AN ELECTRICAL EARTH RESISTIVITY SURVEY OF THE MACON-TAYLORVILLE RIDGED-DRIFT AQUIFER

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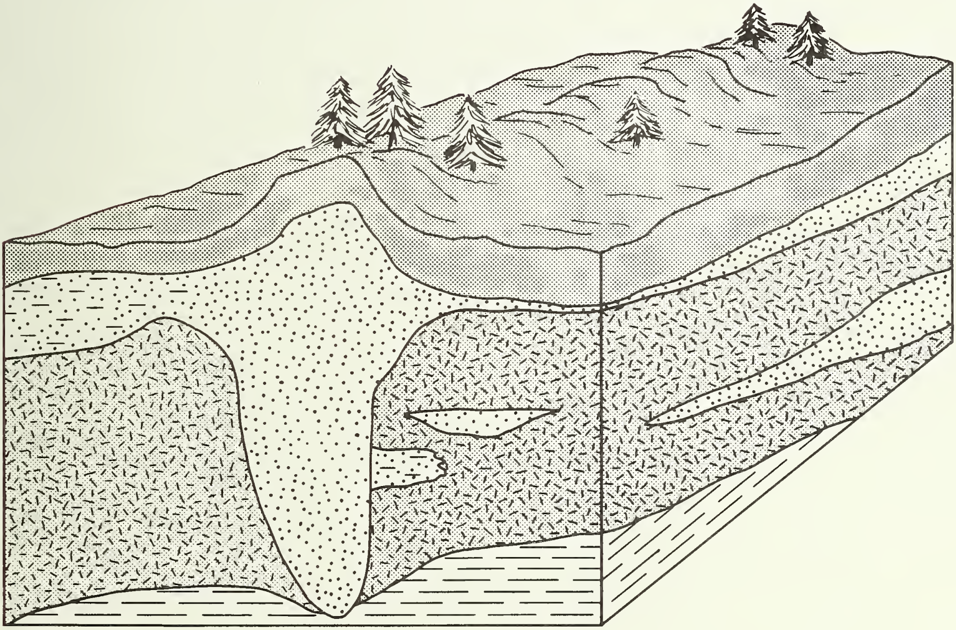

Illinois Department of Energy and Natural Resources
STATE GEOLOGICAL SURVEY DIVISION

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COVER: NE-SW from Old Stonington Cemetery to south of Stonington, adapted from figures 10 and 11 of Burris, C.B., W.J. Morse, and T.G. Naymik, 1981, Assessment of a regional aquifer in central Illinois: Illinois State Water Survey, Illinois State Geological Survey, Cooperative Groundwater Report 6.

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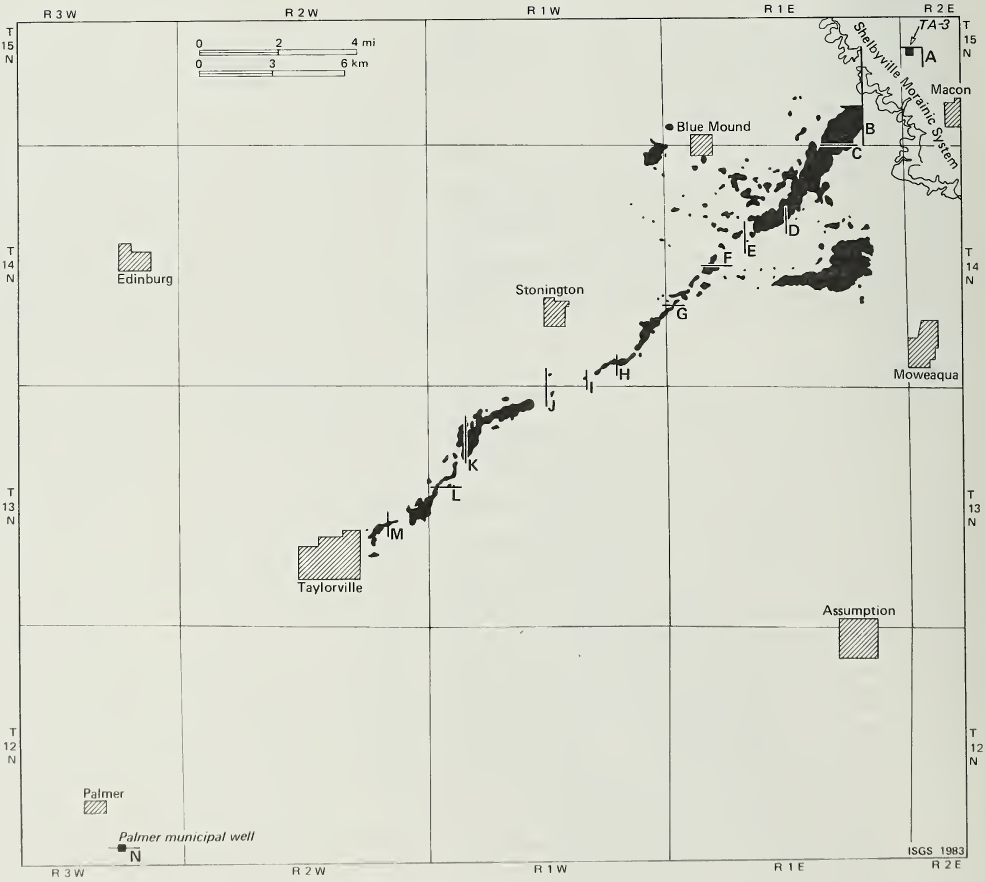

Figure 1. Location of lines of VES (vertical electrical sounding) profiles along Macon-Taylorville ridged-drift deposits in central Illinois.

AN ELECTRICAL EARTH RESISTIVITY SURVEY OF THE MACON-TAYLORVILLE RIDGED-DRIFT AQUIFER

ABSTRACT

Between the towns of Macon and Taylorville in central Illinois lies a ridge that is part of a system of ridges and knolls largely composed of sand and gravel. This ridge contains an important aquifer.

An extensive electrical earth resistivity survey was conducted over the ridged-drift aquifer. Inversion of the resistivity data provided information concerning aquifer thickness and aquifer resistivity. This information, along with pump test data along the aquifer, indicated a direct and geometric relationship between aquifer resistivity and hydraulic conductivity. As a result, it was possible to better define the boundaries and water-producing capabilities of the aquifer.

INTRODUCTION

A sinuous, almost continuous ridge is located between the towns of Macon and Taylorville in central Illinois (fig. 1). This feature is part of a system of elongate ridges and knolls that are composed of glacial drift and extend from the Shelbyville Morainic System (Wisconsinan) in Shelby and Macon Counties, southwestward to St. Clair County, and then southward to Monroe and Randolph Counties (fig. 2) (Jacobs and Lineback, 1969). Since Leverett's initial work in 1899, investigators have examined these ridged-drift deposits and speculated about their origin. Many geologists now believe that these deposits either were of glaciofluvial origin (crevasse fillings, eskers, and kames) (Leighton and Brophy, 1961) or were formed in an interlobate complex (Willman, Glass, and Frye, 1963).

Some of these ridged-drift deposits contain considerable amounts of groundwater; the Macon-Taylorville ridge contains one of the more important drift aquifers in central Illinois. This aquifer has been tapped for domestic, community, and industrial groundwater supplies. Geological, geophysical, and hydrological data from discrete locations in and around the aquifer have been collected and analyzed by the Illinois State Geological Survey and the Illinois State Water Survey (Burris, Morse, and Naymik, 1981). The electrical earth resistivity survey discussed in this paper complements this work, and is part of an Illinois State Geological Survey study observing resistivity signatures of drift aquifers in various geologic settings.

The determination of the boundaries and water-producing capabilities of the Macon-Taylorville ridged-drift aquifer was the primary focus of this study. The resistivity of two deposits, one southwest of Taylorville and another northeast of Taylorville under the Shelbyville Morainic System, was also examined to determine whether these deposits are extensions of the sand and gravel of the ridged-drift aquifer.

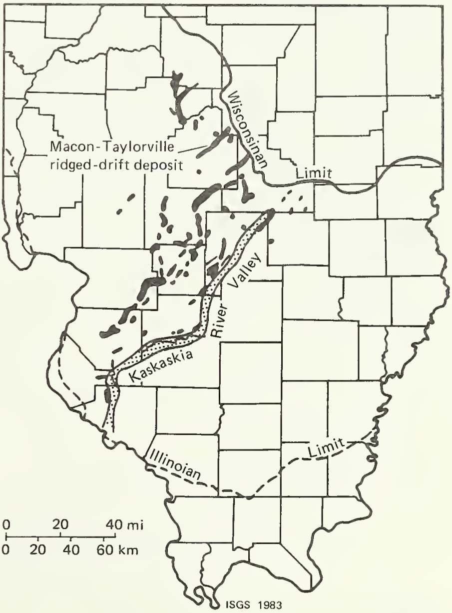

Figure 2. Ridged-drift deposits between Shelbyville Morainic System (Wisconsinan) and Randolph County, Illinois (after Jacobs and Lineback, 1969).

