble have shown that the Squaw channel is also much longer than the Skunk channel. From its mouth in Story County, the Squaw channel trends to the northwest, passing beneath Stratford (Section 7, T 86 N, R 26 W, Hamilton County), and finally ending eight miles north of Fort Dodge. The greater depth and length of this channel relative to the Skunk channel are factors which substantiate an earlier hypothesis by Beyer (1898) that the Squaw channel is the primary headward extension of the bedrock channel which occurs below the confluence of the two streams, and that the Skunk channel is a tributary to it.

Stratigraphy

*Regolith stratigraphy* Beyer, in his work entitled *Geology of Story County* (1898), described the typical sequence of glacial material as follows: Wisconsin till, Iowan loess, post-Kansan gravels, Kansas till.
The term till was used by Beyer to describe all the deposits of the Wisconsin and Kansan stages. Any sands and gravels in those deposits were thus included under the term till. Till is now defined in the American Geological Institute glossary (1960) as an unsorted and unstratified mixture of clay, silt, and sand which includes a minor fraction of material from gravel to boulder size. A more general term, drift, is now applied to all deposits associated with a glacier. It can thus be used to describe not only till but sorted, stratified sand and gravel as well. Use of the terms till and drift to describe material encountered in the present study will conform with the definitions given in the AGI glossary.

Beyer states that the upper till is Wisconsin in age and that it is the only unit which is continuous over the area. It varies in thickness from 20 to 100 feet. The underlying units, when present, have maximum thicknesses of 20 feet (loess), 20 feet (gravel), and 60 feet (Kansan till). Beyer also presents the log from a well located in the NE\textsuperscript{4}, Section 5, T 85 N, R 24 W, as evidence for the presence of a fairly extensive sand and gravel unit at the base of the Pleistocene deposits. The log shows 50 feet of sand and gravel overlain by younger loess and till deposits of Kansan (?) to Wisconsin age. He suggests that the unit is pre-Kansan in age. He cites the occurrence of sand and gravel similarly positioned at the base of the Pleistocene in the deposits underlying Ames, and suggests that the deposits are connected as part of an extensive channel fill.

Ruhe and Scholtes (1955) described and sampled exposures at Clear Creek (SW\textsuperscript{1}, Section 5, T 83 N, R 24 W), in Backsen's area, and Cook's Quarry (NW\textsuperscript{1}, Section 24, T 84 N, R 24 W) in the present study area. Both sections contained two tills. Radiocarbon dates of 12,000±500 years b.p.
obtained from samples at each location have resulted in a tentative identification of the upper till as Cary. The Cary till lies directly on top of the lower till except where sags in the lower till surface have been filled in by lenses of sand and gravel, for which a date of 14,042±1000 years b.p. was obtained. The authors call the lower till Iowan. At Clear Creek the two tills are separated by a fossiliferous organic silt unit which has been dated at 16,367±1000 years b.p., and identified as Iowan-Tazewell.

Backsen (1963) noted the presence of three tills. The upper two tills were continuous over most of his area, whereas the lower till was confined to the bedrock channel underlying Squaw Creek. He described the total sequence as upper till, silt, intermediate till, aquifer, and lower till. All units except the upper till, which is of fairly uniform thickness, were described as thinning to the north. The upper till averaged 50 feet in thickness, the lower two tills 60 feet each in thickness, and the silt and aquifer units 30 and 40 feet in thickness, respectively.

Backsen emphasized that although the aquifer unit was listed in the sequence as underlying the intermediate till, it consists of all the sands and gravels connected hydraulically with the sand and gravel deposit which supplies Ames with water. This could include in some cases modern alluvium and sand and gravel units between the intermediate and upper tills. In general, the aquifer material consists of coarse sand and gravel to the south, with fine sand and clay lenses becoming increasingly common to the north.

**Bedrock stratigraphy** It has been long recognized that the bedrock surface near Ames is composed of rocks of the Mississippian and the
Pennsylvanian systems. White (1870) recognized Mississippian rocks three miles northwest of Ames and assigned them to the St. Louis Formation. Beyer (1898) published a geologic map of the county, on which he showed an inlier of older Mississippian rocks (St. Louis Formation) located at Ames surrounded by younger rocks of Pennsylvanian age.

Zimmerman (1952) showed that the Mississippian rocks are confined to the Skunk River and Squaw Creek bedrock channels and to an area between Ames and Roland which overlies the southwest-northeast trending anticline shown on his structure contour map. According to Zimmerman, the Mississippian bedrock surface consists of at least five formations (in descending order), the St. Louis, Warsaw, Keokuk, Gilmore City, and Hampton. Two well logs used in the present study (443 and 422) indicate that the Burlington, stratigraphically between the Keokuk and the Gilmore City Formations, is also present at the bedrock surface.

Structure

Existence of an anticlinal structure in the bedrock was first inferred by McGee (1891) on the basis of inliers of Mississippian rock exposed along the Skunk River surrounded by younger Pennsylvanian rock. He considered the structure, which he called the "Skunk River Anticlinal," to be an upfold with a southeast-northwest orientation.

Beyer (1898) showed by an analysis of well records from Boone, Ames, and Nevada, that there was such a structure and concurred with McGee on its probable southeast-northwest alignment.

Zimmerman (1952), in a more detailed examination of the structure, showed it to have a southwest-northeast trend with closures at Ames,
"Soper's Mill" (Section 6, T 84 N, R 23 W), and Roland.

Huedepohl (1965) agreed with Zimmerman's interpretation of the trend of the anticline near Ames and suggested that two other domal highs, one at Randall (Figure 1), the other in Grant Township (T 86 N, R 21 W, Hardin County), could be considered extensions of the structure.

Water Supply

Simmons and Norton (1911) listed the following possible sources of underground water available in Story County: alluvium, gravel above Kansan till, Aftonian gravel below Kansan till, near-surface Pennsylvanian and Mississippian bedrock, and deep bedrock units. It was thought that the Aftonian gravels might be a buried channel fill, and, as such, might represent a relatively shallow high yield source of water.

Flowing wells are common near Keigley Creek and Skunk River in the Story City vicinity. "Watkins Well" (Well 478, Figure 7) was cited (Simmons and Norton, 1911) as the largest flowing well in the "Keigley basin". Flow from the well at the time of drilling was measured at 28,000 gallons per hour. A survey of farm wells conducted during the course of this study indicated that many flowing wells still exist in the area (Figure 11). Most of the flowing wells between Keigley Creek and Skunk River do not penetrate bedrock, whereas the flowing wells outside of that area are in bedrock. A large flow (approximately 1,000 gpm) not originating in bedrock was encountered recently when the Iowa Highway Commission drilled a bridge sounding on the Pat Nolan property. The sounding is shown as well 465 in Figure 7.
Of the sources of water listed by Simmons and Norton, Twenter and Coble (1965) assigned the highest yields to the alluvium of the Skunk River and to the lowest bedrock aquifer. A relatively low yield (20 to 100 gpm) is listed for the bedrock channel fill underlying Squaw Creek. However, this estimate is based on the yields of a few small diameter wells and may not represent the true potential of that aquifer, according to Twenter*.

