EVALUATION OF SURFACE GEOPHYSICAL METHODS FOR COLLECTION OF HYDROGEOLOGIC DATA IN THE NEBRASKA SAND HILLS REGION

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FACTORS FOR CONVERTING INCH-POUND UNITS TO THE INTERNATIONAL SYSTEM OF UNITS (SI)

The International System (SI) is a consistent system of metric units adopted by the Eleventh General Conference of Weights and Measures in 1960. Selected factors for converting inch-pound units used in this report are given below:

Multiply	By	To obtain
foot	0.3048	meter
foot per second	0.3048×10^{-3}	kilometer per second
mile	1.609	kilometer
square mile	2.590	square kilometer

Note: SI units were used in the collection of electrical resistivity data; meters are converted to feet by multiplying by 3.2808.

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By Michael J. Ellis* and Robert A. Hiergesell**

ABSTRACT

The practicality of using surface-geophysical methods for obtaining hydrogeologic data in the Nebraska Sand Hills region was studied during the summer of 1984. Seismic-refraction and electrical-resistivity equipment were used, because an evaluation of hydrogeologic data indicated that results of surveys made with this equipment probably would yield the most useful data. The study area, which included parts of Garfield, Holt, and Wheeler Counties, was selected because it is hydrogeologically representative of the eastern part of the Sand Hills region, and because sufficient hydrogeologic data were available for use in evaluating the results of geophysical surveys. Geophysical methods were evaluated for their ability to consistently detect selected hydrogeologic horizons. These horizons, in descending order, are: the water table, the top of Quaternary silt beds, the top of Quaternary sand and gravel beds, the top of the Tertiary Ogallala Formation, and the top of the Cretaceous Pierre Shale. The top of the Pierre Shale generally is the base of the aquifer, which consists of all of the 500 to 700 feet of overlying deposits.

Evaluations of the geophysical data indicate that seismic-refraction surveys are best suited for determining the depth to the water table, but are not effective in studying beds below the water table. Vertical electrical soundings provided data on the depth to water table and the top of the silt beds. Available hydrogeologic data, however, indicate that with some changes in data collection or interpretation techniques, it may be possible to obtain information on the top of the sand and gravel deposits, the top of the Ogallala Formation, and the top of the Pierre Shale with vertical electrical soundings. Use of either geophysical method could enhance the results of hydrogeologic investigations in the Nebraska Sand Hills region.

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INTRODUCTION

Seismic-refraction surveys and electrical-resistivity soundings were made in parts of Garfield, Holt, and Wheeler Counties, Nebraska, during the summer of 1984, as part of a cooperative program between the Nebraska Natural Resources Commission and the U.S. Geological Survey. The purpose of this work was to evaluate the effectiveness and potential usefulness of these methods for obtaining data that can be used in hydrogeologic investigations of the Nebraska Sand Hills region (fig. 1). The combined use of seismic-refraction and electrical-resistivity methods might be expected to provide the following information necessary to hydrogeologic investigations: the configuration of the base of the aquifer, the distribution of the lithologic variations within the water-bearing deposits, and the depth to the water table.

Generally, in Nebraska, data on the base of an aquifer and on lithologic variations within an aquifer are obtained from detailed sample logs and borehole geophysical logs of test holes drilled at selected locations. Most water-level data are obtained by making measurements in existing water wells, but some data are measurements made in specially installed observation wells. These methods of obtaining hydrogeologic data are expensive and time consuming. Surface geophysical methods may provide effective supplements or alternatives to traditional methods of collecting hydrogeologic data. This report provides a qualitative evaluation of the potential effectiveness of using data from seismic-refraction and electrical-resistivity methods to supplement and enhance data collected through test-drilling and water-level measurement programs.

Methods

Surface geophysical prospecting is the utilization of instruments on the land surface to measure physical properties of material within the Earth. Surface geophysical prospecting for petroleum and mineral resources has led to the development of many techniques and instruments to measure these physical properties. Selection of the geophysical methods to evaluate as possible alternative or supplementary methods for obtaining hydrogeological data in the Nebraska Sand Hills region was based on an evaluation of the various physical parameters that can be measured by geophysical methods and on the geology of the area. Two methods of geophysical prospecting were selected -- seismic refraction surveying and electrical-resistivity sounding. These two methods generally have provided the most useful data for hydrogeologic investigations (Lennox and Carlson, 1970).

It is not within the scope of this report to present details on the basic theories of either method of geophysical exploration. For the purposes of this report, however, generalized descriptions of the seismic-refraction and electrical-resistivity methods are included to provide some background on what is involved in collection, interpretation, and evaluation of geophysical data. More detailed information on both methods can be found in general textbooks on geophysics, such as those by Dobrin (1960) and Telford and others (1976).

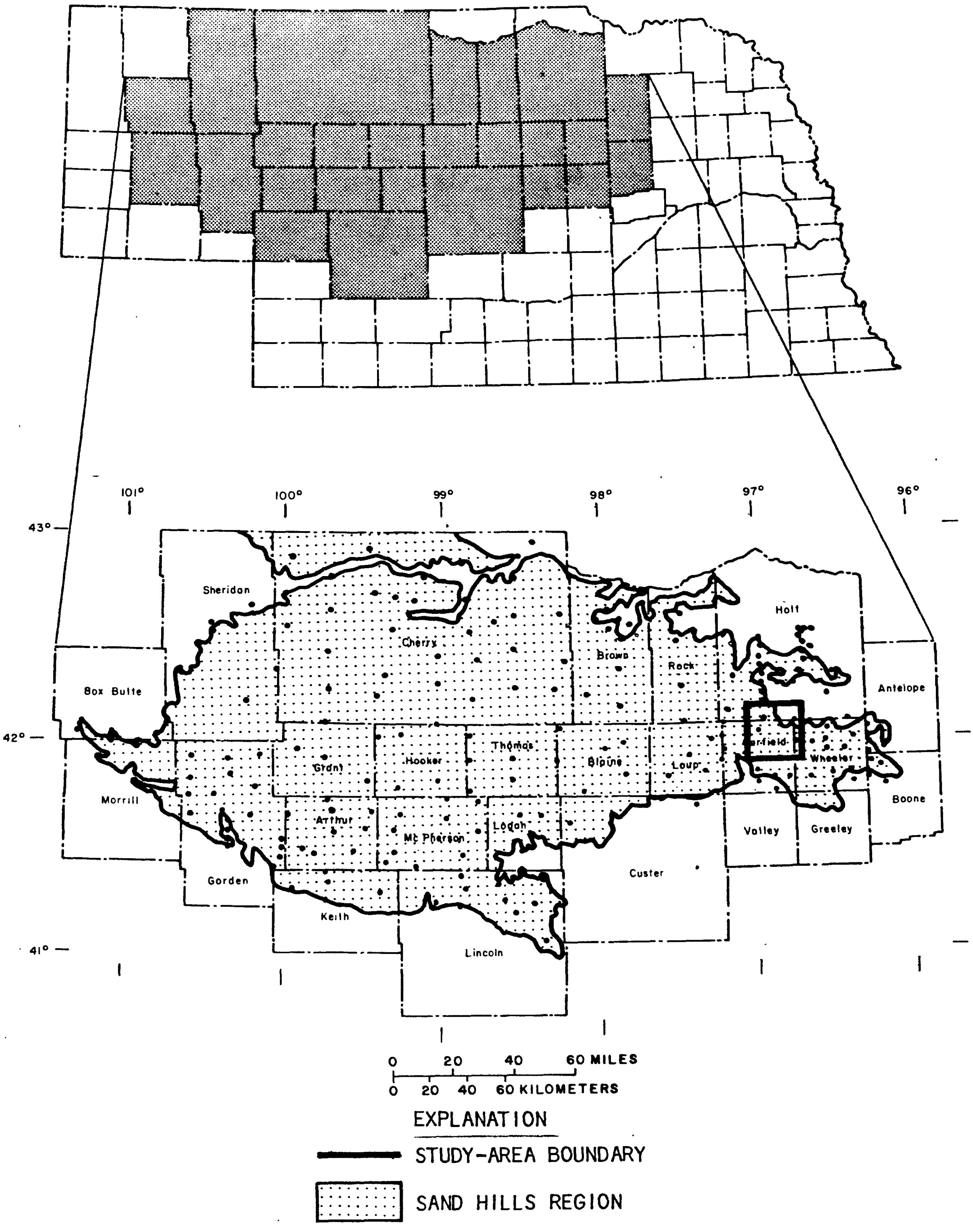


Figure 1.--Extent of Sand Hills region in Nebraska (after Keech and Bentall, 1971) and location of deep test holes that reached the base of the aquifer in or near the region.

Both seismic-refraction and electrical-resistivity methods were developed more than 60 years ago as means for obtaining geophysical information. Through the years there has been a continual effort to improve equipment and field techniques, as well as further development and refinement of the theories involved. During the past 20 years, developments in electronics and other aspects of instrumentation have made it possible to build relatively compact and lightweight geophysical equipment with which accurate measurements can be made. Although these developments have made utilization of geophysical methods much easier, the most significant advances probably have been in the development of computer programs to assist in processing and interpreting data.

Layers detected by a geophysical-surveying method are those that have distinctive physical properties that can be measured by the geophysical equipment being used. These layers are not necessarily equivalents of recognized hydrologic or geologic layers. In seismic-refraction surveys the layers are called "velocity layers" and in electrical-resistivity soundings they are called "geoelectric layers."

Seismic-Refraction Method

The principle of seismic refraction is based on the fact that elastic waves travel through different earth materials at different velocities. In general, the more dense the material is, the greater the wave velocity through it. The approximate range of velocities for some of the more common unconsolidated earth materials are shown in figure 2. The distinct differences in the ranges of seismic velocities that exist between unsaturated and saturated earth materials indicates that the water table normally can be detected readily by seismic-refraction methods.

In seismic-refraction surveys, information on the subsurface usually is obtained from time-distance relationships for seismic waves originating at or near the surface, penetrating into the earth materials, and returning to the surface along minimum time paths, as shown schematically in figure 3A. Seismic waves are initiated by an energy source at the land surface. Usually a small explosive charge is used, but under some conditions the impact of a sledge hammer on a steel plate set on the ground is adequate. A set of detectors, called geophones, are laid out in a line at known distances from the energy source. This layout of geophones is called a spread.

Seismic waves initiated at the land surface, traveling through earth materials and refracted at the critical angle by a "high-velocity" layer at some depth will reach the more distant geophones before waves that traveled through only the low-velocity surface layer. Elapsed time between the initiation of the shock and the first arrival of the seismic waves at each geophone is recorded on a seismograph. These recorded times are used to derive a graph of arrival time versus distance (fig. 3B). This graph, with application of theory, can be used to calculate layer depths and their seismic velocities.