GEOLOGY

The Macon-Taylorville ridge lies in the Springfield Plain Subdivision of the Till Plains Section of the Central Lowland Province (figs. 1 and 3). It is approximately 17 miles long, three-quarters of a mile wide, and has a maximum topographic relief of about 40 feet. It extends from a point in Macon County at the front of the Shelbyville Morainic System (Wisconsinan) to the Sangamon River valley just to the southeast of Taylorville in Christian County. Several sizeable kames flank the northeastern portion of the ridge. For example, there is one kame located one mile west of Blue Mound and another very large kame located approximately two miles northwest of Moweaqua.

The bedrock surface in the Macon-Taylorville area consists mainly of Pennsylvanian shale and sandstone. The surficial glacial deposits immediately to the southwest of the Shelbyville Morainic System are chiefly Illinoian in age and range in thickness from about 50 to 180 feet. These deposits are a complex of ice-laid till, water-laid silt, sand and gravel outwash, and wind-deposited silt and fine sand (Jacobs and Lineback, 1969). Pre-Illinoian Banner Formation deposits occur locally. In ascending stratigraphic order, the Illinoian deposits include the Smithboro Till, the Mulberry Grove and Vandalia Till Members (Glasford Formation), and the Hagarstown Member (Pearl Formation) (fig. 4, Killey and Lineback, 1983). The Hagarstown Member contains the Sangamon soil at the top and consists of water-laid deposits and gravelly till that overlie the Vandalia Till in part of the study area. Southwest of the Shelbyville Morainic System, the Wisconsinan deposits are composed of the blanketing Roxana Silt and Peoria Loess.

Figure 3. Physiographic divisions of Illinois (after Leighton, Ekblaw, and Horberg, 1948).

The Macon-Taylorville ridged-drift aquifer consists mainly of various mixtures of stratified Hagarstown sand, gravel, and silt that range in thickness from 0 to 113 feet. The Hagarstown appears to grade from well-sorted sand and gravel in the ridge to sandy, gravelly ice contact or ablation till away from the ridge.

According to Jacobs and Lineback (1969), the Hagarstown deposits are derived from till that was thrust to the surface of the glacier, subjected to washing and mass movement, and deposited when the ice melted out from beneath it. The well-preserved bedding of the glaciofluvial sediments

<table>
<tr><th colspan="2">TIME STRATIGRAPHY</th><th colspan="3">ROCK STRATIGRAPHY (SOILS)</th></tr>
<tr><th colspan="2">System, Series, Stage</th><th colspan="3">Formation, Member</th></tr>
<tr><td rowspan="6">Pleistocene Series</td><td>Holocene Stage</td><td colspan="3">(Modern Soil)</td></tr>
<tr><td rowspan="4">Wisconsinan Stage</td><td colspan="2">Richland Loess</td><td rowspan="2">Peoria Loess</td></tr>
<tr><td>Wedron Fm.</td><td>Piatt Till Member</td></tr>
<tr><td colspan="3">Robein Silt</td></tr>
<tr><td colspan="3">Roxana Silt</td></tr>
<tr><td>Sangamonian Stage</td><td colspan="3">(Sangamon Soil)</td></tr>
<tr><td rowspan="6">Quaternary System</td><td rowspan="4">Illinoian Stage</td><td rowspan="4">Glasford Formation</td><td>Sand and gravel</td><td>Hagarstown Member</td></tr>
<tr><td>Vandalia Till Member</td><td rowspan="3">Pearl Formation</td></tr>
<tr><td>Mulberry Grove Member</td></tr>
<tr><td>Smithboro Till Member</td></tr>
<tr><td>Yarmouthian Stage</td><td colspan="3">(Yarmouth Soil)</td></tr>
<tr><td>Pre-Illinoian</td><td>Banner Formation</td><td colspan="2">Undifferentiated till, sand and gravel</td></tr>
</table>

ISGS 1983

Figure 4. Principal Pleistocene units in the study area.

indicates large-scale ice stagnation; the variability and relatively poor compaction of the Hagarstown deposits indicate an ablation origin. An ice-walled drainage system developed on or partly in the stagnant ice that deposited the Vandalia Till. Some superglacial debris was washed into ice-walled channels and was sorted by fluvial action. Superglacial material that was not swept into the ice-walled channel was not sorted, and when the ice melted it was deposited on the surface away from the ridges of sand and gravel. A crude sorting resulting from mass movement could have developed the Hagarstown deposits that are texturally gradational between till and outwash.

GEOPHYSICAL BACKGROUND

A conductive type of resistivity method was used in this study, that is, one in which electric current is applied at the earth's surface through two electrodes and potential difference is measured between two other electrodes also located on the earth's surface. The parameter of interest in this method is the resistivity of the earth materials.

The resistance (R) offered to the passage of current through a right cylinder of cross-sectional area (A) and length (L) is directly proportional to the length (L) and inversely proportional to the area (A). The constant of proportionality, ρ, is called the resistivity.

$$R = \rho \frac{L}{A}$$

Resistivity has units of resistance times length, e.g., ohm-feet.

Two important principles govern the resistivity of earth materials. Resistivity tends to decrease with (1) increasing amounts of groundwater in pore spaces, and (2) increasing ionic strength (free ion content) of the groundwater in the pore spaces. Massive rocks with a small amount of pore space have large resistivity values. Sand and gravel deposits, saturated with fresh groundwater, also have large resistivity values due to the low ionic strength of the groundwater. If the sand and gravel contains clay or soil particles, resistivity values will be reduced. Most soils (unless they are very dry) and greatly weathered or highly fractured rocks have medium to small resistivity values (fig. 5). Energy levels of deposition (packing), sorting, grain shapes, and surface conductance of the rocks can also influence the resistivity values of unconsolidated deposits.

The Wenner electrode configuration was employed in this study (fig. 6). In this configuration, four electrodes are equally spaced at intervals (a) along a straight line. The two outside electrodes (I_1 and I_2) are the current electrodes and the two inner electrodes (P_1 and P_2) are the potential electrodes. For this method, the resistivity (ρ) of a homogeneous and isotropic medium in which the electrodes are inserted is given by:

$$\rho = 2\pi a \frac{P_2 - P_1}{I}$$

where a is the electrode spacing, $P_2 - P_1$ is the difference in potential between stakes P_1 and P_2, and I is the current flowing between stakes I_1 and I_2.

When the medium into which the electrodes are inserted is not homogeneous, the resistivity given by the above equation is an apparent resistivity (ρ_a), that is, a weighted average of whatever resistivities may exist in the region between the potential surfaces (P_1 and P_2) that intersect the surface of the earth at the potential electrodes.

As the electrode spacing (a) is increased, the resistivities of deeper materials have an effect on the measured apparent resistivity. The method of expanding the electrode configuration systematically around the center point, measuring the current and the potential differences, and calculating apparent resistivity values is termed vertical electrical sounding (VES). A plot of apparent resistivity values versus electrode spacings is a vertical electrical sound (VES) curve.

Qualitative information can be obtained from the maxima, minima, inflection points, and apparent resistivity values of a VES curve. However, the types of information

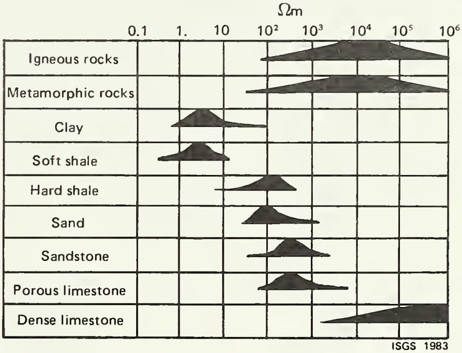

Figure 5. Approximate resistivity ranges of some rock types (adapted from Griffiths and King, 1965).

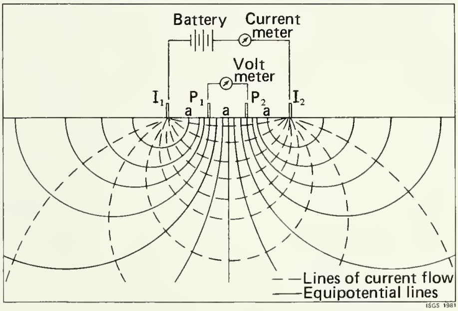

Figure 6. Basic elements of an earth resistivity meter and the Wenner electrode configuration.

most often desired are the layering parameters, that is, the "true" thicknesses and "true" resistivities of the strata immediately below the center stake of the VES profile. Several quantitative interpretation or inversion techniques can be used to determine the layering parameters from VES curves. One such technique, developed by Zohdy and Bisdorf (1975), was used in this study. However, this technique, like most of the others available, provides only one of many geoelectrically equivalent layering parameters solutions for a given VES curve. Prior knowledge of the geologic conditions in the study area helped to compensate for this shortcoming.