The upper bedrock aquifer is shown to be capable of producing over 100 gpm in an area which includes Story City, Roland, and Gilbert (Twenter and Coble, 1965). It is interesting to note that the piezometric surface mapped by Twenter and Coble for the upper bedrock aquifer has elevations of 1000 feet near Story City and about 900 feet at Ames. Thus, the water levels from this source are far above the base of the regolith aquifer, and in some cases, above ground as well.

METHOD OF INVESTIGATION

The study employed geological and geophysical techniques. The geological investigation included: a) review of existing literature on the geology of the area; b) compilation of well data from the Iowa Geological Survey, the Iowa Highway Commission, well drillers in the area, and individuals contacted during a survey of farm wells; c) drilling of 24 test holes in areas of poor control; and d) inspection of outcrops. From these sources, stratigraphic information was obtained at 70 locations with samples from 24 locations, and depth to bedrock information at 85 locations. Control points are shown in Figure 7.

The geophysical study included: a) recording in-hole resistivity and self-potential logs on five of the test holes; and b) conducting a continuous depth profile surface resistivity survey at 146 locations (Figure 7). Virtually all of the resistivity data yielded depth to bedrock, and at many points stratigraphic information was obtained.

Existing data was plotted on maps, and areas deficient in information were delineated. A test hole drilling program in those areas supplied data which was then "tied-in" to existing information by the resistivity network and by stratigraphic correlation. Anomalies detected by the resistivity method were investigated further with subsequent test hole drilling. Nineteen test holes were drilled by a University-owned rig, and five were drilled by Layne Western Drilling Company. Both rigs were the rotary type. Samples were taken from the drill cuttings at two-foot intervals.

Since the resistivity method played an important role in this investigation, and because it has not been used extensively in Iowa, a discussion
of its application in this study is presented.

Electrical Resistivity Method

The electrical resistivity or inverse conductivity of a material reflects characteristic physical and chemical properties of the material. The variables include the amount of fluid contained by the material, the conductivity of the fluid, and to a lesser degree, the dielectric properties of the rock. The amount of fluid depends on the porosity of the material. The conductivity of the fluid is a function of the concentration of ions imparted to it by the material through which it flows. For a thorough discussion of the theoretical background for the resistivity method, see Jakosky (1960).

Two methods used for measuring electrical resistivity in the field are: 1) the in-hole method, which measures true resistivity; and 2) the surface method, which measures apparent resistivity. Both were employed in this study.

In-hole measurements are obtained by raising a "sonde" slowly from the bottom to the top of a bore hole. The "sonde" contains current and potential electrodes which are in electrical contact with the sides of the hole through the drilling fluid. The measurements are taken continuously and recorded at the surface as a function of depth.

The main value of the in-hole method is that the depths at which changes in material take place can be ascertained with more exactness than can be done with the sample cuttings collected during drilling of the hole. The logging instrument used in this study was borrowed from the United States Geological Survey at Iowa City, and was used in five of the test
holes drilled (301, 302, 303, 306, and 319).

In the second resistivity method used in this investigation, all measurements are taken at the surface with four electrodes placed in the ground. The Wenner configuration (Wenner, 1915), in which the four electrodes are placed in a line with an equal spacing (a) between them, was employed in this study. A measured current is applied between the two end electrodes, and the potential between the two central electrodes is measured. The circuitry and distribution of current and equipotential surfaces in a homogeneous material are shown in Figure 3. Distribution of these surfaces in a nonhomogeneous model is shown in Figure 4. Resistivity can be calculated by application of the following equation:

\[ \rho = 2 \pi a \frac{E}{I} \]

where

- \( \rho \) = apparent resistivity
- \( a \) = electrode spacing
- \( E \) = potential between \( P_1 \) and \( P_2 \), volts
- \( I \) = current flowing between \( C_1 \) and \( C_2 \), amperes

As the distance between the electrodes is increased, the effective depth of penetration of the current into the ground also increases. However, the material through which the current flows is usually not homogeneous, but stratified in layers, which have different true resistivities. Where the in-hole device measures the resistivity of each layer separately as the "sonde" passes through the layers, the surface apparatus yields for each spacing a composite value which represents all the layers penetrated. The composite value is really an average and is called apparent resistivity.
Figure 3. Current flow in a homogeneous model

Figure 4. Current flow in a non-homogeneous model
In this survey a series of apparent resistivity readings at regularly increasing electrode (a) spacings were taken for each station. Intervals of five or ten feet between spacings were used, with the maximum spacing being 200 feet in most cases. A continuous profile was obtained at each station by plotting (a) spacing (ordinate) vs. apparent resistivity (abscissa) as shown in Figure 5.

It is generally assumed that the "a" spacing is equal to the depth of penetration. The assumption is based on the conceptual model that equipotential lines describe a hemisphere around the current electrode. This is true only if the material penetrated is homogeneous, as shown in Figure 3. Since geologic conditions are usually more like Figure 4, it is acknowledged that the equality of "a" to depth of penetration is an approximation which needs to be checked against well or borehole information.

Measurements were taken with an instrument of the Gish-Rooney (Gish and Rooney, 1925) type constructed by the Geophysical Instrument Company of Manassas, Virginia. It is possible with this instrument to obtain continuous profile readings for as many as 20 stations per day.

It was decided that the continuous depth profile method should be used for two reasons. First, the required information included depth to bedrock and occurrence of sand and gravel units within the regolith. Second, the subtle nature of the till vs. shale and the sand vs. carbonate resistivity contrasts necessitated a close attention to characteristic patterns and relative changes in patterns with depth.

In this investigation, approximately one-third of the total number of stations were located near points of control. Therefore it was possible in most cases to start from a point where the geologic conditions were known
and project horizons detected by the resistivity survey into areas of poor control. It was often possible to "tie in" to known points along or at the end of a traverse across an area.

An effective method for the interpretation of the resistivity data was devised which employed the use of an isometric panel diagram. The "breaks", or changes in slope, on the resistivity profiles were plotted on a panel diagram, such as Figure 9, along with the water well, borehole and outcrop data. This made possible the analysis of the resistivity data in all directions, and facilitated correlation of the resistivity information with geologic control. Ranges of resistivity values and profile patterns considered characteristic of the materials encountered are found in Table 1 and Figure 5.

Table 1. Representative resistivity values

<table>
<thead>
<tr>
<th>Material</th>
<th>Range of Resistivity Values, Ohm-Centimeters</th>
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<tbody>
<tr>
<td>till</td>
<td>1,000-5,000</td>
</tr>
<tr>
<td>sand and gravel</td>
<td>2,000-10,000</td>
</tr>
<tr>
<td>modern alluvium</td>
<td>3,000-15,000</td>
</tr>
<tr>
<td>shale</td>
<td>1,000-5,000</td>
</tr>
<tr>
<td>carbonate rocks</td>
<td>3,000-15,000</td>
</tr>
</tbody>
</table>

The resistivity profiles show contrasts in electrical patterns between various materials. For example, in profiles A and B in Figure 5 (assuming the positive direction on the abscissa to the right), the occurrence of a sand unit causes a positive deflection of the profile toward higher resistivity values. In the same two profiles, the occurrence of a carbonate
Figure 5. Resistivity profiles from continuous depth profile survey
EXPLANATION
Ohm-cm. X 10^3

- Oxidized till
- Unoxidized till
- Sand
- Shale
- Sandstone
- Limestone
- Dolomite

Geologic Control: 401
Resistivity Station: B-3
layer has a similar effect. However, in profile C the intersection of a carbonate results in a trend toward lower resistivity.