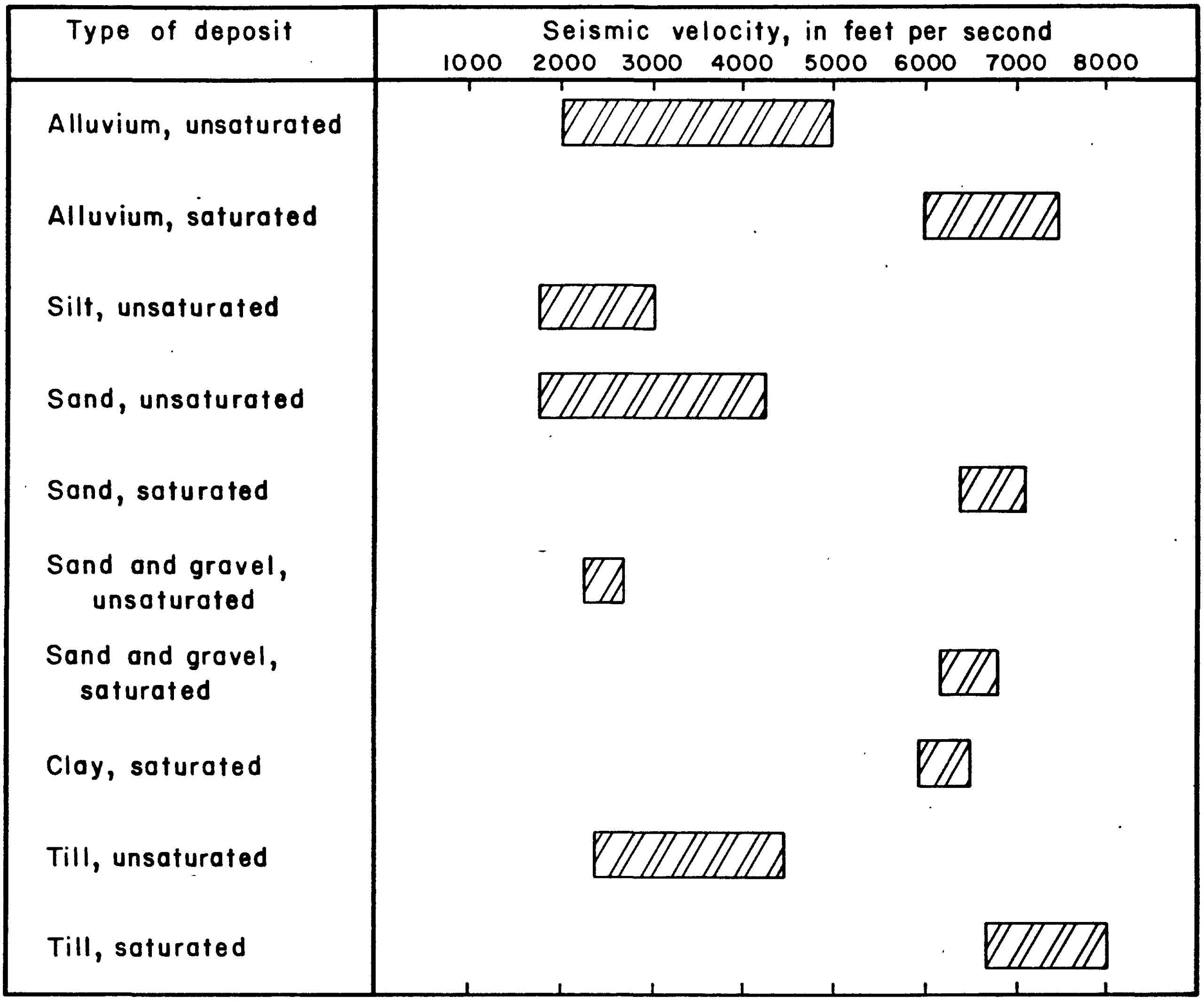


Figure 2.--Ranges of seismic velocities in unconsolidated sedimentary deposits (data from Press, 1966, and Zehner, 1973).

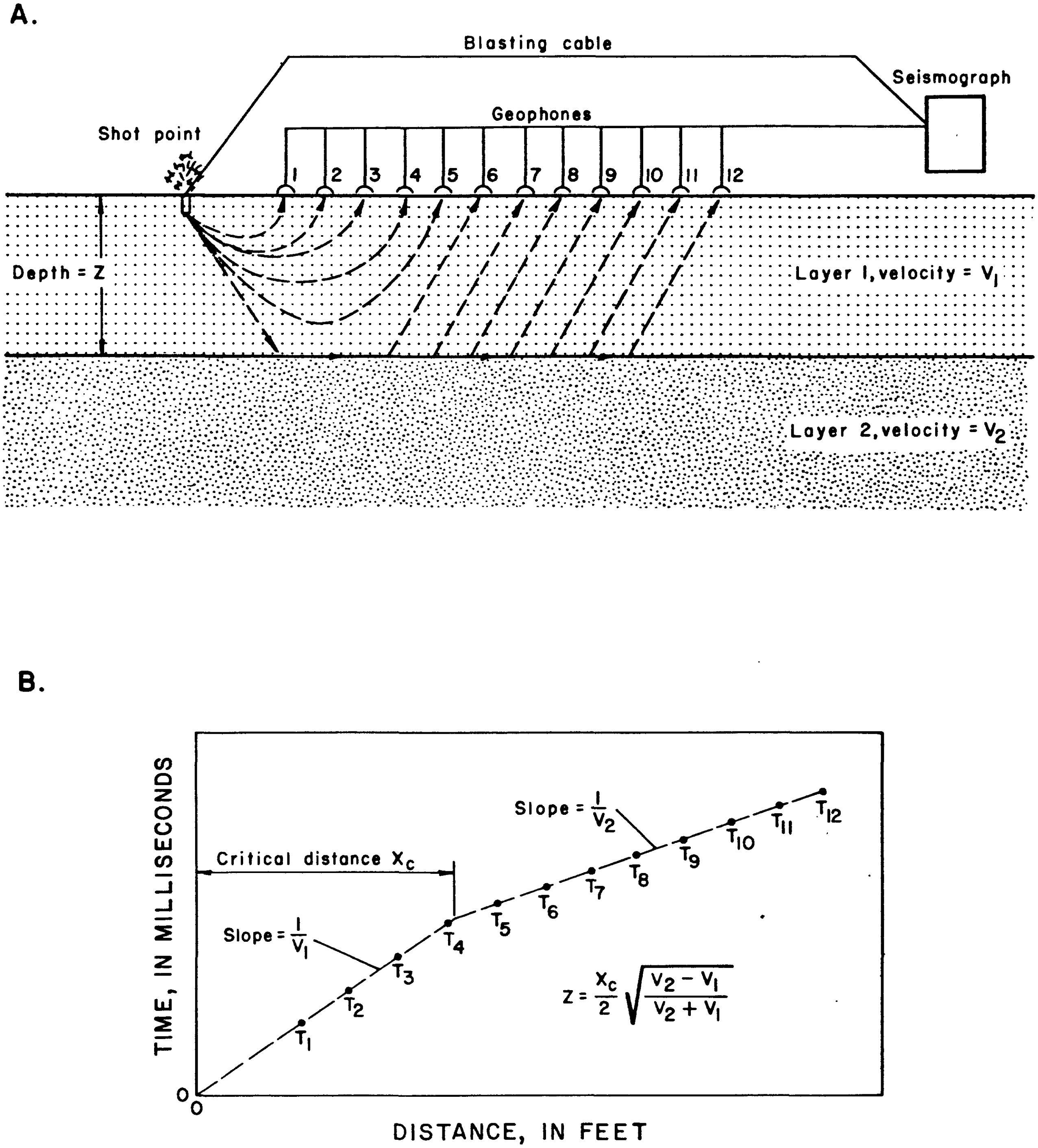


Figure 3.--A, arrangement of seismic-refraction equipment and resulting seismic-wave paths; B, time-distance relationships.

The principal requisite of the refraction method of seismic surveying is that velocity must increase with depth. If the seismic velocity in a layer is less than that of an overlying layer, the seismic wave cannot be refracted at the critical angle along the interface between the two layers and thus be returned to the geophones. Where this velocity inversion occurs, the seismic wave is refracted downward until a layer with a greater seismic velocity is encountered. The presence of a low-velocity layer will not show on a time-distance curve and will lead to errors in the computation of depths for all layers below it, because its thickness will not be taken into account in the calculations.

Seismic-refraction surveying provides the most reliable data in areas where there are only two or three layers, where large velocity contrasts exist between the layers, and where geological conditions are relatively simple. In areas where only slight velocity contrasts occur and/or where more complicated geologic conditions exist, interpretation of seismic data may be more difficult. A summary of most of the problems that may be encountered in seismic-refraction surveying is given by Zohdy and others (1974, p. 73-76).

Electrical-Resistivity Method

The electrical-resistivity method of geophysical surveying is based on the fact that different earth materials usually have different electrical resistivities. These resistivities depend upon the composition of the material, its porosity, and the quantity and physical properties of the fluids in the pore spaces. A concise discussion of the theory and application of electrical-resistivity methods is presented by Zohdy and others (1974), and more detailed information is provided by Bhattacharya and Patra (1968).

Electrical-resistivity determinations are made by passing a constant electric current, I, into the ground through a pair of current electrodes and measuring the potential difference, ΔV, across a pair of potential electrodes. The apparent resistivity, ρ_α, is calculated using the following equation:

$$\rho_\alpha = K \Delta V/I \qquad (1)$$

K is the geometric factor and is determined by the electrode arrangement and spacing. The value of the apparent resistivity is a function of several variables: the spacings between the electrodes; the geometry of the electrode array; and the true resistivities and other characteristics of subsurface materials, such as layer thickness and anisotropy.

There are two general methods of making electrical-resistivity surveys: horizontal electrical profiling and vertical electrical sounding (VES). In profiling, all of the electrodes are moved horizontally without changing their spacing or configuration. This method provides information on the lateral variation of resistivity values for a selected electrode spacing. Vertical electrical soundings are made by changing the positions of the electrodes with respect to a fixed sounding point. This method provides information on the vertical distribution of resistivity values in a geologic section. For this study only vertical electrical soundings were made, because information was needed on the vertical distribution of earth materials for comparison with descriptive and borehole geophysical logs.

Several different electrode arrays, designed to facilitate calculation and interpretation of apparent resistivity values, have been invented. An electrode arrangement known as the Schlumberger array was used for this study because it is suited for deep, vertical electrical soundings and because it requires less manpower and time than most other arrays. The array consists of four electrodes placed along a straight line, with the current electrodes, A and B, placed at the ends of the line and the potential electrodes, M and N, near the center (fig. 4). The distance between the potential electrodes, $\overline{MN}$, is always kept equal to or smaller than one-fifth of the distance between the current electrodes, $\overline{AB}$. When using the Schlumberger array, the geometric factor, K, is calculated using the following equation:

$$K = \pi\overline{MN}\,[(\overline{AB}/2/\overline{MN}) - 0.25] \qquad (2)$$

The electrical-resistivity method does not provide satisfactory quantitative results if the various layers of earth materials are thin relative to depth, because either cumulative effects are obtained or anomalous resistivities are measured, which are difficult or impossible to interpret. Similarly, results may not be satisfactory if the differences between the resistivity values of the beds are sufficiently large. Because of the interpretive techniques that commonly are used, the method generally provides the most detailed data on earth materials near the land surface, and becomes increasingly less sensitive with depth.

Study Area

Field work was done in a 225-square-mile area that includes parts of northeastern Garfield, south-central Holt, and northwestern Wheeler Counties, Nebraska (fig. 5). The area was selected because the soils, topography, and hydrogeology are reasonably representative of conditons in the eastern one-half of the Sand Hills region, and because sufficient geologic and hydrologic data are available to make it possible to assess the validity and reliability of interpretations made from surface geophysical measurements. Most of the study area also is within that part of the Sand Hills region where a detailed investigation of the water and related resources currently (1985) is being conducted by the Nebraska Natural Resources Commission (1984). This study by the Commission is a part of the State Water Planning and Review Process.