COLLECTION, REDUCTION, AND INTERPRETATION OF RESISTIVITY DATA

Field method. A Bison Earth Resistivity Meter, Model 2350 (owned by the Illinois State Geological Survey) was used in the electrical earth resistivity survey of this study. This instrument, which has an alternating current power source, is routinely used by the Survey in exploring for domestic, community, and industrial groundwater supplies.

Field procedures consisted of running a series of lines of VES profiles across the ridged drift and its projected extensions to the southwest and northeast (fig. 3). The positions of several VES profiles were collocated with wells where driller's logs, samples, and pump test data have been gathered. In all VES profiles the a-spacings were expanded to the extent that the associated VES curves adequately represented the coarse-grained aquifer, where present; Wenner electrode configuration a-spacings in many of the VES profiles were as great as 200 feet.

Figure 7 shows a typical VES curve and its layering parameters solution, as determined by the Zohdy and Bisdorf (1975) technique. The corresponding VES profile (G2) (fig. 3 and appendix fig. A-8) was very close to the Village of Assumption Well No. 1-78 on the ridged drift. Also shown in figure 7 is the driller's log for this well. Comparison of the layering parameters solution with the driller's log shows an uppermost layer with a "true" resistivity value of 138 ohm-feet, which corresponds to a layer of fine-grained sediments. The intermediate layers of 446 and 256 ohm-feet correspond to deposits of sand and gravel; the lower layer with a "true" resistivity of 150 ohm-feet corresponds to shale bedrock.

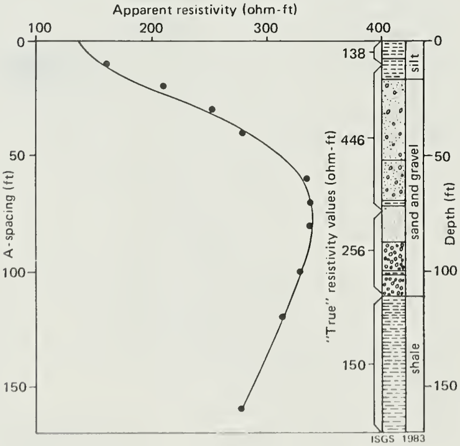

Figure 7. VES curve associated with VES profile G2 on line G, its layering parameters solution, and driller's log of Assumption Well No. 1-78 (after Burris, Morse, and Naymik, 1981).

Boundaries of the Macon-Taylorville aquifer. Layering parameters solutions were determined for all VES curves associated with VES profiles along lines A through N (figs. A-2 to A-15). At locations on the Macon-Taylorville ridged drift where VES profiles were collocated with wells for which driller's logs and/or samples were available, comparisons of "true" resistivity values with lithologies indicate that layers with "true" resistivity values in excess of 200 ohm-feet generally correspond to coarse-grained, water-bearing deposits; layers with values less than 200 ohm-feet are considered aquitards. The layering parameters solutions of the VES curves associated with the VES profiles in lines B through M (figs. A-3–A-14) show the sand and gravel core of the ridged drift to be a lens-shaped body in cross section. The upper and lower boundaries of the body are well-defined because of abrupt transitions from coarse-grained materials with large "true" resistivity values to fine-grained materials with small "true" resistivity values; the lateral boundaries are not as well-defined because of a more gradual transition from coarse- to fine-grained materials.

Along some of the lines of VES profiles that cross the ridged drift (such as line K near Willeys in Christian County) (fig. A-12), extremely large "true" resistivity values are evident at the top of the aquifer. These values are thought to indicate dewatered zones that resulted from gravitation drainage or from excessive pumpage.

Hydraulic conductivity and resistivity. To describe the relationship between hydraulic conductivity (H) and formation factor (F) in a freshwater, clay-free, well-sorted, granular aquifer, Heigold, Gilkeson, Cartwright, and Reed (1979) proposed the equation:

$$H = a_1 F^{b_1}$$

where a_1 and b_1 are constants related to the aquifer. Formation factor (F) is given by the relationship:

$$F = \frac{\rho_{rw}}{\rho_w}$$

where ρ_{rw} is the resistivity of the rock-water complex and ρ_w is the resistivity of the water filling the interstices of the rock. If ρ_w is constant, hydraulic conductivity can be expressed as a function of the resistivity of the rock-water complex:

$$H = a_2 \rho_{rw}^{b_1}$$

where a_2 is another constant related to the aquifer.

Alger (1966) determined a geometric relationship between concentrations of total dissolved solids and water resistivity from a study of electric logs of freshwater wells in unconsolidated sediments. Chemical analyses of 13 water samples from areas of the ridged-drift aquifer where surficial electrical resistivity data were gathered have provided values for concentrations of total dissolved solids (ppm) (Burris, Morse, and Naymik, 1981). The mean and standard deviation of these concentrations were calculated to be 317 and 62 ppm, respectively. From Alger's relationship, the sample mean of the concentrations of total dissolved solids was equivalent to a water resistivity value of 71 ohm-feet. This value was corroborated by specific conductance data available from several locations on the ridged-drift aquifer.

In their study of a central Illinois valley train aquifer, Heigold, Gilkeson, Cartwright, and Reed (1979) showed an inverse relationship between hydraulic conductivity and aquifer resistivity along the axis of that aquifer. This relationship was attributed to a difference in sorting: the fine sands and silts farther down the axis of the valley train aquifer were better sorted than the coarser-grained deposits near the head of the valley train and had smaller resistivity values.

However, sieve analyses of samples from the Macon-Taylorville ridged-drift aquifer showed that no significant change occurred in sorting coefficients anywhere in the main body of the aquifer and that median grain sizes decreased laterally away from the axis of the aquifer (Burris, Morse, and Naymik, 1981). Because grain size probably controls hydraulic conductivity and aquifer resistivity, one would expect a direct relationship between hydraulic conductivity and aquifer resistivity in the ridged-drift aquifer.

Pump tests conducted by the Illinois State Water Survey provided hydraulic conductivity values for several discrete locations along the length of the Macon-Taylorville ridged-drift aquifer (fig. 8). Vertical electrical sounding (VES) data have been collected at selected pump-test sites along the aquifer; inversion of the VES data has provided values for aquifer resistivity. When these values are

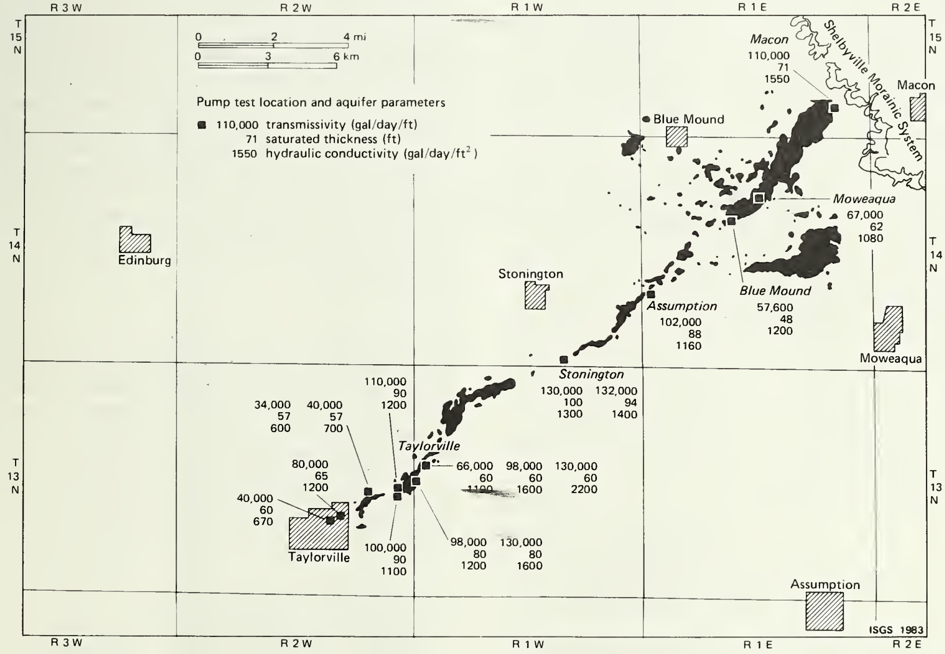

Figure 8. Location and results of pump tests along the Macon-Taylorville ridged-drift aquifer.

used, a plot of hydraulic conductivity versus aquifer resistivity shows a direct relationship between these parameters (fig. 9). A regression curve of the geometric type (a straight line on log-log graph paper) fit to these data gives the equation:

$$H = 22.179\,\rho_{rw}^{\;0.661}$$

where H is hydraulic conductivity in gal/day/ft^2 and ρ_{rw} is "true" aquifer resistivity in ohm-feet.