A till-shale contact is shown in profiles C, D, and E. In profile C, the contact is marked by a positive break, thus indicating that the shale is more resistive than the overlying till. In profile E, however, the negative break at the till-shale contact indicates that the shale is less resistive than the till above. Profile D does not show a very diagnostic resistivity contrast.

The influence of the resistivity of overlying material is suggested in the wide range in values listed in Table 1 for the various bedrock types. In profile F, where alluvium overlies limestone, it is very likely that the high resistivity of the alluvium contributed to the value obtained in the limestone. On the other hand, a "dampening" effect by material of low resistivity is often seen. In profile A, the relatively high conductivity of regolith materials is the probable cause of the low resistivity values of the underlying limestone. Profile G shows the range of values that were obtained when carbonate rocks occurred very near the surface.

The examples cited above illustrate the fact that it is difficult to generalize about the electrical relationships between the materials encountered in this area. The subtle and variable nature of these relationships make necessary the correlation of resistivity data with geologic control at all times. Even in an area such as this, however, the resistivity method has been shown to be a valuable tool, not only because of the information it supplies, but also because of the speed and low cost with which this information can be obtained.
RESULTS

Bedrock Configuration

Figure 8 shows the configuration of the bedrock surface in the study area. As in previous studies, two bedrock channels are indicated, one underlying the Skunk River, and the other underlying Squaw Creek.

The channels are separated by a continuous bedrock high from Randall (Sections 25 and 26, T 86 N, R 24 W) to Section 10, T 84 N, R 24 W, southeast of Gilbert. Further separation is caused by isolated highs in Sections 16 and 21, T 84 N, R 24 W.

Because only a small portion of the main channel underlying Squaw Creek is shown in the present area of study from Section 20 to Section 30, T 84 N, R 24 W, its physical characteristics will not be discussed in detail here. A tributary to the Squaw channel is shown in the northwest quarter of Figure 8.

All of the Skunk channel is included in Figure 8, with the exception of the lower two miles shown by Backsen. From the confluence of the two channels at Ames, the Skunk channel trends northeast to Section 22, T 84 N, R 24 W, where it enters the study area, and from there east to Section 12, T 84 N, R 24 W. From Section 12 the channel trends north to where it ends in Section 1, T 85 N, R 24 W (see Figure 8), just north of Story City. The total length of the channel is shown to be 12 miles. Borehole and geophysical data in the area north of Story City do not indicate presence of a bedrock channel, and thus contradict Zimmerman's earlier interpretation that the channel did extend through that area and was still well defined in Hamilton County.
The modern drainage of the Skunk River lies on the east side of the main bedrock channel, passing over the deepest part of the channel only in Section 19, T 85 N, R 23 W. In Section 13, T 84 N, R 24 W, the modern drainage is cut off from the main channel as it flows along the southeast side of an isolated bedrock high (see Figure 8). This feature was also mentioned by Backsen.

The Skunk channel has four tributaries. Three enter the main channel from the east in Sections 18 and 20, T 85 N, R 23 W, and Section 13, T 84 N, R 24 W. A tributary on the west enters the main channel in Section 26, T 85 N, R 24 W.

The shape of the channel is very irregular. Less than a mile wide in parts of Sections 12 and 22, T 84 N, R 24 N (see Figure 8), it flares out north of the constrictions to a maximum width of three and one half miles. Such variations in the channel configuration are probably due to differences in the erodability of the bedrock in various parts of the channel. Where the channel is constricted, its east wall consists of the highly resistant carbonate rocks of the Mississippian System, which have been elevated as part of the Ames-Roland anticlinal structure. North of the structure, where the channel widens out, the channel walls consist of the softer, more easily eroded Pennsylvanian sandstones and shales.

The Skunk channel is somewhat deeper than indicated in previous studies. The 800-foot elevation contour in the channel has been extended seven miles north from the point where it was terminated by Backsen and three miles north of the point of termination shown by Twenter and Coble.

As in Backsen's study, however, the Squaw channel is still shown to be the deeper of the two bedrock channels. At the southern end of the
present study area, it has a bottom elevation of 740 feet—40 feet lower than the bottom elevation of the Skunk channel.

Bedrock Geology

The areal distribution of Pennsylvanian and Mississippian rocks on the bedrock surface can be seen in Figure 6. A comparison of Figures 6 and 8 shows that the Mississippian rocks are exposed in the bedrock channels underlying Squaw Creek and Skunk River and along the Ames-Roland anticline. To that extent, the present study is in agreement with an earlier interpretation by Zimmerman (1952). However, comparison of Zimmerman's bedrock geology map with the map in this study reveals that they differ in the location of the Skunk channel. As mentioned previously, the Skunk channel is now located to the east of its location in Zimmerman's work.

Geologic information which has become available since Zimmerman's study has made it possible to draw a more detailed picture of the bedrock surface. Well records to date show that the rocks of the Pennsylvanian Cherokee Group comprise the bedrock highs away from the Ames-Roland anticline and the upper reaches of the Squaw and Skunk channels. Also, part of the bedrock surface in the bedrock channels and over the structure are the St. Louis, Warsaw, Keokuk, Burlington, and Gilmore City Formations.

Regolith Stratigraphy

The typical sequence of regolith materials is shown in the isometric panel diagram (Figure 9). The regolith has been divided into upper till, silt, intermediate till, aquifer, and lower till by Backsen (1963). His subdivisions were adopted in this study. An additional unit, sands and gravels which appear at this time not to be in contact with the aquifer
Figure 6. Pre-Pleistocene areal geologic map
system, has been introduced to describe local sand lenses which occur throughout the regolith.

Upper till

Figure 9 shows that the upper till is continuous over the area, except where incised by modern streams. The thickness of the unit on the upland surfaces is about 50 feet, and increases to over 100 feet in some parts of the bedrock channels. The upper five to 25 feet are oxidized and are yellow-brown in color. The unoxidized portion is gray. Over the Story City Flat, the upper till is overlain by five to 10 feet of relatively impermeable brown to black clay.

Silt

The silt averages 40 feet in thickness, with the thickest portion (up to 60 feet) being found over the Squaw channel, where some sand and wood were found. The color of the unit ranges from green to brown. It thins and decreases in sand content toward the center of the area, as shown in wells 411 and 412 and test hole 314 (Figure 9). There is no evidence of its presence in the Story City Flat area.

Intermediate till

The intermediate till thins and is sometimes absent near the center of the area. It is completely absent from the Story City Flat. Thicknesses of 50 feet are found over the bedrock channels, although even in these regions the unit is not always present. A yellow-brown oxidized upper portion is observed in wells 423 and 425, and in test hole 308 (Figure 10). The unoxidized portion is gray.
Lower till

The lower till is, with few exceptions, restricted to the bottom of the Squaw channel in the southwest part of the study area, where it averages 90 feet in thickness. An oxidized zone on the surface of the lower till may be indicated by the yellow-brown color of the upper three feet of the unit in well 439. The unoxidized zone is gray in color.