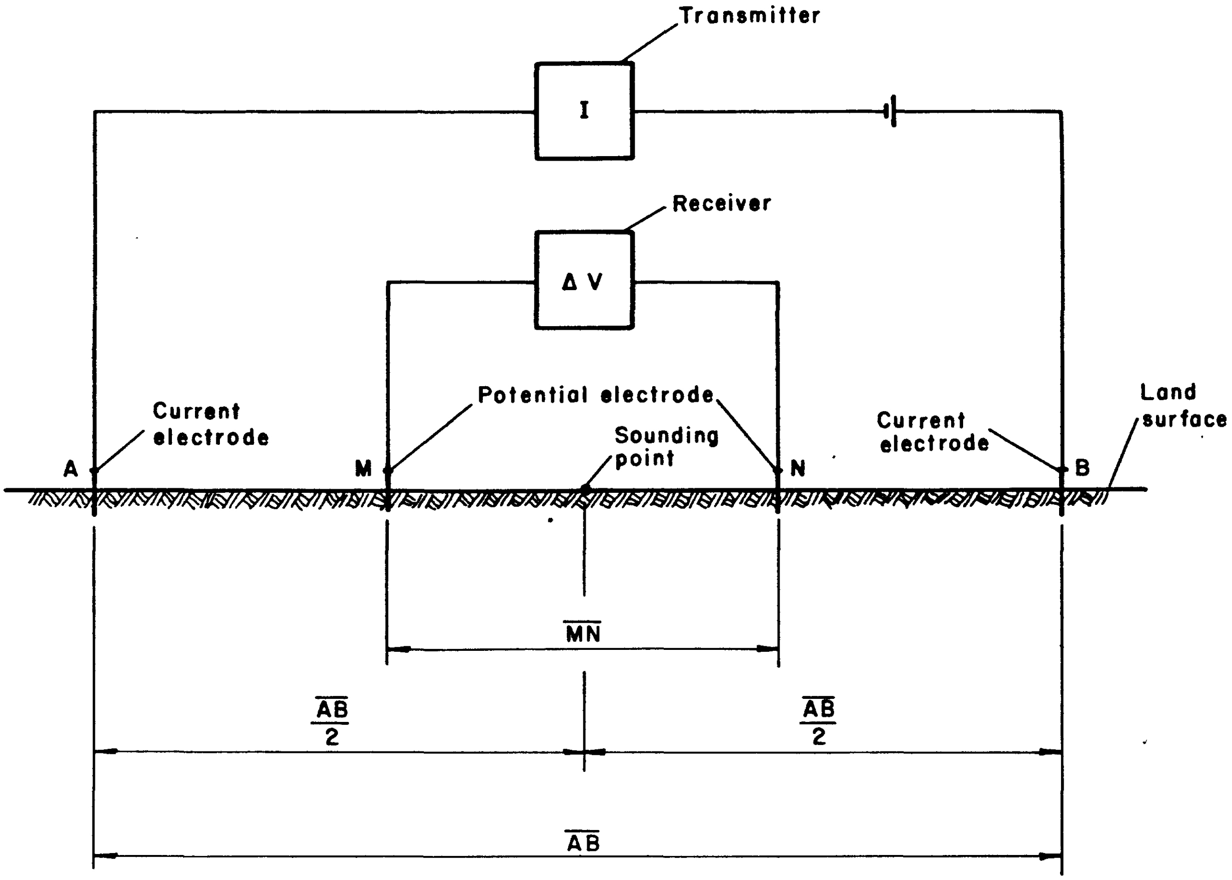


Figure 4.--Schlumberger array used for vertical electrical soundings showing equipment arrangement and distances used in calculations.

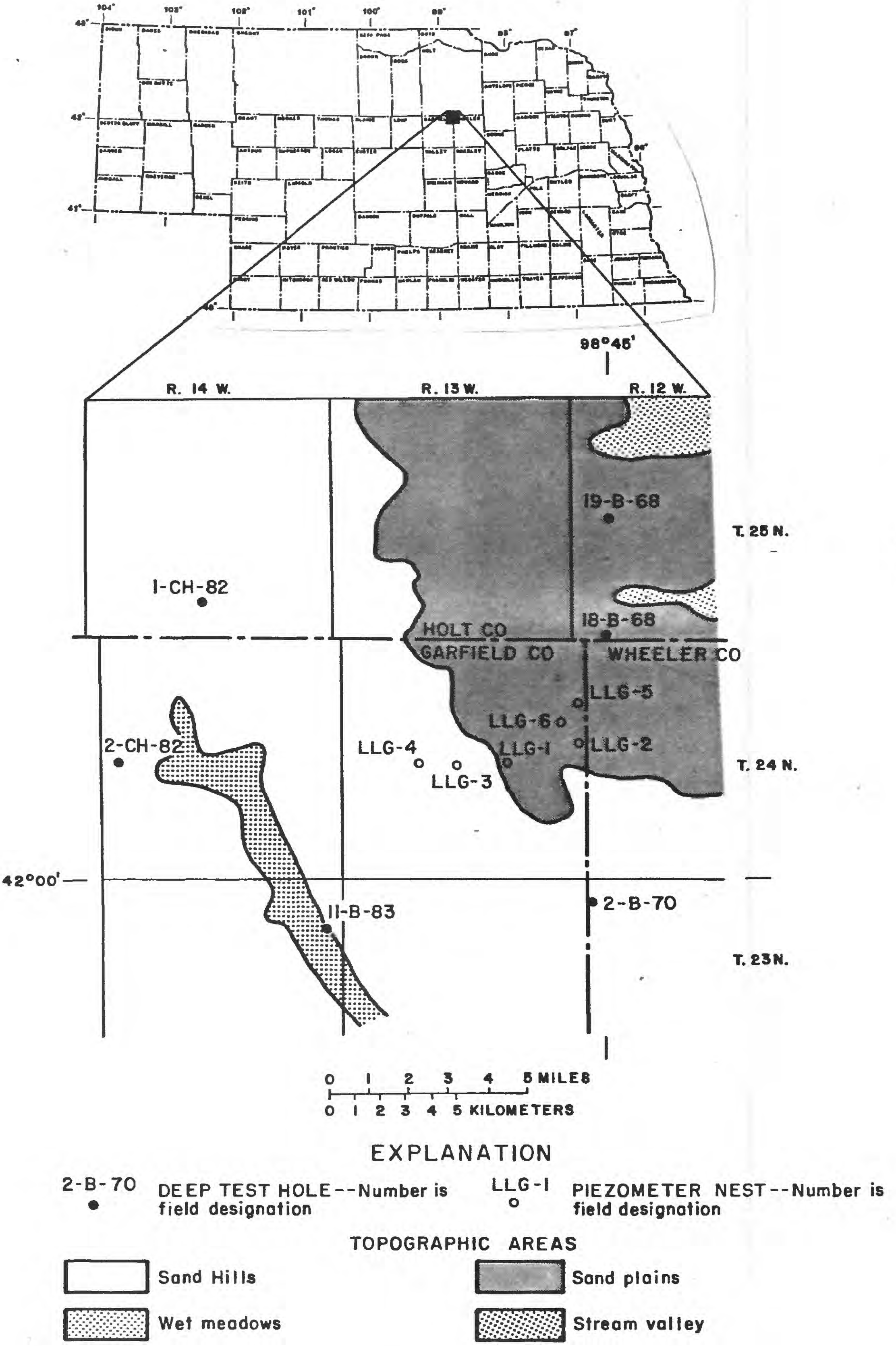


Figure 5.--Location of study area, deep test holes, piezometer nests, and topographic areas.

Published information on the hydrogeology of the area included in this study is contained in reports describing the Elkhorn River basin (Newport, 1957, and Bentall and others, 1971) and the Loup River basin (Sneigocki, 1959). These are reconnaissance-level reports and provide only generalized hydrogeologic information. Well logs resulting from test-hole drilling programs and from the installation of piezometer nests have not been published but are available in the files of the Conservation and Survey Division of the University of Nebraska's Institute of Agriculture and Natural Resources.

Acknowledgments

The authors appreciate the assistance of Richard Beran, Manager of the Lower Loup Natural Resources Distrit, who researched land ownership and obtained permission for access to parts of the area where this study was conducted. Unpublished water-quality and water-level data pertaining to the piezometer nests were made available by Dennis R. Lawton, Conservation and Survey Division, University of Nebraska-Lincoln (written commun., 1984). These data were collected by the Lower Loup Natural Resources District and the Conservation and Survey Division. The authors also wish to acknowledge the cooperation of landowners who allowed us access to their land and allowed us to store equipment on their property.

HYDROGEOLOGY OF THE STUDY AREA

The study area is in the eastern part of the 19,300-square-mile Nebraska Sand Hills region, described by Keech and Bentall (1971). This region is the largest sand-dune area in the Western Hemisphere, and includes all or parts of 25 counties in Nebraska and parts of 3 counties in South Dakota. This region of grass-stabilized sand dunes is unique, not only in its size and geomorphology, but also in its hydrology. Because most of the surficial material is very permeable, most precipitation infiltrates into the ground at or very near the point at which it falls and there is amost no overland runoff. The many perennial streams and lakes that occur in the region are maintained by natural ground-water discharge.

The eolian sands of Holocene age (Ahlbrandt and others, 1983) that occur in the study area are underlain by deposits of Pleistocene and Tertiary age. Most of these deposits are sand-size material; however, as might be expected with deposits laid down by fluvial systems, there are large spatial variations in composition and permeabilities. Cretaceous deposits, generally consisting of shale, underlie the younger deposits throughout the study area. A generalized description of Quaternary, Tertiary, and Cretaceous deposits that occur in the study area is given in table 1.

Table 1.--Summary of the hydrogeology of Quaternary, Tertiary, and Cretaceous deposits that occur in the study area

SYSTEM	SERIES	FORMATION	LITHOLOGY AND THICKNESS	HYDROLOGY
Quaternary	Holocene	Eolian deposits	Well sorted, very fine to medium grained quartz sand. Generally is less than 30 feet thick, but may be as much as 100 feet thick in some dune areas.	Very permeable, allows for rapid infiltration of precipitation.
		Lacustrine deposits	Silty and sandy clay containing organic matter. Usually less than 2 feet thick.	Ranges from slightly permeable to moderately permeable; however, due to limited extent, the deposits have only a very localized effect on the hydrology.
		Alluvial deposits	Generally cannot be differentiated from eolian deposits; however, along some of the larger streams some sand and gravel deposits can be recognized. No data on thickness are available.	Moderately permeable to permeable; because of limited extent, the deposits are not hydrologically significant in the study area.
	Pleistocene	Undifferentiated alluvial and eolian deposits	In descending order, generally consists of sandy silt and clay, silt and clayey silt, and sand and gravel beds. Thickness ranges from 150 to 400 feet.	Ranges from slightly permeable to very permeable. All deposits are saturated below the water table; however, silt and clay beds may be local semiconfining layers. Basal sand and gravel beds are the principal source of water in the Sand Hills region.
Tertiary	Miocene	Ogallala Formation	Predominantly fine to medium grained sandstone, but local interbeds of clay, limestone, and poorly consolidated sand and gravel are common. Thickness ranges from 150 to 300 feet.	Ranges from moderately permeable to very permeable. Usually has good hydraulic connection with overlying deposits. In areas where there is insufficient saturated thickness in overlying deposits, the formation is the major source of water.
Cretaceous	Upper Cretaceous	Pierre Shale	Shale. Thickness ranges from 300 to 500 feet.	Relatively impermeable, and forms base of aquifer system.