The inversion of the VES curves associated with the VES profiles that cross the Macon-Taylorville ridged-drift aquifer have provided "true" thicknesses and "true" resistivities for discrete locations of the aquifer. The hydraulic conductivity of the aquifer at these locations was readily calculated from the above equation. In order to graphically display the water-producing capability of the Macon-Taylorville ridged-drift aquifer, the aquifer transmissivity (hydraulic conductivity multiplied by saturated thickness) has been calculated and plotted as a function of horizontal distance for each of the VES lines B through M (figs. A-3—A-14).

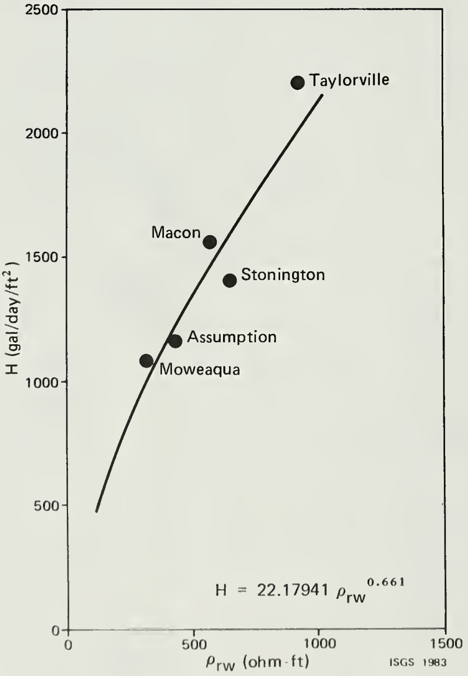

Figure 9. Hydraulic conductivity (H) versus aquifer resistivity (ρ_{rw}) at selected pump test sites along the Macon Taylorville ridged-drift aquifer.

Deposits southwest of Taylorville. The resistivity of the linear, water-bearing, coarse-grained deposits to the southwest of Taylorville was also examined. Even though there is no associated ridge, these deposits are thought to be an extension of the sand and gravel that forms the core of the ridged drift between Macon and Taylorville. VES curves associated with an east-west line of VES profiles (fig. 1) that crosses these deposits approximately one mile southeast of Palmer in Christian County were inverted according to the Zohdy and Bisdorf (1975) technique. The layering parameters solutions (fig. A-15) show a shallow zone of large "true" resistivity values in the vicinity of the Palmer municipal well (350 ft NL, 15 ft EL, NE NE SW, Section 35, T. 12 N., R. 3 W.). These resistivity values are similar to those produced by the sand and gravel at the core of the Macon-Taylorville ridged-drift aquifer.

Boundaries of the deposits. In order to place lateral boundaries on the aquifer along line N, the smallest "true" resistivity value thought to be associated with coarse-grained aquifer material must be lowered slightly below 200 ohm-feet, the value specified as the lower boundary for ridged-drift aquifer material between Macon and Taylorville. The large "true" resistivity value zone extends from approximately 800 feet west to approximately 1600 feet east of the center of Section 35, T. 12 N., R. 3 W.

Determination of the lower boundary of the aquifer by resistivity methods is difficult. Comparison of the layering parameters solutions for the VES curve associated with the VES profile near the Palmer municipal well with the driller's log of that well does not show enough resistivity contrast between the coarse-grained aquifer materials and the subjacent bedrock to accurately define this boundary. The driller's log of the Palmer well indicates a bedrock of alternating shale and limestone at a depth of 77 feet. The combination of shale with small resistivity values and limestone with large resistivity values should yield a resistivity value similar to that of the superjacent coarse-grained, unconsolidated sediments.

Deposits northeast of Macon-Taylorville. The sand and gravel deposits of the Macon-Taylorville ridged-drift aquifer might also extend northeastward under the Shelbyville Morainic System. To examine this possibility, line A of VES profiles (fig. 1) was located a short distance from the front of the moraine so that it crossed the projected extension of the ridged drift to the northeast; however, the layering parameters solutions of the VES curves associated with the VES profiles of this line (fig. A-2) do not indicate such an extension. Except for the occasional presence of a low resistivity layer at the surface, the "true" resistivity values associated with the surficial deposits along line A show little variation vertically or laterally.

A 165-foot test hole (TA-3) was drilled southwest of VES profile A2 (1800 ft N, 1500 ft W, SE/c, Section 19, T. 15 N., R. 2 E.) (figs. 1 and 8). Analysis of cuttings and split-spoon samples from this hole (Burris, Morse, and Naymik, 1981) indicated that a fine to coarse sand with gravel extends from a depth of 78 feet to 153 feet, where it rests on shale bedrock. These deposits are thought to be laterally equivalent to the Hagarstown Member of the Pearl (Glasford) Formation (the deposits composing the core of the ridged-drift aquifer). Overlying the sand and gravel are 9 feet of Robein Silt, 53 feet of the Piatt Till Member, and 16 feet of Richland Loess (figs. 4 and 10).

After these data were analyzed, another VES profile was located near this hole (fig. 8). The layering parameters solution for the VES curve associated with this VES profile was similar to those obtained from VES data gathered along line A (fig. A-2). Again, it was not possible to determine the presence of the sand and gravel.

Closer examination of the cuttings, split-spoon samples, and the natural gamma radiation log of the Piatt Till at test hole TA-3 explains the inability of the surficial electrical earth resistivity method to delimit the sand and gravel. As previously noted, the Piatt Till is the thickest unconsolidated unit overlying the Hagarstown-related sand and gravel in this area. Burris, Morse, and Naymik (1981) indicated the presence of silt and sand seams in the Piatt Till. This was confirmed by zones of reduced radiation on the natural gamma radiation log (fig. 10). The "true" resistivity of the Piatt Till unit along line A and at test hole TA-3 has a mean value of approximately 150 ohm-feet. This value is somewhat greater than expected for a Wisconsinan till, and suggests the presence of a considerable amount of coarse-grained material.

In addition, the "true" resistivity value of the sand and gravel aquifer under the moraine is not as great as that in front of the Shelbyville Morainic System to the southwest, where it is covered only by a thin veneer of silt and loess. This difference might be due to the amount of groundwater in the aquifers. Low pumpage of the aquifer under the moraine results in less chance for dewatering the aquifer, thereby naturally decreasing its "true" resistivity. Excessive pumpage of the aquifer near Taylorville has dewatered the top of the aquifer, appreciably increasing its "true" resistivity. Water quality can also affect the resistivity of the aquifer—the higher the ionic strength of the water in the aquifer under the moraine, the lower the overall "true" resistivity of the aquifer.

All of these factors would tend to reduce the resistivity contrast between the sand and gravel and the rest of the unconsolidated sediments in the moraine. Possibly the contrast is too small to be detected by either the VES curves or the layering parameters solutions provided by inversion techniques.

CONCLUSIONS

The extensive electrical earth resistivity survey of the ridged-drift aquifer between Macon and Taylorville in central Illinois has yielded a considerable amount of information about this important aquifer. The Zohdy and Bisdorf (1975) inversion technique applied to vertical electrical sounding (VES) data has allowed a good definition of the boundaries of the aquifer. Aquifer resistivity values at pump test sites along the axis of the aquifer were used to develop a relationship between aquifer resistivity and hydraulic conductivity. This relationship, along with aquifer thickness, was then used to calculate transmissivity values at the VES profile locations on the aquifer.

A direct and geometric relationship between hydraulic conductivity and aquifer resistivity for the ridged-drift aquifer was found. The significant variations in these two parameters take place laterally rather than along the axis of the aquifer; the larger values of hydraulic conductivity and aquifer resistivity occur nearer to the axis of the

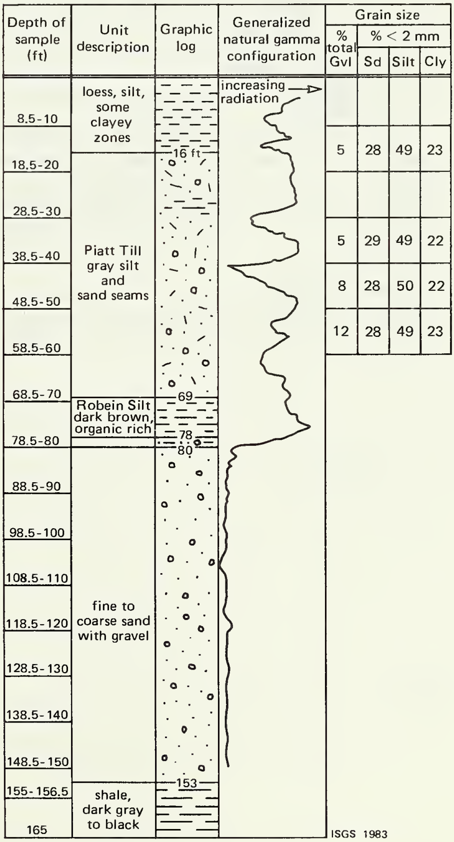

Figure 10. Unit description, graphic log, natural gamma radiation log, and grain size data for test boring TA-3 (after Burris, Morse, and Naymik, 1981).

aquifer. Sieve analyses of samples of aquifer materials gathered in an organized drilling program (Burris, Morse, and Naymik, 1981) showed that the median grain diameters of these samples decreased away from the axis of the aquifer and that sorting coefficients of these samples were uniformly low throughout the aquifer. These findings are consistent with the relationship found between hydraulic conductivity and aquifer resistivity.