The lower of two tills recognized in well 453 is questioningly assigned to the lower till of the sequence here described. This till has an oxidized layer five feet thick which is overlain by a dark brown weathered zone. Although well 453 is located west of the deep part of the Squaw channel, its proximity to the channel and the indication of long exposure of the basal till (i.e., the weathered zone) has led to the correlation of that till unit with the lower till.

Aquifer

The aquifer has been defined as consisting of all the sands and gravels hydraulically connected to the sand and gravel at the base of the till underlying Ames (Backsen, 1963). As shown in Figure 9, the modern alluvium of Skunk River, Squaw Creek, and Keigley Creek is included as part of the aquifer. The Skunk River alluvium intersects the main body of the aquifer in Section 19, T 85 N, R 23 W. This connection may be imperfect in many areas because the fine sand and silt fraction of the alluvium may act as a partial seal between the modern alluvium and the rest of the aquifer.

Figure 10 shows the configuration of the Skunk River arm of the aquifer and the lower portion of the Squaw Creek segment, including a
tributary to the Squaw Creek system in the northwest part of the study area. Only the Skunk River arm will be discussed in detail here. It underlies an area of approximately 25 square miles and is of quite variable thickness, averaging 60 feet, and reaching a maximum thickness of at least 115 feet in the vicinity of test hole 312 (Figure 10). Electrical resistivity measurements from station 1-9 adjacent to the test hole extend beneath the bedrock surface, and indicate that the thickness of the aquifer reaches 160 feet. The extent of this variability over a short lateral distance is well demonstrated in the abrupt decrease in thickness of the aquifer between test hole 312 and well 409, where only 15 feet of aquifer material are encountered.

The total volume of the sands and gravels in the Skunk River segment of the aquifer has been calculated to be approximately 31.7 billion cubic feet. This volume was computed by measuring the cross-sectional area of the aquifer at mile intervals. The volume for each mile interval was considered to be equal to the average of the cross-sectional areas at each end of the interval multiplied by the one mile length.

Although the sorting of the sands and gravels is generally poor, two trends are noted in the texture of the aquifer material. First, particle size increases with depth so that a coarse sand and a veneer of gravel overlies the bedrock surface at the base of the aquifer. Visual inspection of samples from test holes 319 and 322 and wells 405, 409, 423, 427, 443, and 445 substantiate this trend. Second, particle size appears to decrease to the north, as shown in test holes 305, 206, and 312. Four sizable deposits of gravel are known to exist in the southern half of the study area, whereas none have been discovered in the northern half. Three are
located in gravel pits (center, Section 22, NW $\frac{1}{4}$, Section 13, and SE $\frac{1}{4}$, Section 12, T 84 N, R 24 W), and the fourth has been identified from samples of test hole 319, where 70 feet of gravel was overlain by 45 feet of till.

Figure 9 shows that the relationship of the aquifer to other Pleistocene materials exhibits considerable variability. North of Keigley Creek, under the Story City Flat, the aquifer interfingers with and is overlain by the upper till. The upper surface of the aquifer is quite irregular in this region, so that the aquifer is confined by anywhere from 20 to 100 feet of till, except where connected with the modern alluvium. South of Keigley Creek, the aquifer, except for the modern alluvial segment, underlies not only the upper till, but in many cases, the silt and intermediate till as well. There the interfingering relationship between the aquifer and till is not observed. The upper surface of the aquifer has little relief in this area.

The relationship of the aquifer to the bedrock surface is more constant. A comparison of Figures 8 and 10 reveals that the bedrock channel and the aquifer configurations are quite similar. That the aquifer is essentially a channel fill is indicated by the similarity of its shape to that of the bedrock channel. Well logs used in this study indicate that the aquifer is in direct contact with the bedrock surface of the Skunk channel (Figure 9). This is in contrast to the situation in the Squaw channel, where the lower till normally occupies the bottom of the channel.
Figure 7. Base map showing location of data and depth to bedrock
EXPLANATION

Identification number

- Bedrock elevation
- Bedrock depth
- B-1-a - N-12 resistivity
- 100 - 199 bedrock depth
- 200 - 299 outcrop
- 300 - 399 test hole
- 400 - 499 well

- Section represented by panel diagram
- Corporation line
Figure 8. Map of the bedrock topography of the area
Figure 9. Isometric panel diagram
Isometric Pan
Panel Diagram
Sand and gravel not connected with aquifer

Upper till oxidized

Upper till unoxidized

Silt
EXPLANATION

Gravel not connected with aquifer system

oxidized
unoxidized

Slate till
oxidized
unoxidized

Upper limit of panel: land surface
Lower limit of panel: bedrock surface

- 199 bedrock depth only
- 299 outcrop
- 399 test hole
- 499 well
- N-12 resistivity
Figure 10. Aquifer thickness map
Contour Interval: 20 ft.

Scale in Miles
DISCUSSION

Geology

The Story City Flat is unique in both its surface and subsurface characteristics. The low surface relief and the absence of Pleistocene materials older than the upper till differentiates this area from the surrounding regions. This absence strongly suggests that Pleistocene deposits predating the upper till were locally removed, either prior to or during the most recent glacial stage.

The interfingering relationship of the aquifer and the upper till in the Story City Flat area suggests that the two units were deposited contemporaneously, and probably represent a fluctuating glacial front located somewhere near the north end of the study area. The abrupt change in the thickness and surface elevation of the aquifer from test hole 312 to well 409 may indicate a prolonged period of stagnation of a glacier between the two points, such that till was deposited directly by the glacier near well 409, while sand was being washed off the front and deposited to the south.

South of the Story City Flat, removal of the pre-upper till deposits was incomplete. Here, parts of the aquifer underlie not only the upper till, but the silt layer and the intermediate till also. Hence, in contrast to the part of the aquifer occupying the upper part of the Skunk channel, that in the lower portion consists not only of modern alluvium and sand and gravel deposits in contact with the upper till, but also includes sands and gravels older than the intermediate till. The interfingering relationship between the aquifer and the upper till is not
evident in this area. Hence, no part of the aquifer below Keigley Creek is thought to be contemporaneous with the upper till.

Water Supply

Ground Water Storage

In order to evaluate ground water storage, the nature of the peizometric surface must be known. Piezometric elevations in the upper bedrock and regolith aquifers are shown in Figure 11. These elevations were measured at various times of the year over the past 20 years, and are thus only approximate values.

One method of assessing the available water supply in an aquifer is to determine the volume of water which it contains. If the aquifer is assumed to be full, that volume will be equal to the total volume of the aquifer multiplied by the specific yield of the sands and gravels in the aquifer. Although the Skunk River aquifer may not be completely saturated over its entire extent, peizometric levels are above or close to the top of the aquifer at most locations (see Figure 11), so that the assumption serves as a good approximation. According to Linsley, Köhler, and Paulhus (1958) the specific yield of an aquifer is the ratio of the water which will drain freely from the material to the total volume of the aquifer. They state that the specific yield for sand and gravel is 16 per cent. Assuming a specific yield of 16 per cent, the total obtainable volume of water stored in the Skunk River arm of the aquifer is approximately $3.8 \times 10^{10}$ gallons. This is 35 times the amount of water now used by the City of Ames each year. Recharge and discharge of the aquifer will be
Figure 11. Approximate piezometric elevations
discussed in the following sections.