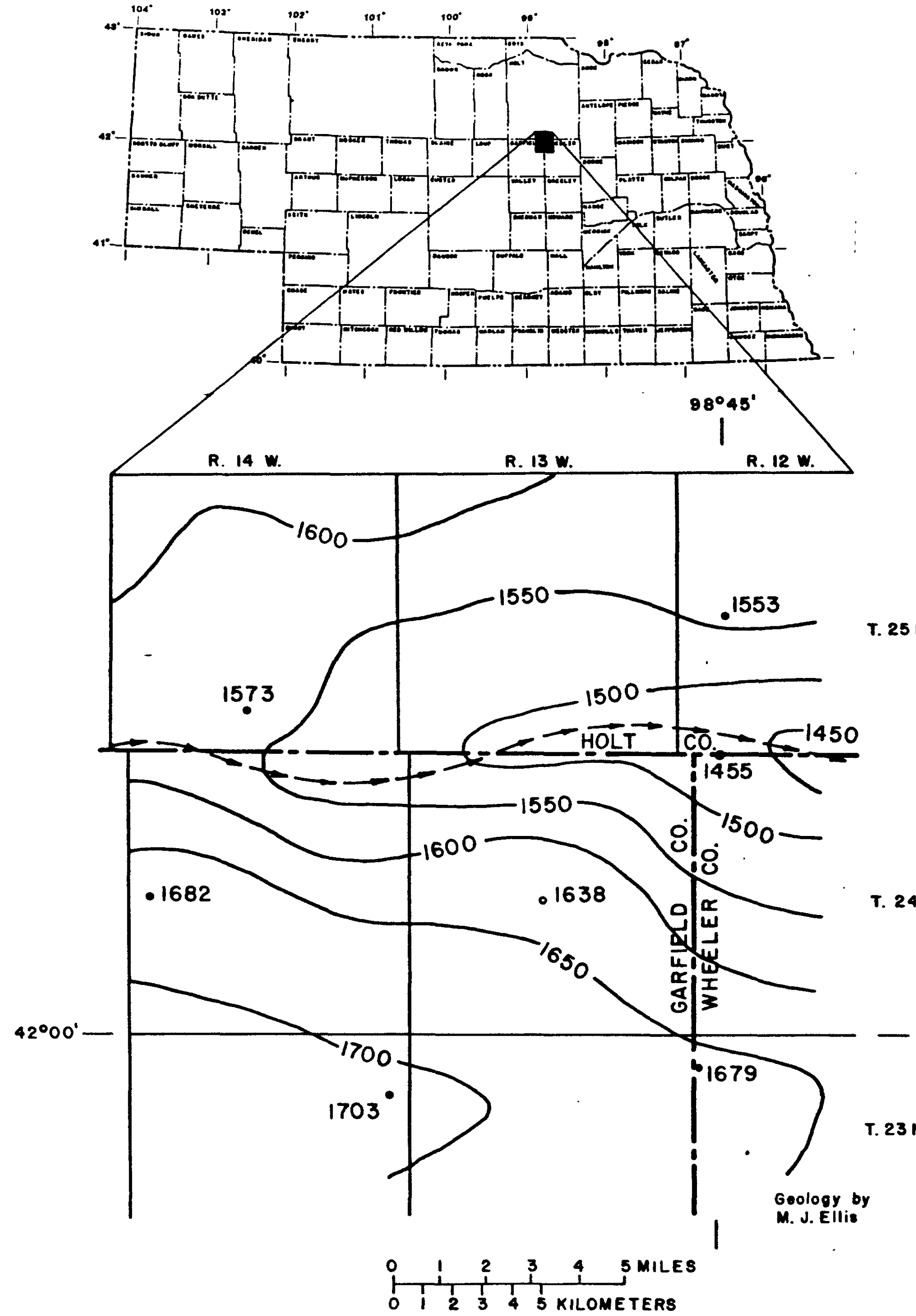
The aquifer in the study area, as considered in this report, consists of the Ogallala Formation and the unconsolidated deposits of Quaternary age that overlie the Ogallala. The aquifer can be divided into four major hydrogeologic units. These units, in ascending order, are the Ogallala Formation, sand and gravel beds of Pleistocene age, silt beds of Pleistocene age, and eolian deposits of Holocene age. Alluvial and lacustrine deposits of Holocene age are present in the study area, but they are not considered in this report because they are very thin and have a very restricted areal extent.

Generally, the base of the aquifer is the top of the Pierre Shale, which is the uppermost formation of Cretaceous age in the area. The top of the aquifer is the land surface, and the water table generally is 0-40 feet below the land surface. Recharge to the aquifer is from infiltration of precipitation and water applied for irrigation. Discharge from the aquifer occurs as seepage into streams and lakes; evapotranspiration; and pumpage for domestic, stock, and irrigation supplies. Available data indicate that movement of water within the aquifer is a complex phenomenon involving local, intermediate, and regional flow systems (Toth, 1963).

A local flow system has its recharge area at a topographic high and its discharge area at a topographic low that are located adjacent to each other. The occurrence of these local flow systems is common throughout the study area, especially in areas of dune topography. The aquifer is recharged under the dunes and discharges in the many interdune depressions and valleys. Most of the local flow systems are shallow and occur in the eolian deposits and silt beds. The major characteristic of intermediate flow systems is that, although their recharge and discharge areas do not occupy the highest and lowest altitudes, respectively, in the area, one or more topographic highs may be located between them. Within the study area, most intermediate flow systems probably occur in the deposits overlying the Ogallala Formation. The lateral extent of regional flow systems in the area is unknown, but they probably involve movement of ground water through the entire thickness of the aquifer. A single regional flow system may underlie the entire area, or the major streams and their drainage divides may define the limits of several regional flow systems.

Cretaceous Pierre Shale

Based on data from nearby oil test holes, it is estimated that the thickness of the Pierre Shale in the study area ranges from about 300 to about 500 feet. Most, if not all, of this variation in thickness probably is a result of post-depositional erosion. There is more than 250 feet of relief in the surface of the Pierre (fig. 6). Available data indicate that the top of the Pierre Shale ranges between about 500 and 750 feet below the land surface. Virtually no information is available on the physical properties of the Pierre in the study area. However, data from borehole geophysical logs run in oil test holes that have been drilled in the vicinity of the study area do provide some approximate values. These logs indicate the resistivity of the shale ranges between 10 and 20 ohm-meters, and that seismic velocities in the Pierre range between 6,400 and 6,600 feet per second.



EXPLANATION

1573 ●	DEEP TEST HOLE--Number is altitude of the top of the Pierre Shale, in feet above National Geodetic Vertical Datum of 1929
○ 1638	PIEZOMETER NEST--Number is the altitude of the top of the Pierre Shale, in feet above National Geodetic Vertical Datum of 1929
—1600—	STRUCTURE CONTOUR--Shows altitude of the top of the Pierre Shale. Contour interval 50 feet. National Geodtic Vertical Datum of 1929
→—→—→	AXIS OF BURIED VALLEY

Figure 6.--Configuration of the top of the Pierre Shale.

At some locations within the study area the basal 5 to 10 feet of the Ogallala Formation are very silty and clayey. Therefore, locally, the effective base of the aquifer may be slightly higher than the top of the Pierre.

Tertiary Ogallala Formation

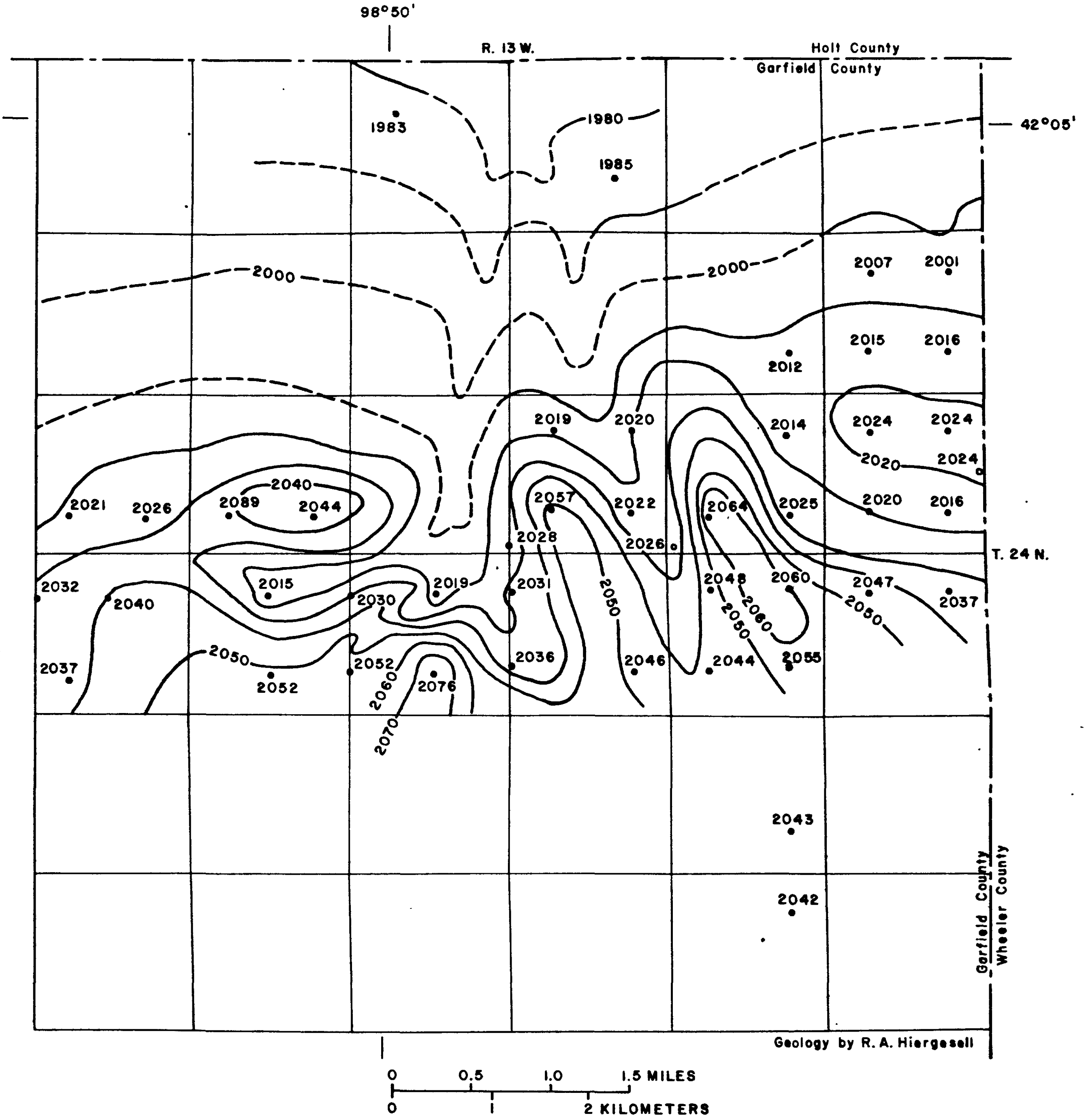
The thickness of the Ogallala Formation in the study area ranges from 250 to 550 feet, with the greatest thicknesses generally occurring along the trend of the buried valley shown in figure 6. For the most part, the Ogallala consists of sand and poorly consolidated sandstone. However, some thin sandy silt beds (less than 20 feet thick) occur throughout the formation and a few very thin clayey silt beds (less than 5 feet thick) occur in the basal 100 feet of the formation.

Sufficient data to define either the thickness of the Ogallala or the configuration of the top of the formation for the entire study area are not available. However, in the northeastern-most township of Garfield County (T.24 N., R.13 W.), a large number of driller's logs for irrigation wells are available. Using data from these logs to supplement data from detailed geologic and borehole geophysical logs for the piezometer nests, which are located in the same township, the configuration of the top of the Ogallala Formation in most of the northern two-thirds of the township was defined (fig. 7). This map was prepared to assist in the evaluation of data from seismic surveys.

Data on the physical properties of the Ogallala Formation, which would help in the interpretation and evaluation of surface geophysical data, are scant. Borehole geophysical logs that were run in an oil test hole drilled about 10 miles south-southwest of the study area include information on the basal 40 feet of the Ogallala. Data from these logs indicate that the resistivity of the basal part of the formation ranges between 40 and 60 ohm-meters and the seismic velocity in the basal part of the Ogallala is about 5,700 feet per second.

Pleistocene Sand and Gravel Beds

The Pleistocene sand and gravel beds in the study area range in thickness from 20 to 220 feet. Because they were deposited on an erosional surface and were subjected to post-depositional erosion, large lateral variations in thickness occur within short distances. The composition of the beds also is quite variable. At some locations, the beds may consist entirely of intermixed sand and gravel, and at other locations sand beds may be interbedded with the sand and gravel, or beds of intermixed sand and gravel may be interbedded with thick sand deposits. Borehole-geophysical logs and geologic logs indicate that thin beds of silt or clay (usually less than 2 feet thick) occur at some locations. The top of sand and gravel beds usually is 50-170 feet below the land surface.