The sand and gravel that forms the core of the ridged-drift aquifer appears to extend to the southwest beyond Taylorville and to the northeast under the Shelbyville Morainic System. To the southwest, where there is no associated ridge, the presence of these coarse-grained materials has been verified by VES data and by drilling. To the northeast, on the Shelbyville Morainic System, driller's logs, natural gamma radiation logs, and split-spoon samples have confirmed the presence of these coarse-grained Hagarstown related deposits below generally finer-grained Wisconsinan deposits. Unfortunately, on the moraine, VES data provided little help in defining the boundaries of the coarse-grained aquifer.

The results of this study should be useful for the future management of the ridged-drift aquifer. The results also mark another step toward understanding the relationships between the hydraulic conductivity and aquifer resistivity of aquifers that are deposited in a variety of geologic environments.

ACKNOWLEDGMENT

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APPENDIX

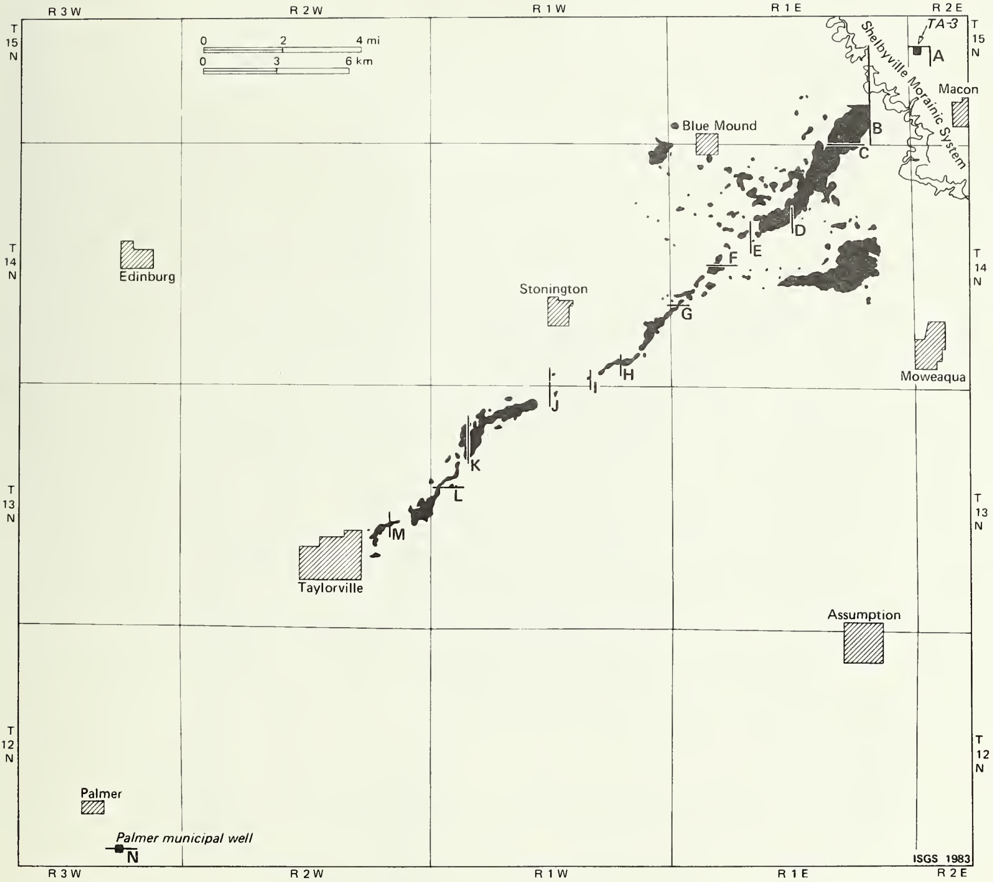

Figure A-1. Location of lines of VES profiles along Macon-Taylorville ridged-drift deposits in central Illinois.

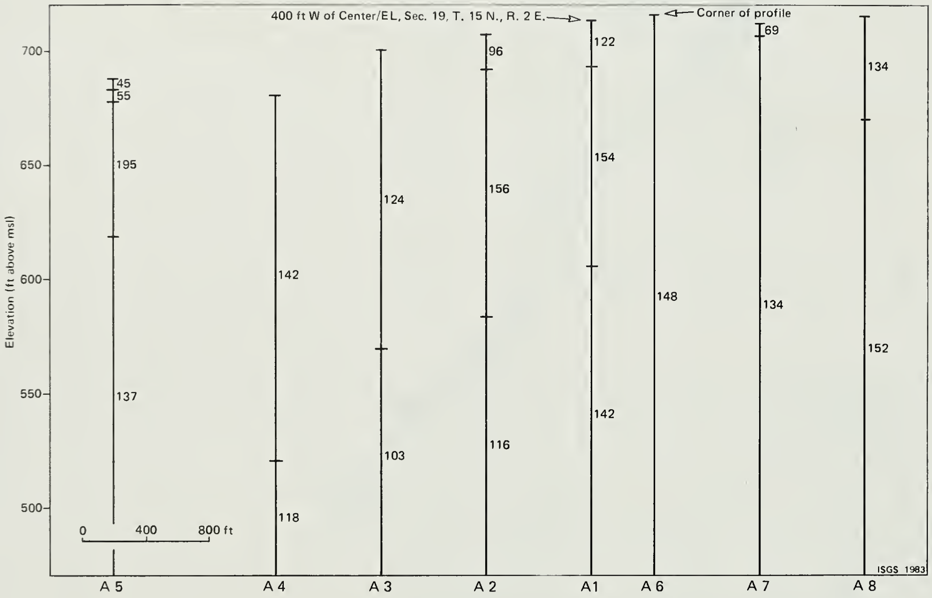

Figure A-2. Layering parameters solutions of VES curves associated with VES profiles along line A and VES profile near test hole TA-3.

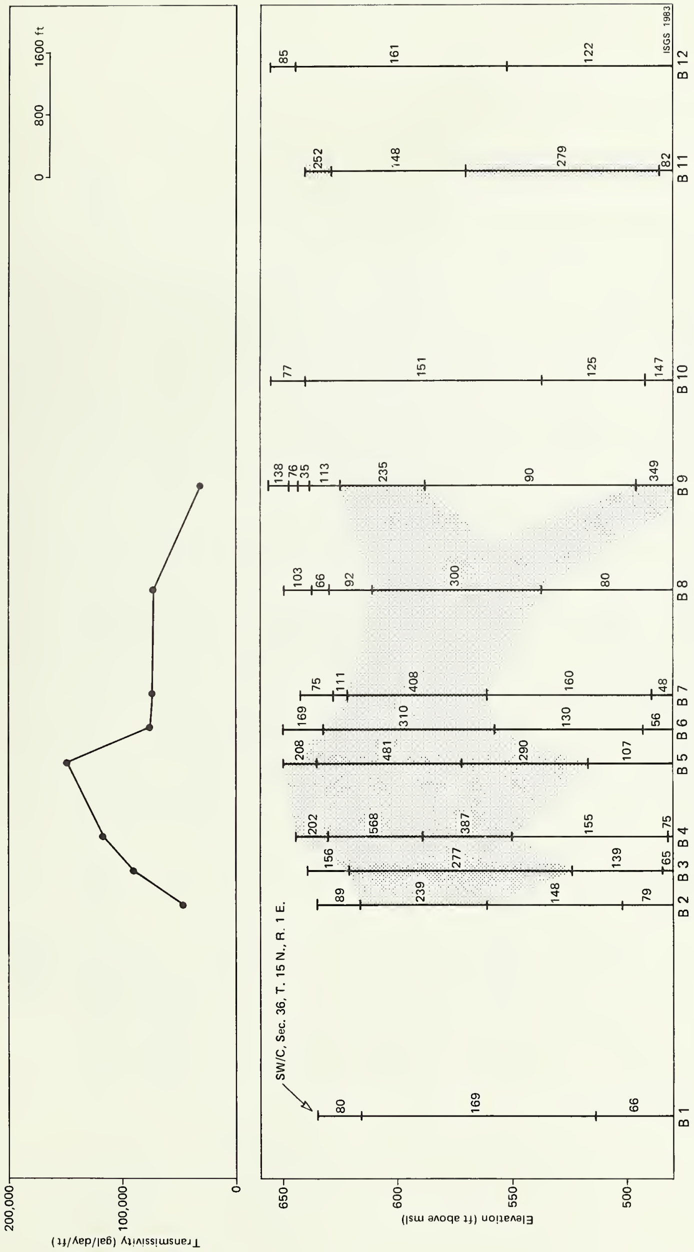

Figure A-3. Layering parameters solutions of VES curves associated with VES profiles and aquifer transmissivity along line B. (Note different scale.)