Recharge

One of the original objectives of this study was to evaluate the Story City Flat as a recharge area for the regolith aquifer supplying Ames. The surface characteristics of the area made it appear to be an ideal collecting basin for water. It is wide, flat, and topographically lower than the uplands on the east and west. Drainage is only poorly developed. Thus, removal of water by surface runoff is slow, and there would seem to be an opportunity for infiltration of the water into the ground water regime. It was hypothesized that the Story City Flat was underlain by sands and gravels which were linked to the south with the regolith aquifer described by Backsen, and that such an arrangement would allow for transportation of surface inflow from the Story City Flat into the sand and gravel at Ames.

Although the Story City Flat is in fact underlain by the extensive sand and gravel deposits which constitute the Skunk River arm of the aquifer, several factors prevent rapid recharge of the aquifer by surface infiltration in that area. First, a thick blanket of till overlain by a dense clay covers the aquifer everywhere except the Skunk River. Second, much of the water which does infiltrate the top five to 10 feet of clay and till is transported to Keigley Creek and Skunk River by the extensive tile drainage system beneath the Story City Flat. It is possible that some of this water moves downward through the alluvium into the aquifer. Third, the common occurrence of flowing wells in the area even during the dry periods of the year indicates that the sands and gravels are being
recharged from a continuous source.

Data used in this study indicate that most of the recharge to the Skunk River arm of the aquifer comes from the Mississippian bedrock aquifer. The Skunk channel cuts through all of the formations in the bedrock aquifer (Figure 6), and piezometric levels in the bedrock are well above the elevations of the bottom of the channel. Well logs used in this study show the regolith aquifer in direct contact with the bedrock in the channel (see Figure 9). Other evidence pointing to a hydraulic connection between the two aquifers is the close agreement of the piezometric levels of wells in the bedrock and regolith (Figure 11). That the recharge is from the bedrock aquifer to the regolith aquifer is attested to by the fact that piezometric gradient slopes toward the aquifer in the bedrock wells studied to date.

Discharge

Discharge from the aquifer is accomplished in several ways: 1) by natural discharge at the surface through processes of surface runoff, evaporation, and transpiration; 2) by discharge from wells; and 3) by subsurface flow through the aquifer.

Evaporation and transpiration remove water from the aquifer where it is exposed at the surface in the modern alluvium. Elsewhere the 20 to 100 feet of till overlying the aquifer provides a fairly effective seal against upward movement of water. There is also probably some discharge from the aquifer to surface runoff in the segment of the Skunk River between Section 19, T 85 N, R 23 W, where the modern alluvium intersects the main body of the aquifer, and Section 12, T 84 N, R 24 W, where the northwernmost
constriction in the aquifer occurs. The effluent nature of this portion of the stream is suggested by the high piezometric levels near the river (Figure 11) and the occurrence of springs on the floodplain.

The wells drilled into the part of the aquifer studied here are all of the domestic and farm type. The average capacity of these wells is about five gallons per minute. Thus the water withdrawn by wells is a small portion of the total discharge.

Subsurface flow in the aquifer is in the direction of lower elevation of the piezometric surface. It is of interest here to establish an approximate value for the underflow contributed to the sands and gravels underlying Ames by the Skunk River branch of the aquifer. The underflow passing a certain point may be determined by applying the equation \( Q = K \cdot i \cdot A \) where

\[
Q = \text{flow} \\
K = \text{field permeability} \\
i = \text{hydraulic gradient} = \frac{\text{change in head (} h_o - h_l \text{)}}{\text{distance from } h_o \text{ to } h_l} \\
A = \text{cross-sectional area}
\]

Since no pumping tests have been conducted in the area of study, it is necessary to assume a value for permeability. This value should not exceed the range of permeability values obtained by Backsen because the material in the Skunk River arm of the aquifer is characterized by smaller grain size and poorer sorting than the portion of the aquifer studied by Backsen. Todd (1959) states that the typical range for permeability in sands and gravels is 100 to 10,000 gallons per day per square foot.
Since the flow is constant throughout any individual portion of the aquifer, the value for the flow in the Skunk River arm of the aquifer is controlled by the flow through its smallest cross-sectional area. The cross-sectional area thus chosen is located where the width of the aquifer is most severely constricted, at the south end of the study area in Section 22, T 84 N, R 24 W (see Figure 9).

The hydraulic gradient from the north end to the south end of the Skunk River arm of the aquifer represents a change in head of approximately 105 feet in eight and one-half miles. A piezometric surface elevation of at least 1,000 feet was encountered in the drilling of test hole 312, which produced a small flow (see Figure 11). During this study it was determined that the elevation of the water in the gravel pit in Section 22 is equal to the water surface elevation in the Skunk River directly to the east. That elevation is approximately 895 feet.

Table 2. Subsurface flow in the Skunk channel

<table>
<thead>
<tr>
<th>( K ) (gal/day/ft²)</th>
<th>( i ) (ft/ft)</th>
<th>( A² ) (ft²)</th>
<th>( Q ) (gal/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5000 105 ( \frac{44200}{16600} )</td>
<td>16600</td>
<td>1.9 x 10⁶</td>
<td></td>
</tr>
<tr>
<td>3000 105 ( \frac{44200}{16600} )</td>
<td>16600</td>
<td>1.1 x 10⁶</td>
<td></td>
</tr>
<tr>
<td>1000 105 ( \frac{44200}{16600} )</td>
<td>16600</td>
<td>0.4 x 10⁶</td>
<td></td>
</tr>
</tbody>
</table>

Table 2 shows the estimates of the subsurface flow in the Skunk River branch of the aquifer. The estimates, based on the known characteristics and on three assumed values for permeability, range from 1.9 x 10⁶ to
0.4 \times 10^6 \text{ gallons per day. The present rate of withdrawal of water by the City of Ames alone is } 3 \times 10^6 \text{ gallons per day*}. The stability of the water levels in the area (Backsen, 1963) suggest that the present rate of withdrawal does not exceed the recharge rate. Therefore, it is clear that a significant amount of water is being supplied from source areas other than the Skunk River branch of the aquifer.

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SUMMARY AND CONCLUSIONS

The results show that a sand and gravel regolith aquifer occurs beneath the Skunk River north of Ames. This aquifer is an extension of the aquifer underlying Ames which was previously described by Backsen. It is approximately 12 miles long, and trends north from Ames to Story City. It underlies an area of approximately 25 square miles.

The aquifer consists of glaciofluvial deposits and modern alluvium. These deposits are characterized by fair to poor sorting and by a decrease in grain size from the south to the north. The above characteristics are likely to be reflected in decreasing permeability values in the aquifer to the north relative to the values assumed for permeability near the gravel pit in Section 22, T 84 N, R 24 W. However, the greater cross-sectional area of the upper end of the aquifer may compensate for the lower permeability there, with the result that the flow is not reduced below the assumed value for flow at the greatest contraction of the aquifer.

Recharge to the regolith aquifer appears at this time to come mainly from the underlying upper bedrock aquifer. Probably some recharge is also contributed to the system by the surface runoff of the Skunk River in the southern half of the aquifer (below Section 6, T 84 N, R 24 W). Backsen (1963) has shown that, in this area, stream level coincides with the water table in the aquifer, so that the stream is influent during periods of high flow and effluent in times of low flow.