EXPLANATION

● 2040 IRRIGATION WELL--Number is altitude of the top of the Ogallala Formation, in feet above National Geodetic Vertical Datum of 1929

○ 2028 PIEZOMETER NEST--Number is altitude of the top of the Ogallala Formation, in feet above National Geodetic Vertical Datum of 1929

——1980——— STRUCTURE CONTOUR--Shows altitude of the top of the Ogallala Formation Dashed where approximately located. Contour interval 10 feet. Nation Geodetic Vertical Datum of 1929.

Figure 7.--Configuration of the top of the Ogallala Formation in the northeastern-most township of Garfield County.

Information is not available that would provide some indication of reasonable seismic velocities in the deposits, and the only data pertaining to electrical resistivities are the results of chemical analyses of water from the sand and gravel beds. Resistivities of the few analyses that are representative of water from the sand and gravel beds ranged between 40 and 70 ohm-meters.

Pleistocene Silt Beds

In the study area, the thickness of the silt beds of Pleistocene age ranges from 30 to 150 feet. These beds are predominantly sandy silt; however, interbedded sand layers 5-20 feet thick are common; and, locally, clayey silt beds 5-15 feet thick occur. The top of the silt beds generally ranges between 5 and 100 feet below the land surface.

Although the presence of the silt beds is common throughout much of the eastern one-third of the Nebraska Sand Hills region, no information as to their continuity or extent is available. The presence of these beds, at least locally, may significantly retard recharge to underlying beds that are the principal sources of ground water in the area. Also, the beds may significantly affect the movement of contaminants into the aquifer.

Available water-quality data indicate that resistivities of water from the interbedded sand that occur in the silt beds range from 43 to 87 ohm-meters. No water-quality data are available for the silt beds.

Holocene Eolian Deposits

The eolian deposits of Holocene age are the surficial deposits throughout the study area, except for the small areas where thin alluvial or lacustrine deposits of Holocene age occur. Where the topography of the study area is predominantly sandhills (fig. 5), the eolian deposits consist almost entirely of fine-grained sand. In the other topographic areas, some clay and silt are mixed in with the sand or occur as thin interbeds. The thickness of the eolian deposits ranges between 5 and 100 feet.

Information on physical properties of the eolian deposits, which is pertinent to the evaluation of surface-geophysical measurements, is not available. No water-quality data are available for the eolian deposits.

DATA COLLECTION AND INTERPRETATION

Seismic-refraction surveys were made at six sites in the study area and electrical-resistivity soundings at eight sites. All of the sites, except where one seismic survey was made, were adjacent to either a piezometer nest or a test hole. The location of all piezometer nests and test holes in the study area is shown in figure 5. Selection of sites used in this study was based on their accessibility and on the availability of hydrogeologic data. For convenience, test-hole and piezometer-nest field numbers have been used in the descriptions of field work and in the interpretation and evaluation of field data. The seismic-refraction survey site not adjacent to a piezometer nest or test hole is located in the SW1/4 NW1/4 SE1/4 SW1/4 sec. 23, T.24 N., R.13 W. and is referred to in this report as the "water-table site." A listing of the selected sites that are adjacent to a piezometer nest or a test hole and the geophysical methods used at each site is given in table 2.

Table 2.--Summary of geophysical methods used at selected sites adjacent to a piezometer nest or a test hole

Field number		Geophysical method	
Piezometer nest	test hole	Seismic-refraction	Electrical-resistivity
LLG-1	--	X	X
LLG-2	--	X	X
LLG-3	--	X	X
LLG-4	--	X	X
LLG-5	--	X	X
--	2B-70	--	X
--	1CH-82	--	X
--	11B-83	--	X

Seismic-Refraction Data

All of the seismic-refraction surveys were made in that part of the study area where the piezometer nests are located (fig. 5), because data indicated the most reliable information from seismic surveys probably would be for deposits in the upper part of the aquifer, and that logs of piezometers and irrigation wells in this part of the study area would provide a reliable basis for evaluation of the seismic data. In all of the surveys that were made, 12 geophones were utilized. Information describing the layout of the geophones and shotpoints and a summary of the first arrival times of seismic waves at the geophones for each survey is given in table 7 (located at the end of this report). Two surveys were made to verify that the method is well suited for detecting a velocity horizon that correlates closely with the water table, and five surveys were made to determine the utility of the method for detecting velocity layers below the water table.

The effectiveness of different geophone spacings was tested in the two surveys made to verify that the seismic-refraction method is well suited for detecting a velocity horizon that correlates closely with the water table. In the survey made adjacent to piezometer nest LLG-1, a combination of 5- and 10-foot geophone spacings was used. At the "water-table site," 10-foot geophone spacings were utilized. This site is located in a dune field near piezometer nest LLG-4 and is near the crest of a sand hill. Interpolations made from available data indicate the water table was approximately 25 feet below the land surface at this site when the survey was made.

Five surveys, to evaluate the utility of seismic-refraction methods for detecting deeper velocity layers, were made adjacent to piezometer nest LLG-1 through LLG-5. Spreads for these surveys were run in an approximately northerly direction with 100-foot geophone spacings. The spreads were centered on the piezometer nests. During the time when field work was being done, the water table in the vicinity of all the piezometer nests was near the land surface (2-7 feet). Under these field conditions, accurate determinations of depths to the velocity interface between the unsaturated and saturated deposits was not expectd, because the shortest shotpoint offset was 20 feet and the 100-foot geophone spacings were used.

Seismic data were analyzed by using a computer program that generates a two-dimensional model representing a layered-earth depth interpretation of the data. This computer program uses the delay-time method to obtain a first approximation of model layers and iterative ray tracing is used to refine the model. The criterion for adjusting and refining the model is that discrepancies between travel times obtained from field measurements and those obtained by computer ray tracing are minimized. The computer program, originaly developed by the U.S. Bureau of Mines, is well documented (Scott and others, 1972, and Scott, 1973). Scott (1977) made changes and improvements in the original program and developed a version of it called SIPT for use on timeshare computer systems. The latter version was used in this investigation of the Nebraska Sand Hills region.

Basic assumptions that apply to the modeling procedures used in SIPT include the following:

1. Layers are continuous for the entire length of the geophone line.
2. The seismic velocity of each layer is greater than the seismic velocity of the layer that overlies it.
3. The horizontal seismic velocity in any given layer is equal to or greater than the vertical seismic velocity.
4. Vertical and horizontal seismic velocites are constant for the entire length of the geophone line.
5. The program user determines and specifies the refraction layer that is represented by each arrival time entered.
6. The program user determines and specifies the three-dimensional coordinates of each shotpoint and geophone for which arrival times are entered.

The output from the computer analysis of seismic-refraction survey data includes a table of depths to the top of each seismic layer beneath each geophone and the average seismic velocity of each layer. These data make it possible to construct a seismic profile the length of the geophone spread that shows the thickness and average velocity of each seismic layer.

Electrical-Resistivity Data

Electrical-resistivity soundings were made adjacent to five piezometer nests (LLG-1 through LLG-5) and at three locations where test holes had been drilled (2-B-70, 1-CH-82, and 11-B-83). The $\overline{\text{MN}}$ electrode spacings ranged from 0.3 to 100 meters, and the $\overline{\text{AB}}$ electrode spacing ranged from 2.0 to 1,768 meters. Data collectd at each site are summarized in table 8 (at the back of this report), and visually smoothed VES curves for each site are shown in figures 8 through 15. The VES curves are constructed by plotting values of $\overline{\text{AB}}/2$ versus apparent resistivities on log-log paper. Unsmoothed plots consist of several curved-line segments. These segments overlap each other and usually are slightly offset where the lap occurs. The different segments correspond to the different potential electrode spacings used in making the soundings.

Data were analyzed by using computer programs (Zhody, 1974a, 1974c, and 1975) that automatically interpret Schlumberger-type VES curves, which are obtained over horizontally stratified and laterally homogeneous earth materials. The computer interpretation is made by an iterative procedure in which the observed VES curve is matched to a modified Dar Zarrouk (MDZ) curve. This MDZ curve is then solved for layer thickness and resistivities. Input data for this analysis are the apparent-resistivity values calculated from field data and their associated AB/2 values, and output includes a table of layer thicknesses and calculated true resistivities.

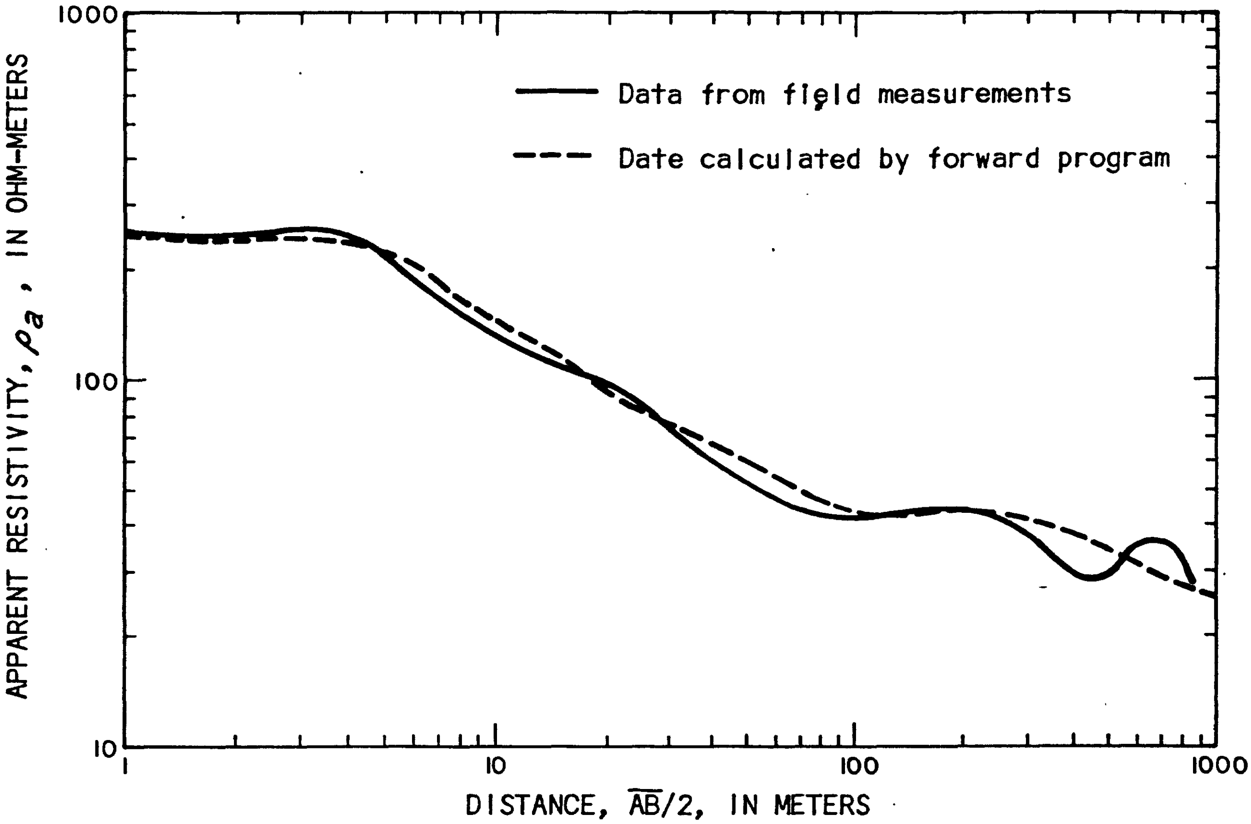


Figure 8.--Vertical electrical sounding curves at site adjacent to piezometer nest LLG-1.