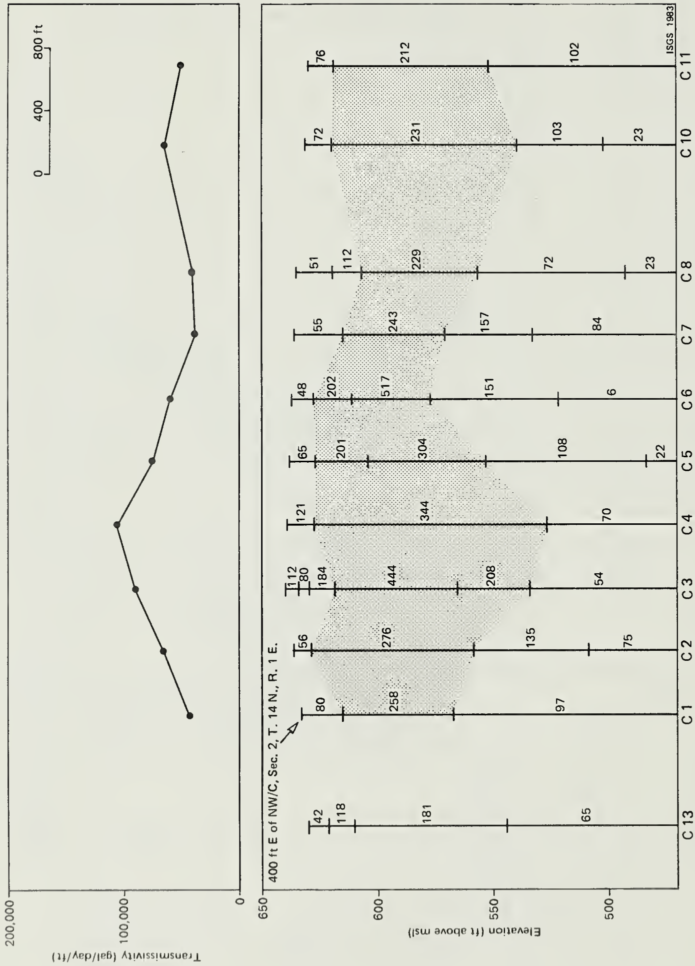

Figure A-4. Layering parameters solutions of VES curves associated with VES profiles and aquifer transmissivity along line C.

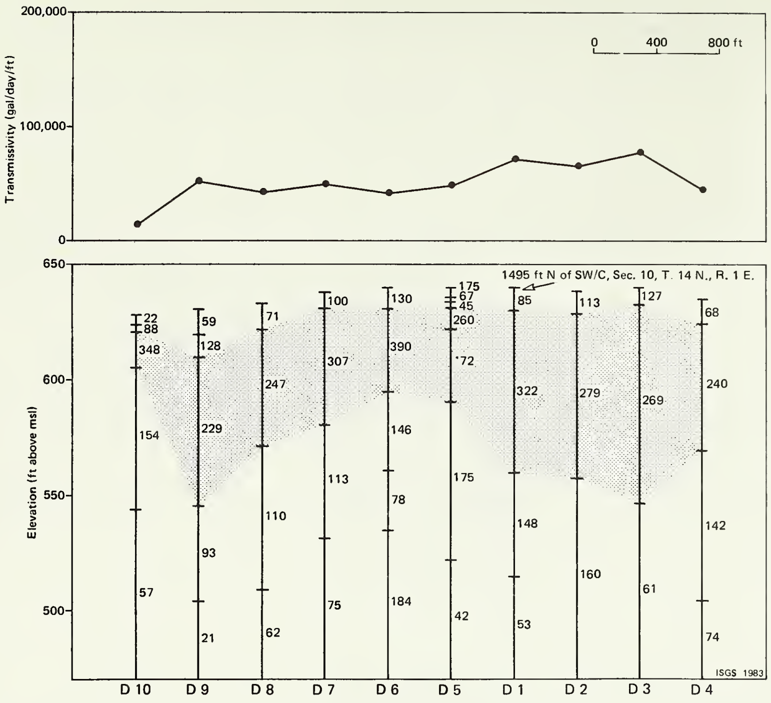

Figure A-5. Layering parameters solutions of VES curves associated with VES profiles and aquifer transmissivity along line D.

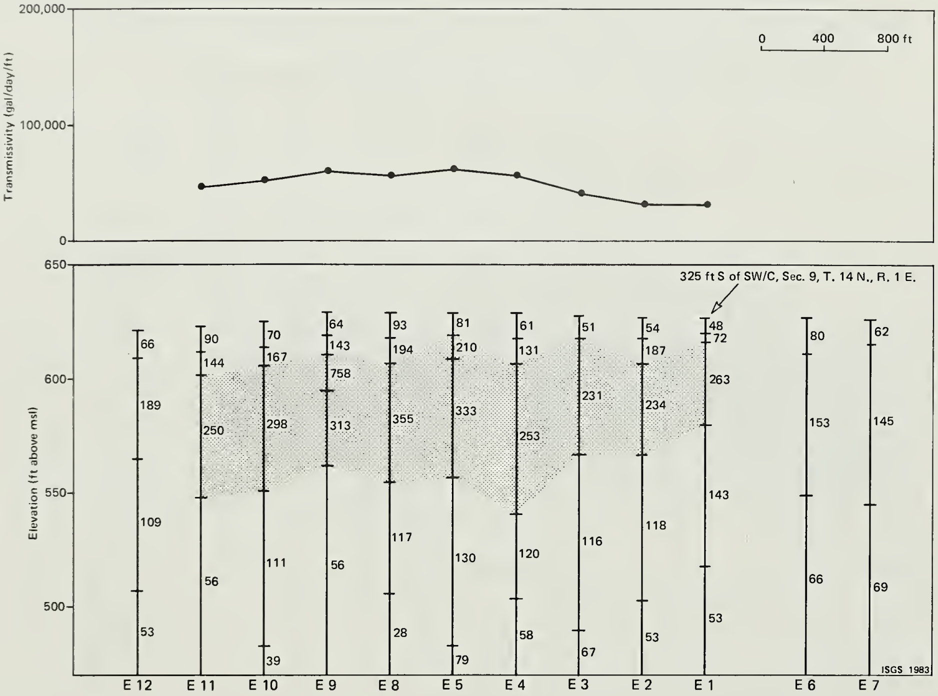

Figure A-6. Layering parameters solutions of VES curves associated with VES profiles and aquifer transmissivity along line E.

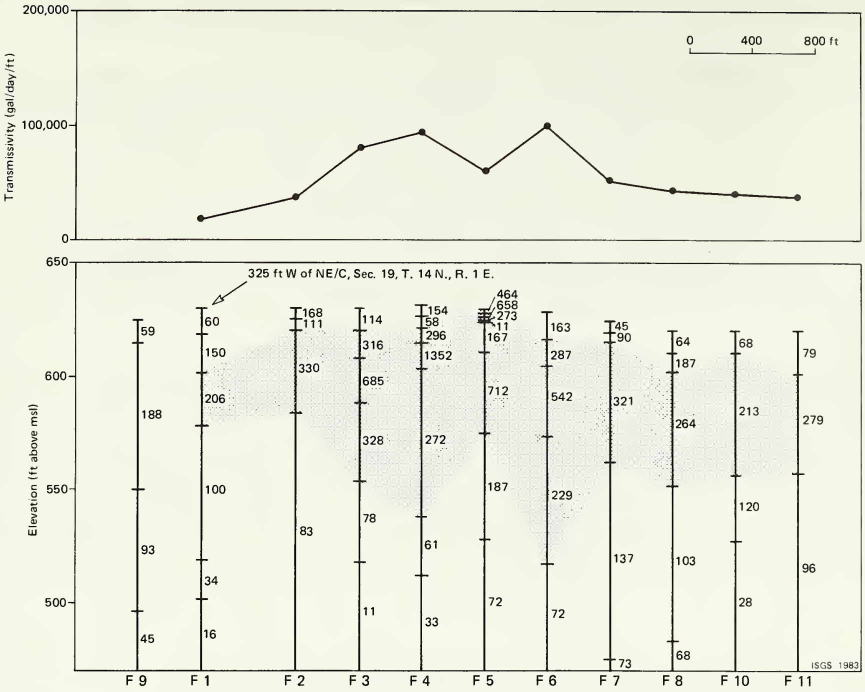

Figure A-7. Layering parameters solutions of VES curves associated with VES profiles and aquifer transmissivity along line F.