Pollution of the water in the aquifer through surface recharge may be a problem. Although most of the aquifer is sealed off by overlying till, farm waste and fertilizer chemicals carried to the Skunk River by tributary
streams could cause contamination. Potential sources of pollution are the gravel pits in Sections 12, 13, and 22, T 84 N, R 24 W. Present information indicates that these pits are hydraulically connected with the aquifer. When the pits are abandoned, indiscriminate dumping in them could result in contamination. Increased pumping on the aquifer, with the resulting rise in inflow from these points, would increase their potential to pollute the water in the aquifer.

A major portion of the discharge from the aquifer is in the form of subsurface flow into the sands and gravels underlying Ames. The subsurface flow may be as much as 1.9 million gallons per day. Although this estimate is only approximate, it represents the order of magnitude of the flow.

The aquifer is confined by 20 to 100 feet of till except where it is intersected by the modern alluvium of the Skunk River. Water levels are generally above the base of the overlying till.

It is concluded that the portion of the aquifer studied is essentially a reservoir which is storing a large amount of water. However, subsurface flow from the reservoir to Ames is limited by constrictions in the reservoir body.

Present estimates of this flow indicate that it is significantly less than the amount pumped by the City of Ames. Ames is thus receiving additional water from other sources. Two such sources are the portion of the aquifer underlying Ames and the Squaw Creek branch of the aquifer. Backsen concluded that the Ames segment of the aquifer was locally recharged by direct infiltration and by surface runoff from Skunk River and Squaw Creek. It seems likely that recharge from the upper bedrock aquifer also occurs. Piezometric elevations from that aquifer are well above the base of the
regolith aquifer in Ames.

The Squaw Creek branch of the aquifer has not been studied in detail. Preliminary investigation indicates that the lower end of the branch has a maximum thickness of 60 feet. The channel which it occupies is shown by Twenter and Coble to be approximately 50 miles long. If the aquifer occurs throughout the length of the channel, the contribution of this part of the aquifer to the Ames water supply could be quite large.
SUGGESTIONS FOR FUTURE STUDY

1. A study similar to this and the previous study by Backsen should be initiated to trace the Squaw Creek arm of the aquifer.

2. It is necessary to evaluate more fully the recharge to and the discharge from the regolith aquifer. The following steps should be taken to supply the necessary information:
   
a. Representative water samples from the regolith aquifer, the bedrock aquifer, and from surface water supplies should be chemically analyzed. A comprehensive sampling program of this kind would also supply information valuable to the placement of future wells.

b. A survey of piezometric elevations in bedrock and regolith wells should be undertaken to establish ground water flow patterns in each aquifer. Not only would more knowledge be obtained concerning discharge and recharge, but a better understanding of variations in permeability throughout the aquifers would result.

c. A hydrologic study of the entire Skunk River basin above Ames is needed to determine the net amount of water lost to or gained from surface streams by the aquifers.

d. A study of the infiltration capacities of the various surficial materials over the regolith is required for the assessment of potential recharge to the aquifer by percolation through the glacial drift.

e. Pumping tests should be conducted in the regolith aquifer and in adjacent portions of the upper bedrock aquifer to establish storage and transmissibility constants for each. Observation wells for each
test should be located in both the regolith and bedrock aquifers. Pumping tests in the Skunk River regolith aquifer should be conducted in at least two locations. One test should be run in Section 12, T 84 N, R 24 W, where the northernmost constriction of the aquifer occurs. Another should be located in Section 24, T 85 N, R 24 W,now the greatest thickness of the aquifer.

In the Ames area, transmissibility, storage, and water quality data from bedrock wells would provide valuable information relative to the feasibility of withdrawing water directly from the bedrock aquifer.

3. Tracer analysis in the vicinity of potential areas of pollution (e.g., floodplain areas, gravel pits) is needed to establish the degree of hydraulic connection and hence the degree of danger of contamination from each area to the water in the regolith aquifer.

4. An electric analogue study of the regolith aquifer should be undertaken to reproduce the subsurface flow patterns in the regolith aquifer and to aid in the prediction of the effect on the piezometric surface of increasing withdrawal of water from the aquifer by the City of Ames, Iowa State University, and other communities. An electrical model would utilize the data collected in the recommendations listed above.
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The rotary drill rig used in the test hole program of June-August, 1964, was formerly on loan to the Earth Science Department and the Engineering Experiment Station, Iowa State University, by the Office of Naval Research. It is now owned by the Earth Science Department, Iowa State University.

Gratitude is given to my wife, who was a continuous source of encouragement and enthusiasm.
APPENDIX
Test Hole Logs

Test Hole 301
Location: T 85 N, R 23 W, Section 30
Elevation 980

0-1       topsoil
1-12      brown to buff oxidized till
12-48     gray till
48-54     sand and gravel
54-80     gray till
80-120    gray till with sand and wood
120-140   hard clay

Test Hole 302
Location: T 85 N, R 24 W, Section 1
Elevation 1020

0-4       black clay soil
4-12      fine buff sand
12-20     oxidized till with some sand
20-47     dark gray clay
47-50     rust colored sand

Test Hole 303
Location: T 85 N, R 24 W, Section 2
Elevation 1020

0-3       soil
3-12      oxidized till with some sand
12-44     unoxidized till
44-54     gravel
54-95     unoxidized till
95-115    soft black shale

Test Hole 304
Location: T 85 N, R 24 W, Section 9
Elevation 1020

0-4       topsoil
4-6       oxidized till
6-9       sand
9-14      oxidized till
17-93     unoxidized till
93-       shale (?)
Test Hole 305
Location: T 85 N, R 24 W, Section 11
Elevation 1020

0-6 topsoil
6-43 sandy, unoxidized till
43-49 fine to medium sand
49-59 gray gravel
59-100 gray sand and till
100-105 rust colored sand and gravel
105- shale (?)

Test Hole 306
Location: T 85 N, R 24 W, Section 14
Elevation 995

0-3 topsoil
3-11 oxidized till
11-35 unoxidized till
35-45 sand and gravel
45-100 unoxidized till
100-120 sand and wood
120-130 clay
130-150 sand
150-155 clay
155-170 sandy calcareous shale

Test Hole 307
Location: T 85 N, R 24 W, Section 15
Elevation 1020

0-4 soil
4-18 oxidized till
18-32 sandy unoxidized till
32-38 sand and gravel

Test Hole 308
Location: T 85 N, R 24 W, Section 17
Elevation 1020

0-5 topsoil
5-11 oxidized till
11-42 sandy unoxidized till
42-66 sandy oxidized till
66-80 unoxidized till
Test Hole 309
Location: T 85 N, R 24 W, Section 18
Elevation 1060

0-4 topsoil
4-12 oxidized till
12-52 sandy unoxidized till
52-85 water bearing fine to medium sand
85-110 sand and till

Test Hole 310
Location: T 85 N, R 24 W, Section 19
Elevation 1050

0-4 topsoil
4-12 oxidized till
12-58 sandy unoxidized till
58- glacial erratic

Test Hole 312
Location: T 85 N, R 24 W, Section 24
Elevation 1005

0-4 topsoil
4-26 unoxidized till
26-141 water bearing fine to medium sand

Test Hole 313
Location: T 85 N, R 24 W, Section 25
Elevation 980

0-4 topsoil
4-15 sandy oxidized till
15-58 sandy unoxidized till
58- water bearing (flow) fine sand

Test Hole 314
Location: T 85 N, R 24 W, Section 27
Elevation 1020

0-4 topsoil
4-12 oxidized till
12-103 sandy unoxidized till
103- limestone
Test Hole 315
Location: T 85 N, R 24 W, Section 30
Elevation 1040
0-6  topsoil
6-18 sandy oxidized till
18-68 sandy unoxidized till
68-128 fine to medium sand
128- limestone (?)