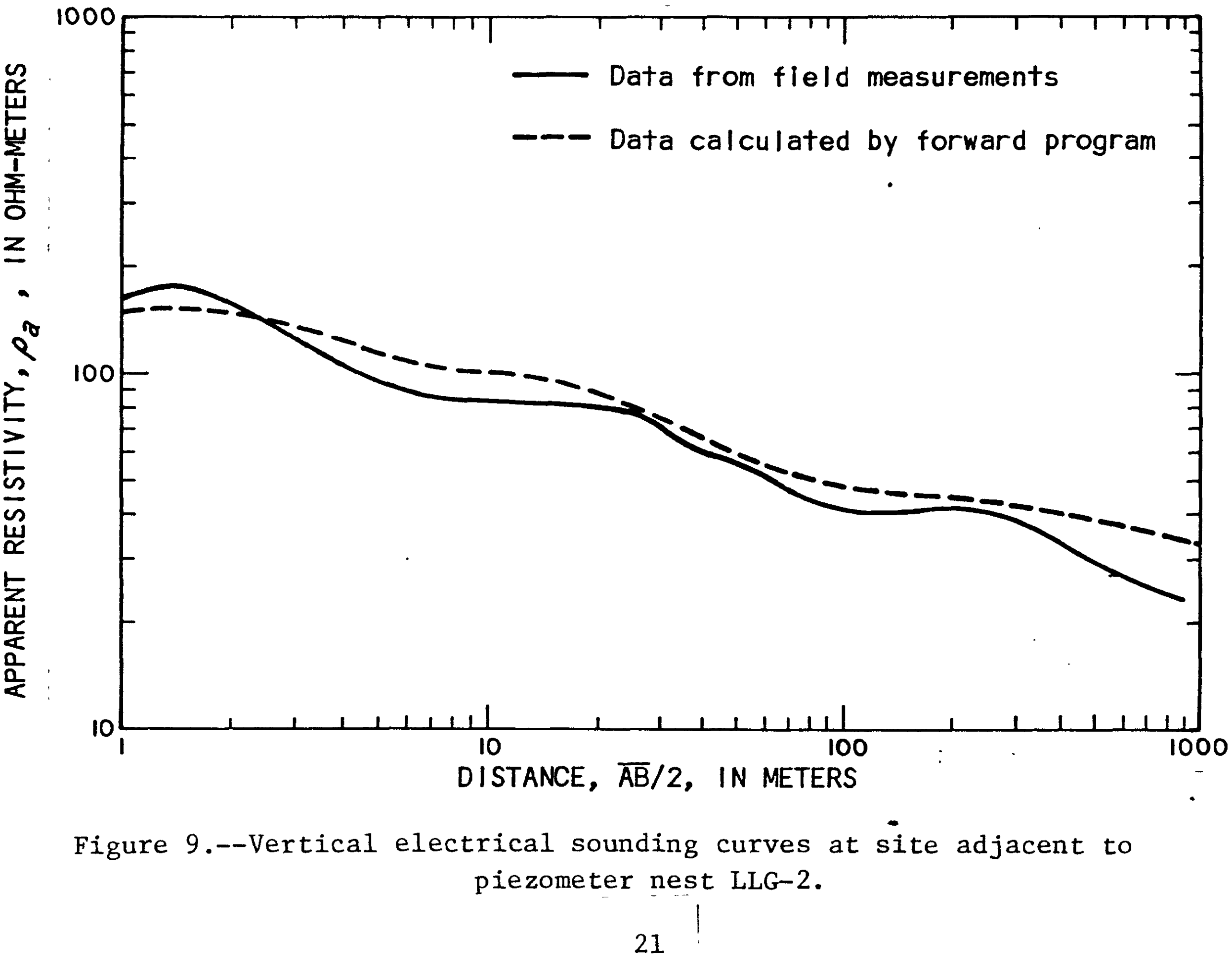


Figure 9.--Vertical electrical sounding curves at site adjacent to piezometer nest LLG-2.

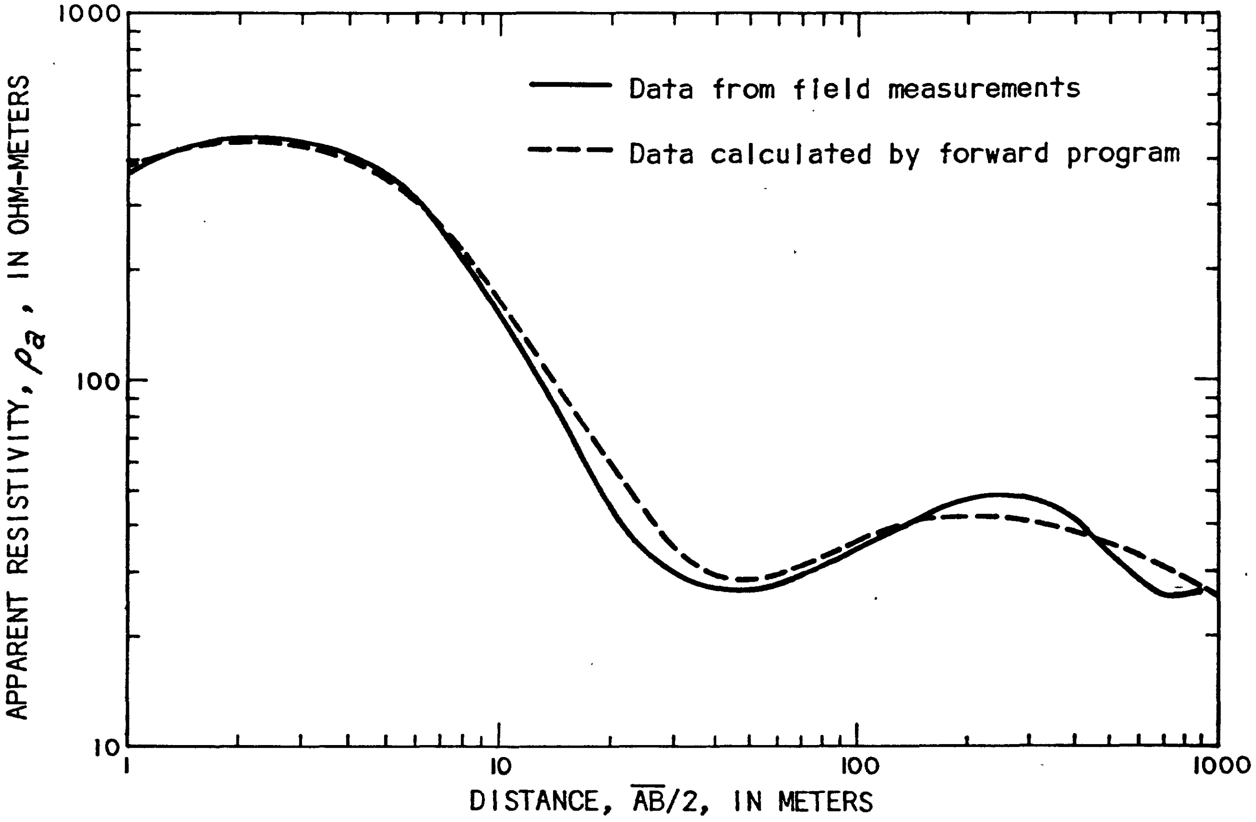


Figure 10.--Vertical electrical sounding curves at site adjacent to piezometer nest LLG-3.

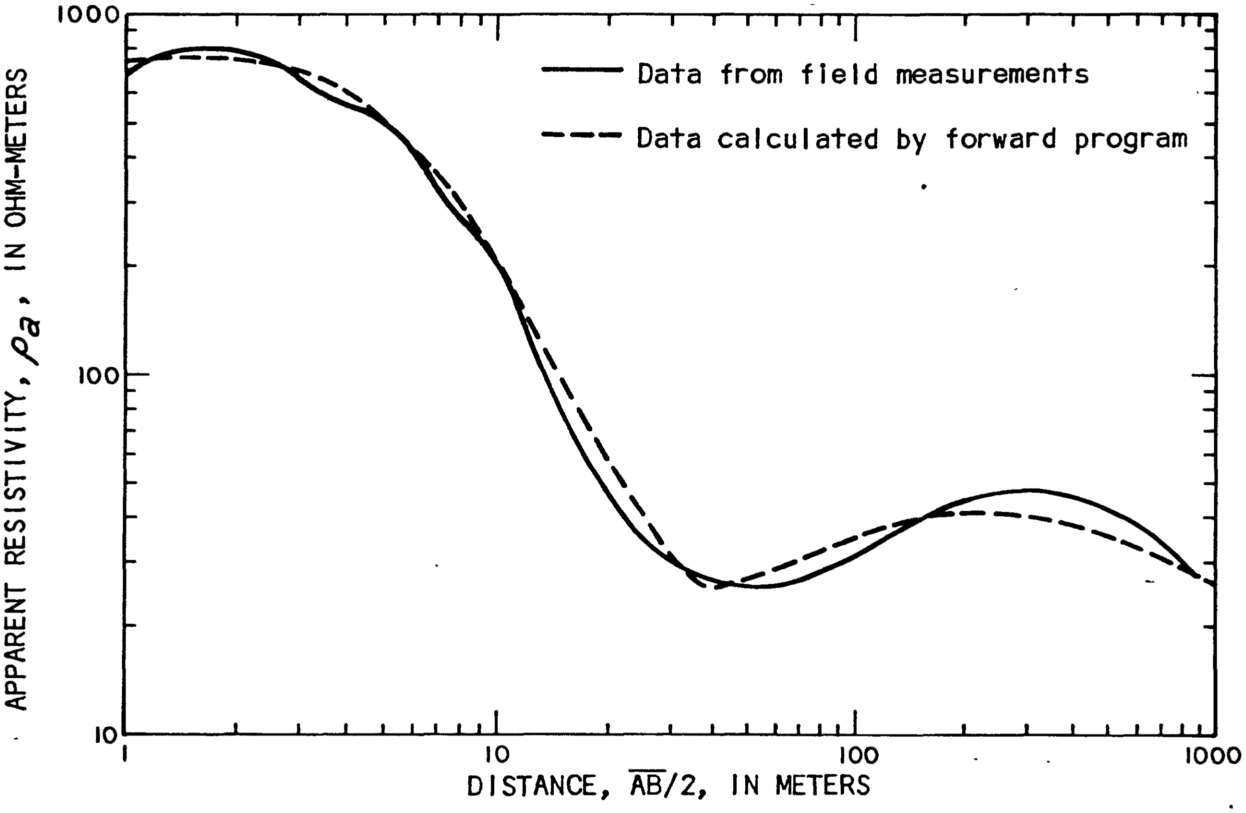


Figure 11.--Vertical electrical sounding curves at site adjacent to piezometer nest LLG-4.