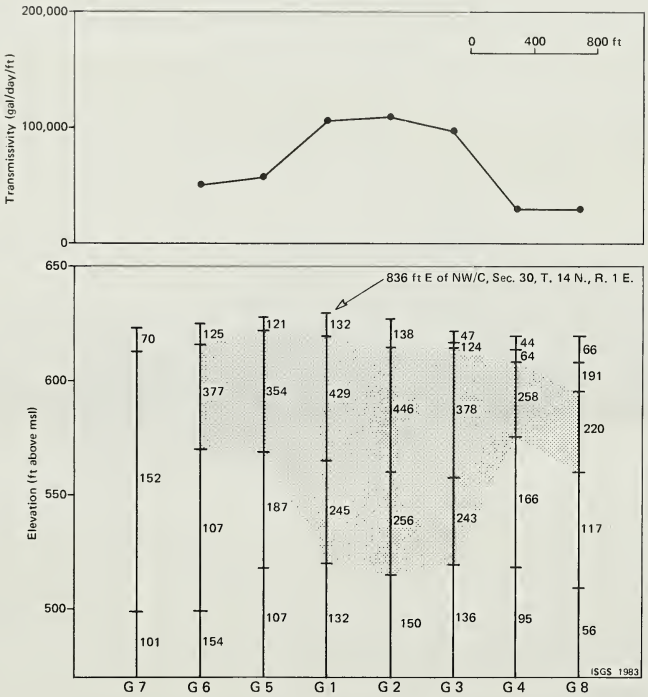

Figure A-8. Layering parameters solutions of VES curves associated with VES profiles and aquifer transmissivity along line G.

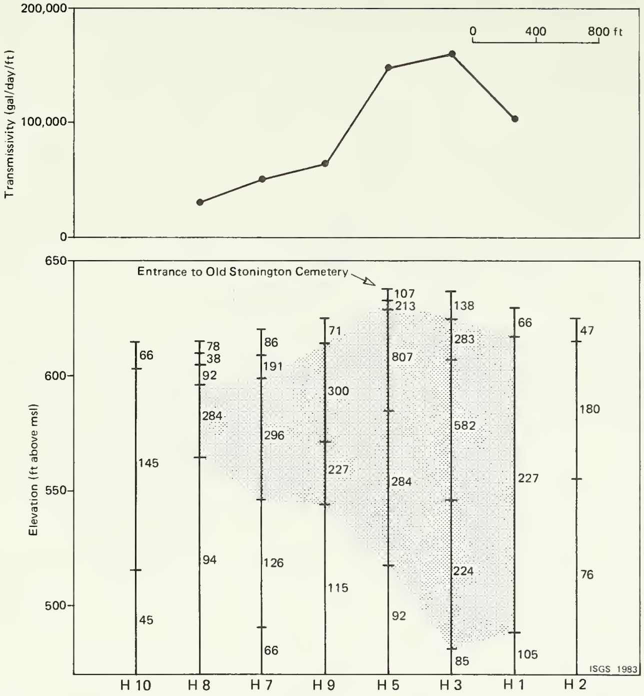

Figure A-9. Layering parameters solutions of VES curves associated with VES profiles and aquifer transmissivity along line H.

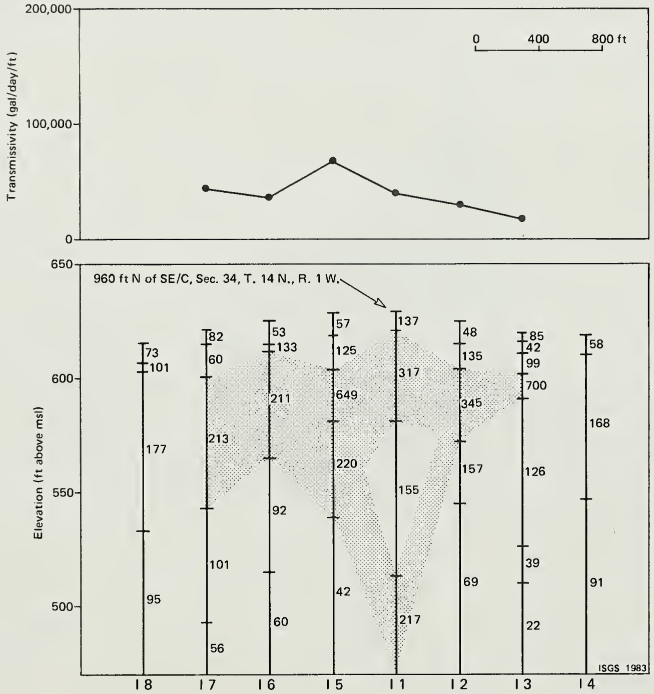

Figure A-10. Layering parameters solutions of VES curves associated with VES profiles and aquifer transmissivity along line I.

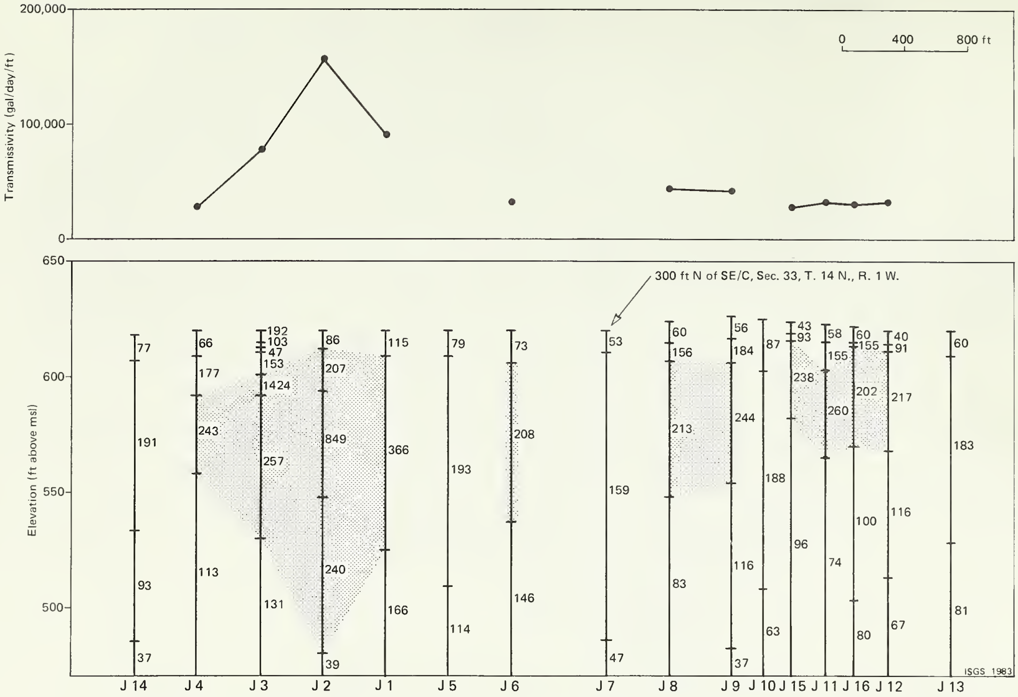

Figure A-11. Layering parameters solutions of VES curves associated with VES profiles and aquifer transmissivity along line J.