Test Hole 316
Location: T 85 N, R 24 W, Section 32
Elevation 1020
0-5  topsoil
5-14 sandy oxidized till
14-52 sandy unoxidized till
52-62 sand with wood
62-67 sandy unoxidized till
67-88 sand with some till
88- rubble zone (gravel?)

Test Hole 317
Location: T 85 N, R 24 W, Section 35
Elevation 1020
0-5  topsoil
5-14 oxidized till
14-45 sandy unoxidized till
45-49 buff sand and till
49- limestone (?)

Test Hole 318
Location: T 85 N, R 23 W, Section 32
Elevation 950
0-7  till
7-17 silty sand
17-22 broken limestone
22-25 limestone
Test Hole 319
Location: T 84 N, R 23 W, Section 6
Elevation 950

0-3  topsoil
3-15  oxidized till
15-40  unoxidized till
40-72  sand and gravel
72-75  hard clay
75-135  sand and gravel
135-140  coarse gravel

Test Hole 320
Location: T 84 N, R 24 W, Section 1
Elevation 1015

0-7  sandy oxidized till
7-45  sandy unoxidized till
45-65  sandy oxidized till
65-70  silt
70-  sandy oxidized till

Test Hole 321
Location: T 85 N, R 24 W, Section 2
Elevation 1040

0-90  buff-gray, sandy till
90-  gray buff till

Test Hole 322
Location: T 84 N, R 24 W, Section 4
Elevation 1000

0-5  topsoil
5-15  oxidized till
15-23  unoxidized till
23-95  sand
95-  limestone (?)
Test Hole 323
Location: T 84 N, R 24 W, Section 7
Elevation 960

0-4    topsoil
4-18   oxidized till
18-26  unoxidized till
26-55  silt
55-117 sand and gravel
117-   limestone (?) rubble

Test Hole 324
Location: T 84 N, R 24 W, Section 8
Elevation 980

0-5    topsoil
5-18   oxidized till
18-90  sandy unoxidized till
90-    gray sand

Test Hole 325
Location: T 84 N, R 24 W, Section 11
Elevation 1000

0-3    topsoil
3-18   oxidized till
18-120 sandy unoxidized till

Test Hole 326
Location: T 84 N, R 23 W, Section 5
Elevation 1000

0-18   yellow till
18-25   gray till
25-65   brown sand
65-70   limestone
Well Logs

Well 401
Location: T 86 N, R 24 W, Section 21
Elevation 1040

0-15oxidized till
15-115unoxidized till
115-125sand and gravel
125-135till
135-150sand and gravel
150-160shale

Well 402
Location: T 86 N, R 24 W, Section 25
Elevation 1020

0-2soil
2-35drift
35-87shale

Well 403
Location: T 86 N, R 24 W, Section 32
Elevation 1040

0-5soil
5-105drift
105-110sand and gravel
110-140drift
140-150sand and gravel
150-155drift
155-165sand and gravel

Well 404
Location: T 86 N, R 24 W, Section 33
Elevation 1020

0-18yellow clay
18-30sand
30-150blue clay
150-200slate
Well 405
Location: T 85 N, R 23 W, Section 20
Elevation 980

0-5 soil
5-80 drift
80-125 sand and gravel
125-150 cherty limestone with dolomite

Well 406
Location: T 85 N, R 24 W, Section 5
Elevation 1020

0-10 soil and yellow clay
10-15 blue clay
15-20 quicksand
20-25 blue and yellow clay
25-26 quicksand
26-103 blue clay and gravel
103-153 sand and gravel
153-159 sandstone

Well 407
Location: T 85 N, R 24 W, Section 9
Elevation 1015

0-5 soil
5-70 drift
70-90 sand and gravel

Well 408
Location: T 85 N, R 24 W, Section 12
Elevation 1010

0-12 soil and blue clay
12-34 blue clay
34-34.5 silt
34.5-86.5 blue clay
85.5-86.5 silt
86.5-87 organic matter
87-90 fire clay
90-99 sandstone with 1-2 in. seams of clay
Well 409
Location: T 85 N, R 24 W, Section 12
Elevation 988

0-90 no sample
90-105 gravel
105-130 cherty dolomite
130-230 cherty dolomite and limestone
230-261 limestone

Well 410
Location: T 85 N, R 24 W, Section 19
Elevation 1010

0-155 sandy drift
155-190 sand

Well 411
Location: T 85 N, R 24 W, Section 21
Elevation 1060

0-3 soil
3-23 yellow clay
23-28 blue clay
28-29 blue sand
29-69 silt
69-95 sand and gravel
95-96 hard rock

Well 412
Location: T 85 N, R 24 W, Section 21
Elevation 1040

0-3 soil and clay
3-23 yellow clay
23-28 blue clay
28-74 silt
74-94 yellow sand
94-95 hard rock
### Well 414
Location: T 85 N, R 24 W, Section 30  
Elevation 1040

<table>
<thead>
<tr>
<th>Depth</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-15</td>
<td>yellow till</td>
</tr>
<tr>
<td>15-25</td>
<td>gray till with sand and gravel</td>
</tr>
<tr>
<td>25-30</td>
<td>gray till</td>
</tr>
<tr>
<td>30-40</td>
<td>yellow till</td>
</tr>
<tr>
<td>40-75</td>
<td>gray till</td>
</tr>
<tr>
<td>75-85</td>
<td>yellow till</td>
</tr>
<tr>
<td>85-90</td>
<td>gray sandy till</td>
</tr>
<tr>
<td>90-100</td>
<td>slightly yellow to gray sandy till</td>
</tr>
<tr>
<td>100-185</td>
<td>gray, sandy (pebbly below 165') till</td>
</tr>
<tr>
<td>185-190</td>
<td>sand and gravel</td>
</tr>
</tbody>
</table>

### Well 417
Location: T 84 N, R 23 W, Section 7  
Elevation 1000

<table>
<thead>
<tr>
<th>Depth</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-5</td>
<td>soil</td>
</tr>
<tr>
<td>5-35</td>
<td>drift</td>
</tr>
<tr>
<td>35-100</td>
<td>cherty dolomite</td>
</tr>
</tbody>
</table>

### Well 418
Location: T 84 N, R 23 W, Section 7  
Elevation 1030

<table>
<thead>
<tr>
<th>Depth</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-3</td>
<td>soil</td>
</tr>
<tr>
<td>3-30</td>
<td>drift</td>
</tr>
<tr>
<td>30-45</td>
<td>cherty dolomite</td>
</tr>
</tbody>
</table>