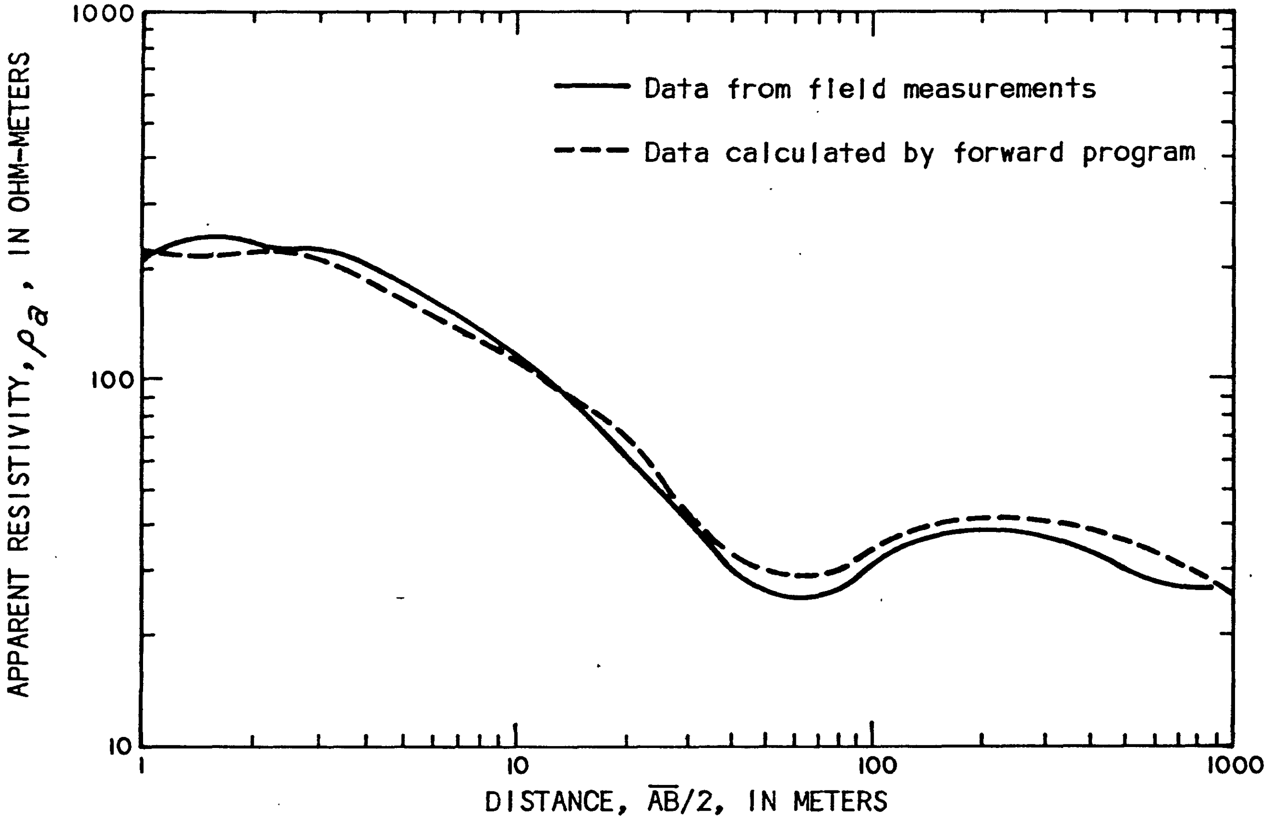


Figure 12.--Vertical electrical sounding curves at site adjacent to piezometer nest LLG-5.

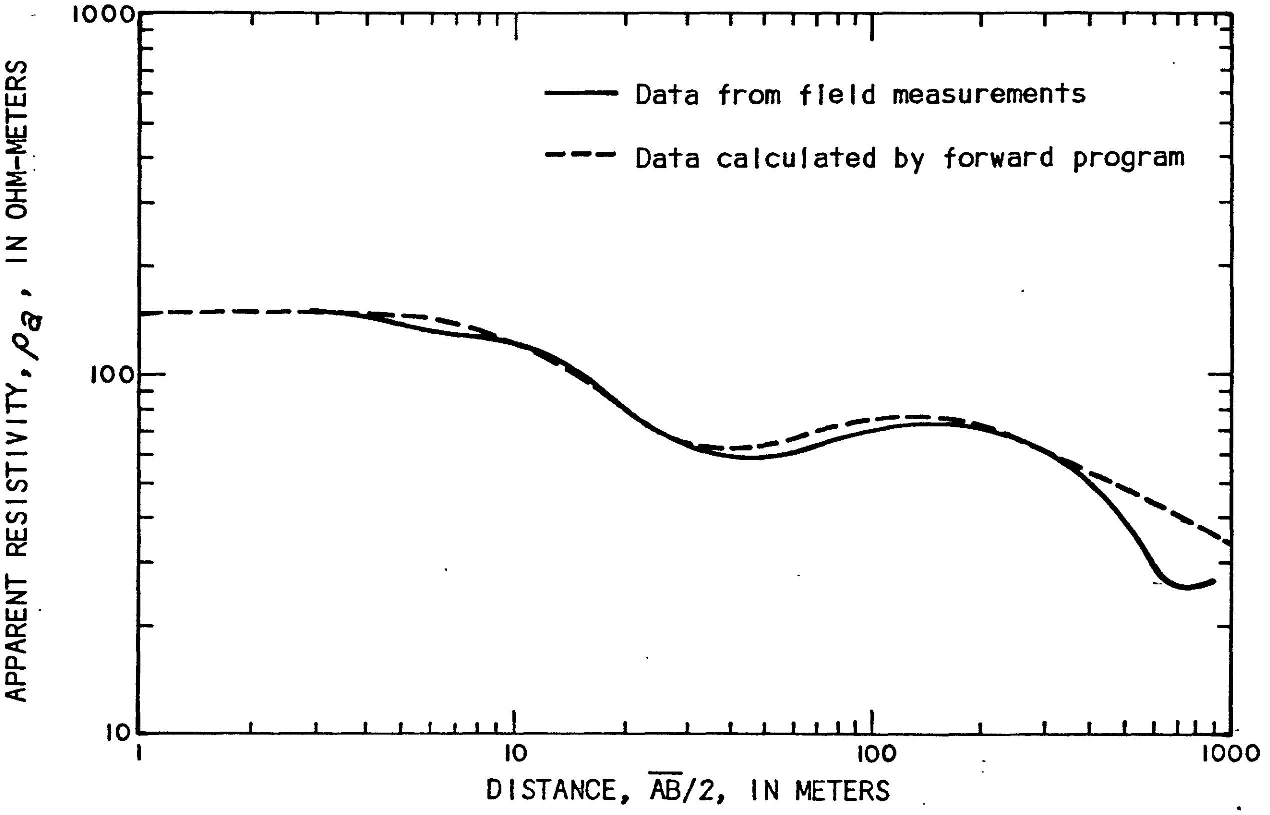


Figure 13.--Vertical electrical sounding curves at site adjacent to test hole 2-B-70.

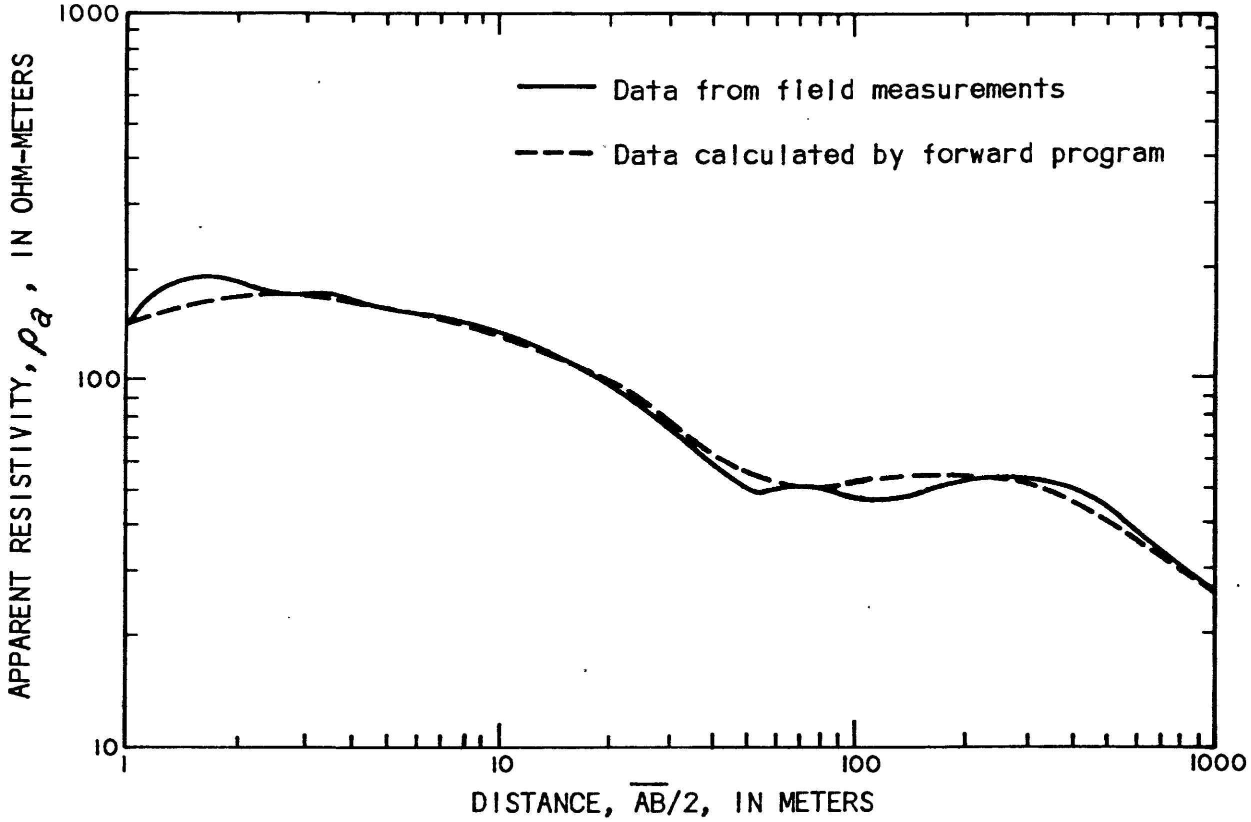


Figure 14.--Vertical electrical sounding curves at site adjacent to test hole 1-CH-82.

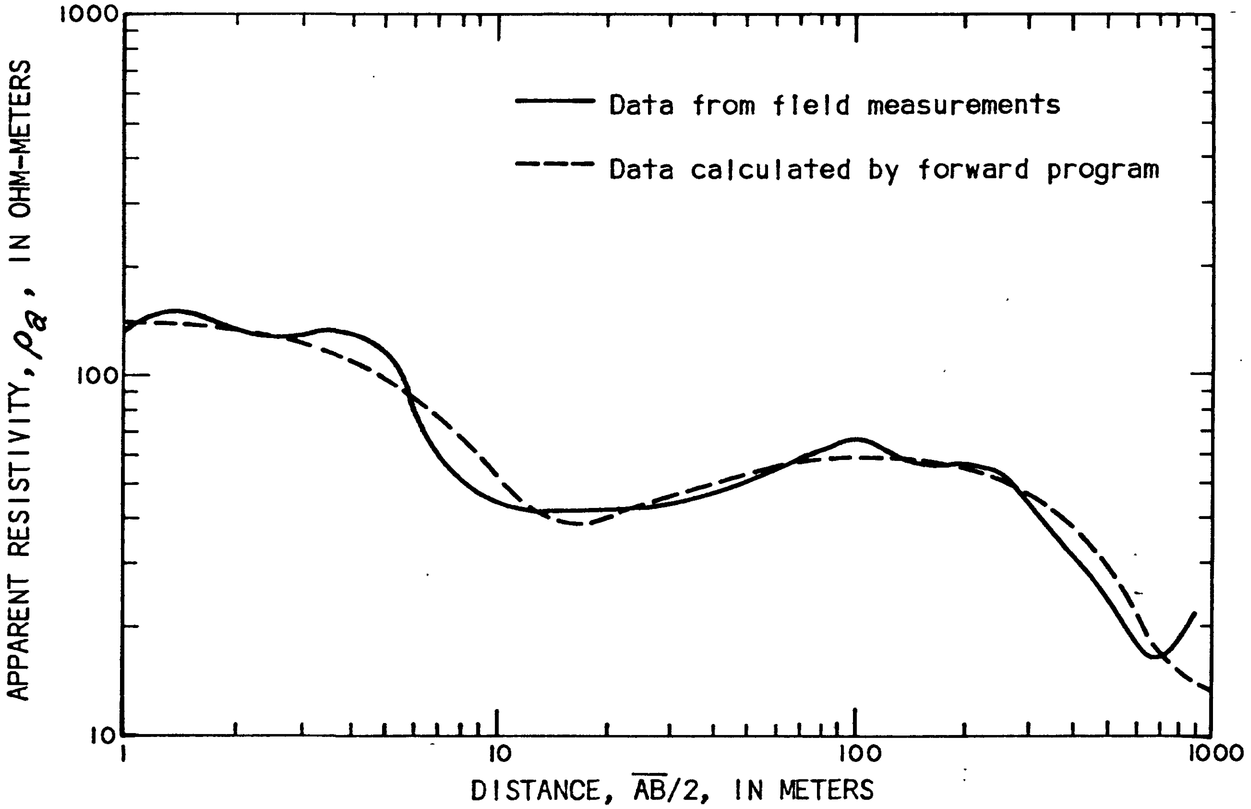


Figure 15.--Vertical electrical sounding curves at site adjacent to test hole 11-B-83.