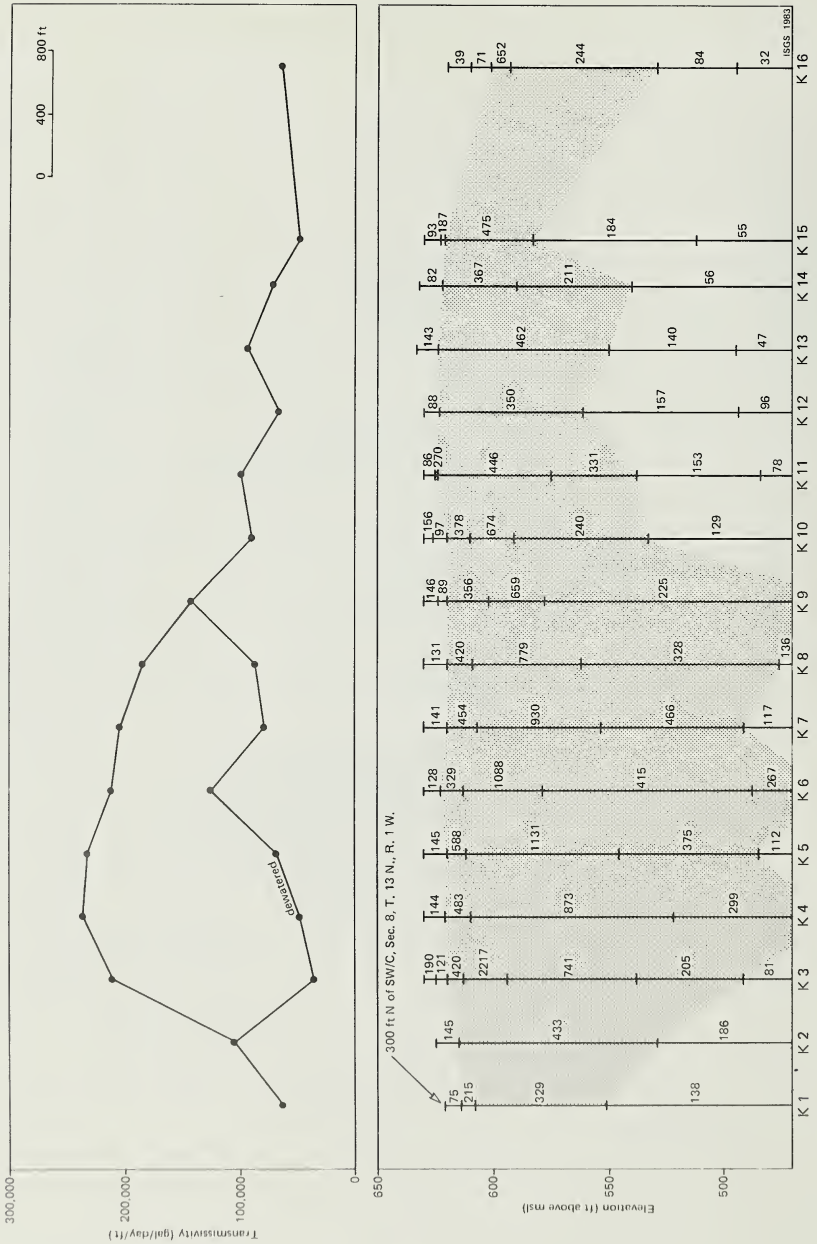

Figure A-12. Layering parameters solutions of VES curves associated with VES profiles and aquifer transmissivity along line K.

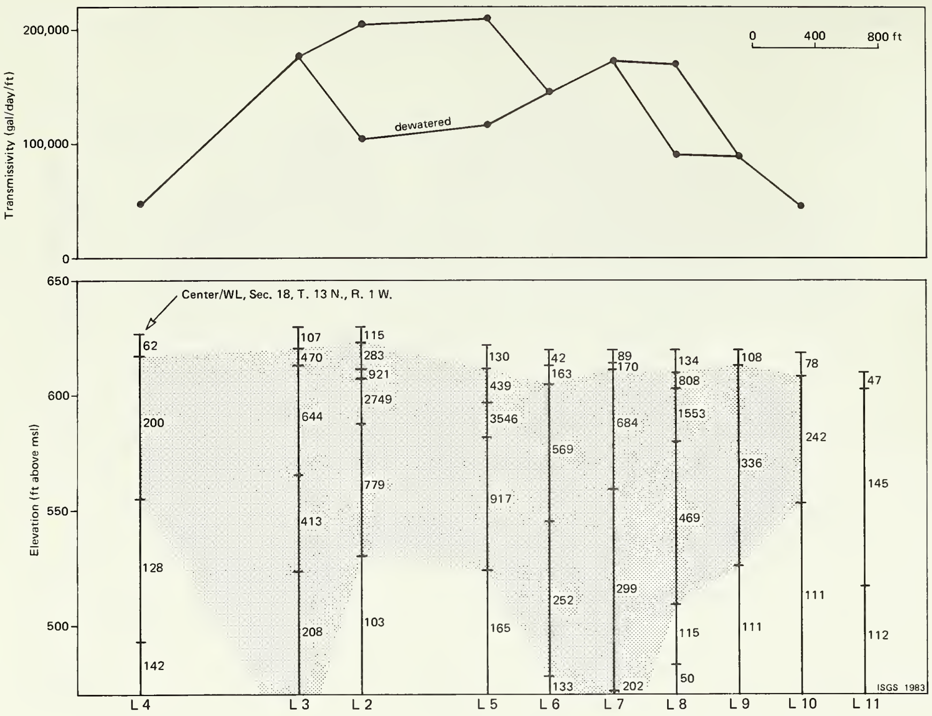

Figure A-13. Layering parameters solutions of VES curves associated with VES profiles and aquifer transmissivity along line L.

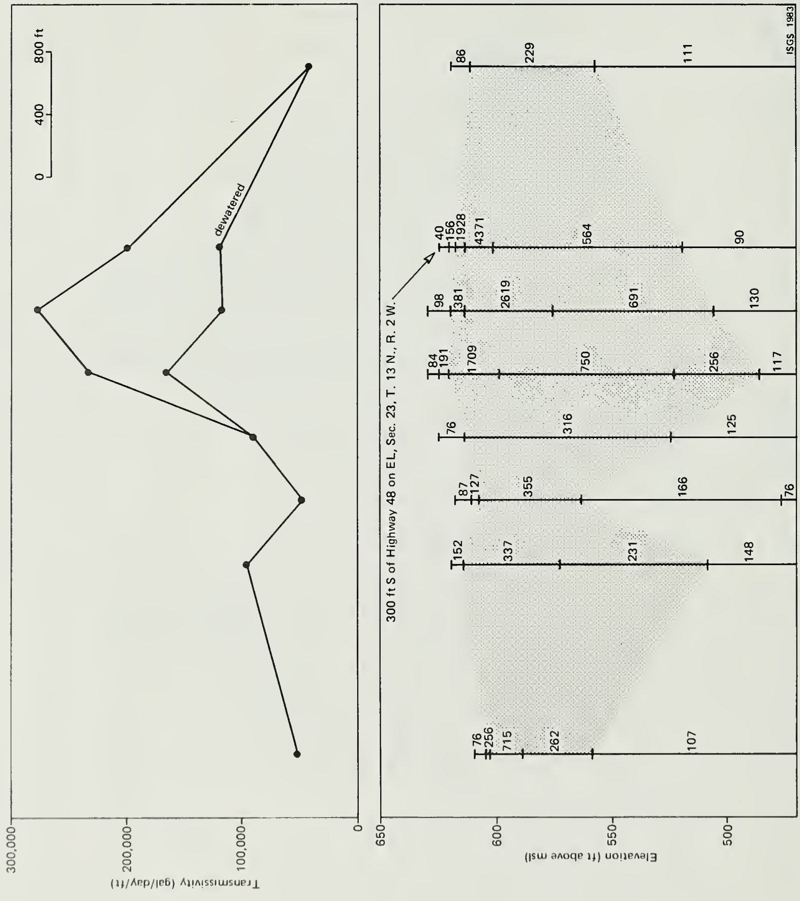

Figure A-14. Layering parameters solutions of VES curves associated with VES profiles and aquifer transmissivity along line M.

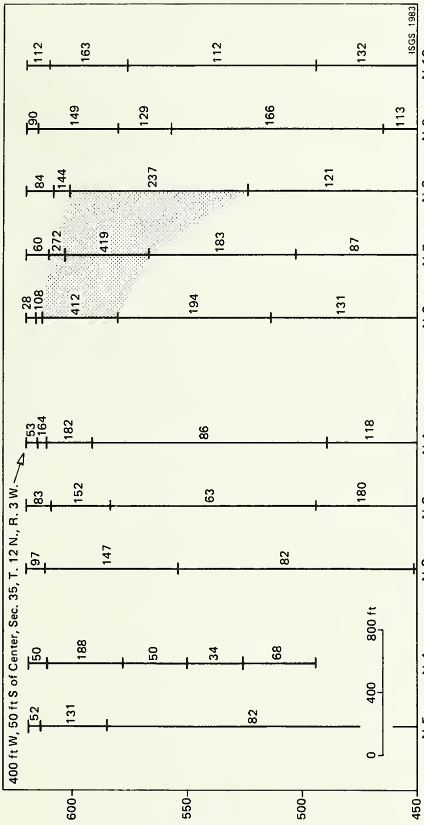

Figure A-15. Layering parameters solutions of VES curves associated with VES profiles along line N and driller's log from Palmer Municipal Well.


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