### Well 419
Location: T 84 N, R 23 W, Section 18  
Elevation 1020

<table>
<thead>
<tr>
<th>Depth</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-72</td>
<td>no sample</td>
</tr>
<tr>
<td>72-125</td>
<td>cherty dolomite</td>
</tr>
</tbody>
</table>

### Well 420
Location: T 84 N, R 23 W, Section 15  
Elevation 1000

<table>
<thead>
<tr>
<th>Depth</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-40</td>
<td>oxidized till</td>
</tr>
<tr>
<td>40-55</td>
<td>unoxidized till</td>
</tr>
<tr>
<td>55-130</td>
<td>soft shale</td>
</tr>
</tbody>
</table>
Well 421
Location: T 84 N, R 23 W, Section 18
Elevation 1040

0-18 oxidized till
18-47 unoxidized till
47-60 oxidized leached till
60-65 cherty dolomite and sandstone
65-75 cherty dolomite

Well 422
Location: T 84 N, R 23 W, Section 19
Elevation 1020

0-175 no sample
175-190 limestone

Well 423
Location: T 84 N, R 24 W, Section 2
Elevation 1025

0-4 soil
4-40 oxidized unleached till
40-50 unoxidized unleached till
50-65 gray calcareous silt
65-90 oxidized leached to unleached till
90-106 unoxidized unleached till
106-145 sand and gravel
145- shale

Well 424
Location: T 84 N, R 24 W, Section 4
Elevation 980

0-2 soil
2-8 yellow sandy clay
8-109 gray sandy clay and gravel
109-112 black shale
Well 425
Location: T 84 N, R 24 W, Section 11
Elevation 1020

0-5  no sample
5-28  sand
28-75  blue clay
75-85  brown clay
85-110  blue clay
110-126  brown sand
126-150  rock and sandstone

Well 426
Location: T 84 N, R 24 W, Section 12
Elevation 950

0-45  soil and yellow clay
45-55  sand and clay
44-118  blue clay
118-130  bedrock
130-138  sandstone, with coal and water

Well 427
Location: T 84 N, R 24 W, Section 14
Elevation 1000

0-4  soil
4-18  till
18-51  blue till; wood
51-68  sand; gravel; wood; clay streaks
68-71  blue-gray till
71-89  sand; gravel; silt; wood
89-107  blue-gray till
107-110  gray-yellow clay; pebbles
110-129  blue till
129-132  gravel; limestone fragments
132-136  limestone

Well 428
Location: T 84 N, R 24 W, Section 14
Elevation 980

0-3  soil
3-100  drift
100-110  sand and gravel
Well 429
Location: T 84 N, R 24 W, Section 15
Elevation 985

0-3  soil
3-23  buff till
23-62  gray till
62-68  brown sand
68-72  gray brown till
72-98  sand; silt; wood
98-102  sand; gravel.
102-  limestone

Well 430
Location: T 84 N, R 24 W, Section 5
Elevation 960

0-150  sand and gravel with some till

Well 432
Location: T 84 N, R 24 W, Section 15
Elevation 960

0-5  soil
5-15  loess
15-95  drift
95-115  sand and gravel

Well 433
Location: T 84 N, R 24 W, Section 15
Elevation 980

0-5  no sample
5-85  drift
85-95  sand and gravel

Well 434
Location: T 84 N, R 24 W, Section 19
Elevation 990

0-4  soil
4-9  yellow till
9-48  blue till
48-58  sand; gravel; wood
58-112  silty sand; some gray till; wood
112-  sandstone (?)
Well 435
Location: T 84 N, R 24 W, Section 20
Elevation 970

0-196 no sample
196- bedrock

Well 437
Location: T 84 N, R 24 W, Section 20
Elevation 970

0-15 buff till
15-25 buff-gray till
25-35 gray buff till
35-115 gray till
115-145 gray sand
145-220 gray till
220-250 limestone

Well 438
Location: T 84 N, R 24 W, Section 21
Elevation 980

0-5 soil
5-10 yellow till
10-55 gray, sandy, clayey till
55-62 yellow gravel
62-83 limestone and dolomite
Well 439
Location: T 84 N, R 24 W, Section 21
Elevation 980

0-14    soil and sandy clay
14-31   blue clay
31-33   sand
33-34   blue clay
34-35   sand and gravel
35-67   blue clay
67-76   yellow clay
76-83   blue clay
83-85   yellow clay
85-97   gray clay
97-100  yellow clay
100-105 limestone

Well 440
Location: T 84 N, R 24 W, Section 21
Elevation 975

0-9     soil and yellow sandy clay
9-69    blue sandy clay
69-72   yellow clay
72-80   blue sandy clay
80-91   gray silt and wood
91-94   broken limestone and gravel
94-96   limestone

Well 443
Location: T 84 N, R 24 W, Section 23
Elevation 945.7

0-95    no sample
95-110  sand and gravel
110-160 cherty dolomite

Well 444
Location: T 84 N, R 24 W, Section 23
Elevation 950

0-40    yellow till
40-60   gray till
60-     dolomite
Well 445
Location: T 84 N, R 24 W, Section 23
Elevation 900

0-4  black silty topsoil
4-12  brown silty fine sand
12-44 medium to coarse sand and gravel; mud loss
44-51 loose gravel; broken limestone
51-52 hard limestone

Well 445
Location: T 84 N, R 24 W, Section 23
Elevation 970

0-4  soil
4-15 yellow, sandy clay
15-54 gray clay
54-63 red clay; sand
63-83 rock

Well 448
Location: T 84 N, R 24 W, Section 23
Elevation

0-45 no sample
45- limestone

Well 447
Location: T 84 N, R 24 W, Section 23
Elevation 980

0-45 no sample
45-60 sandstone

Well 449
Location: T 84 N, R 24 W, Section 23
Elevation 980

0-40 oxidized, unleached till
40-55 limestone
Well 451
Location: T 84 N, R 23 W, Section 19
Elevation 1030
0-5 soil
5-15 yellow till
15-40 gray till
40-65 yellow till
65-70 yellow sandy till
70- chert

Well 452
Location: T 84 N, R 24 W, Section 25
Elevation 980
0-6 yellow, slightly oxidized and leached till
6-8 sand and gravel
8-10 blue, hard till
10-20 gray to buff massive limestone

Well 453
Location: T 84 N, R 25 W, Section 12
Elevation 980
0-20 till
20-25 paleosol
25-50 oxidized till
50-60 sand and gravel
60-65 oxidized till
65-70 unoxidized till
70-75 coal
75-95 shale

Well 454
Location: T 84 N, R 25 W, Section 13
Elevation 1000
0-100 no sample
100-125 unoxidized till
125-160 shale
Well 455
Location: T 84 N, R 24 W, Section 23
Elevation 950

0-97 no sample
97-109 gravel; yellow sand
109- dolomite

Well 456
Location: T 84 N, R 24 W, Section 22
Elevation 950

0-3 soil
3-18 yellow till
18-42 gray till
42- limestone

Well 457
Location: T 84 N, R 24 W, Section 7
Elevation 960

0-2 soil
2-210 drift
210-300 cherty dolomite with shale and limestone