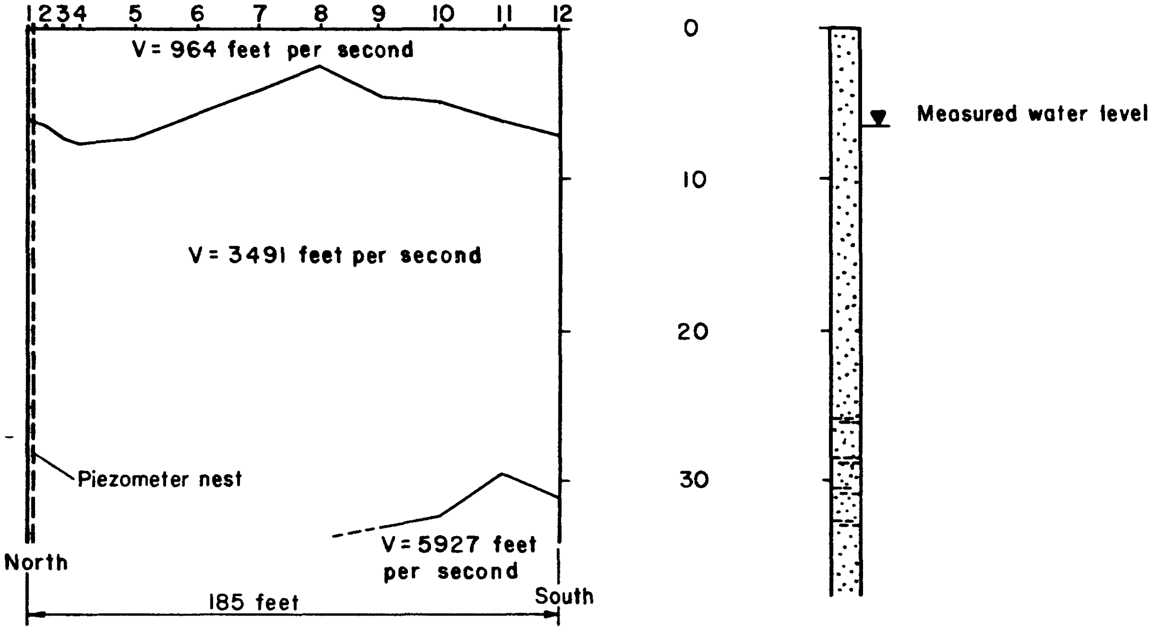
This output can be used to construct a geoelectric section that shows the thickness and calculated true resistivity of each geoelectric layer at the sounding site. Differences between modeled and actual layers of resistive material can occur, because a large number of possible combinations of layer thicknesses and resistivities can yield identical curves.

A second computer program, in which the sounding curve is calculated by convolution methods (Zohdy, 1974b), was run to evaluate the reasonableness of the computer analysis by the iterative procedure. Input into this second analysis was modifid so that it matched depths and resistivities for the Pierre Shale, estimated from hydrogeologic data. The $\overline{AB}/2$ values and corresponding resistivity values generated by the convolution method were compared with the measured data by plotting the curve defined by the generated data on the same graphs the VES field curves were plotted on (figs. 8-15). In all cases there is good correspondence between the two curves, and modification of the depth to, and the apparent resistivity of the shale bedrock did little to affect the closeness of the fit of the two curves. The similarity of the curves indicates that with the available resistivity data, iterative analysis of the data is reasonable. However, the electrical-resistivity data for the deeper layers probably is not sufficient to make a good evaluation. This is shown by the insensitivity of the convolution method to changes in the depth and the resistivity of the shale bedrock.

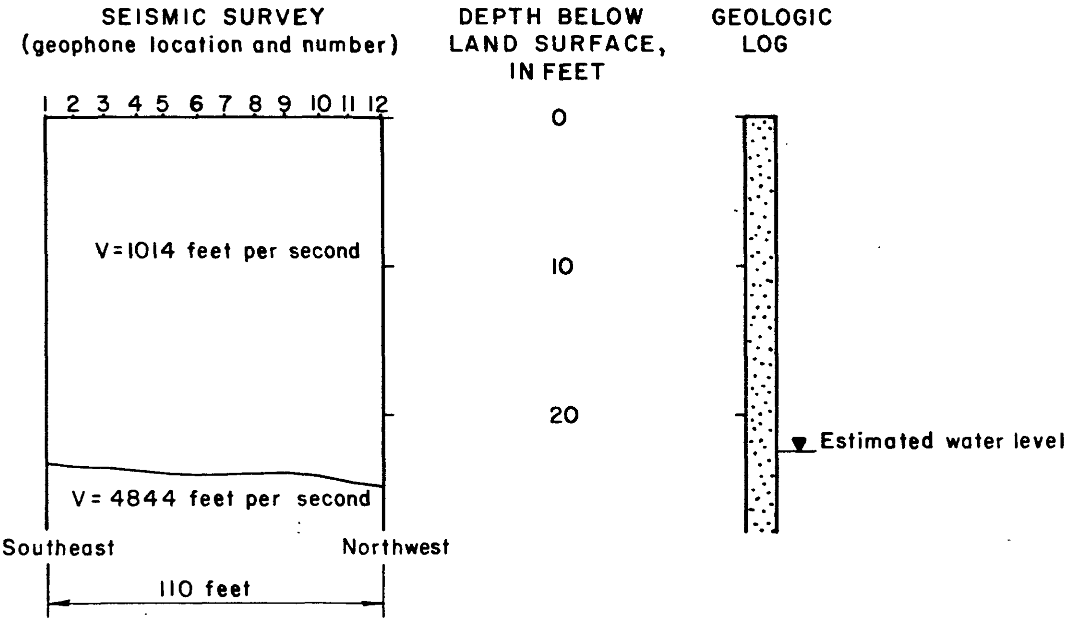
COMPARISON OF GEOPHYSICAL DATA WITH HYDROGEOLOGIC DATA

In the following discussion, results obtained from the analyses of seismic-refraction and electrical-resistivity data are compared with hydrogeologic data. Based on an evaluation of geologic and borehole geophysical data, five hydrogeologic horizons were selected as being potentially correlatable with velocity and geoelectric horizons. These hydrogeologic horizons, in descending order, are: the water table, the top of the silt beds, the top of the sand and gravel beds, the top of the Ogallala Formation, and the top of the Pierre Shale.

In order to facilitate comparison of geophysical and hydrogeologic data, the available data have been shown graphically. Data from the two seismic surveys designed to provide information on shallow horizons are shown in figure 16. Hydrogeologic, seismic-survey, and vertical electrical sounding data at sites adjacent to piezometer nests LLG-1 through LLG-5 are summarized in figures 17 through 21. The seismic data used in preparing figures 17-21 are from the seismic surveys where 100-foot geophone spacings were used. Data from vertical electrical soundings made at sites adjacent to the three test holes are compared with hydrogeologic data in figure 22.



Piezometer Nest LLG-1



Water-Table Site

Figure 16.--Comparison of water-level data and data interpretations from seismic-refraction surveys at site adjacent to piezometer nest LLG-1 and at water-table site.

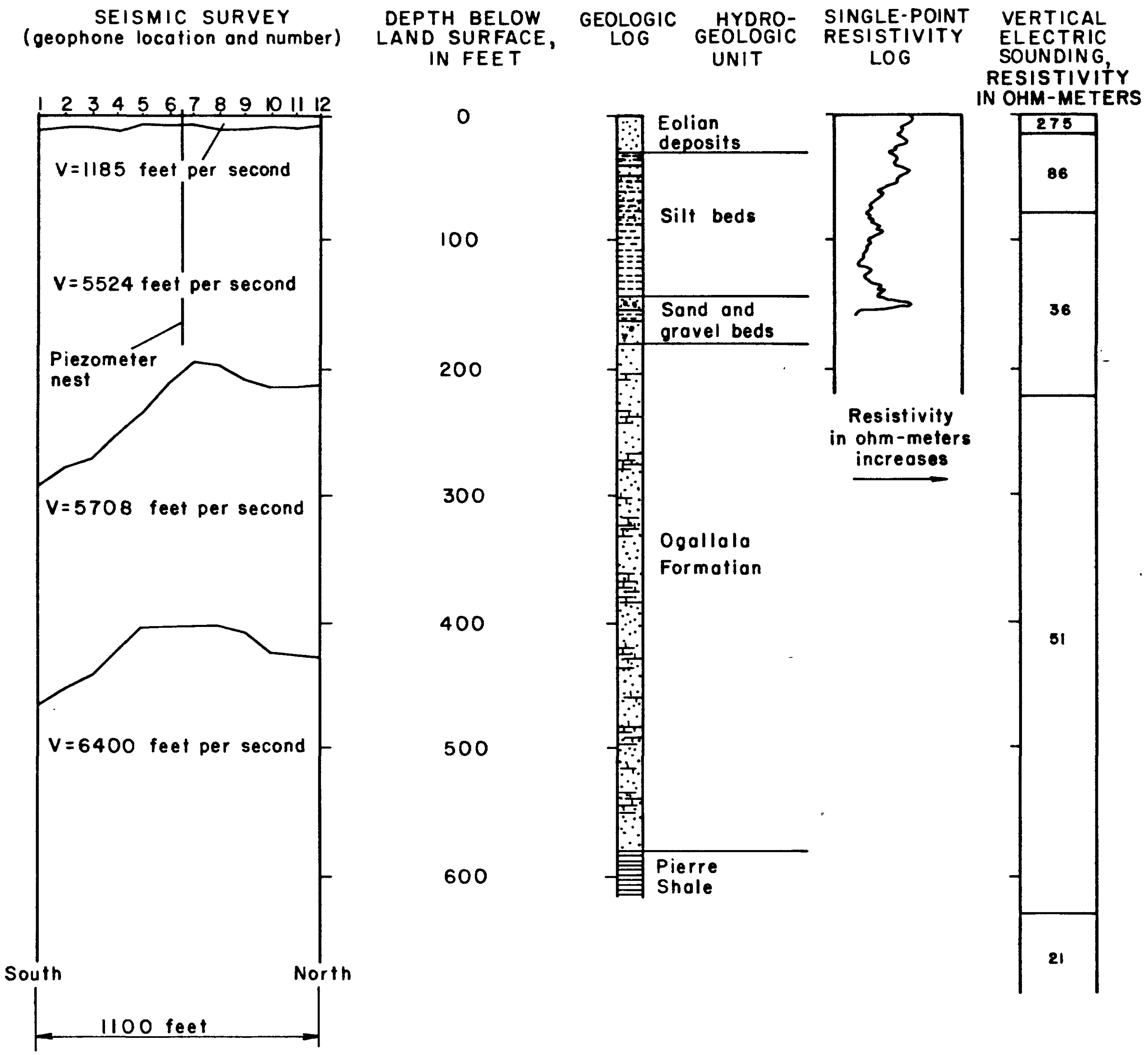


Figure 17.--Comparison of hydrogeologic data and interpretations of geophysical data at site adjacent to piezometer nest LLG-1.

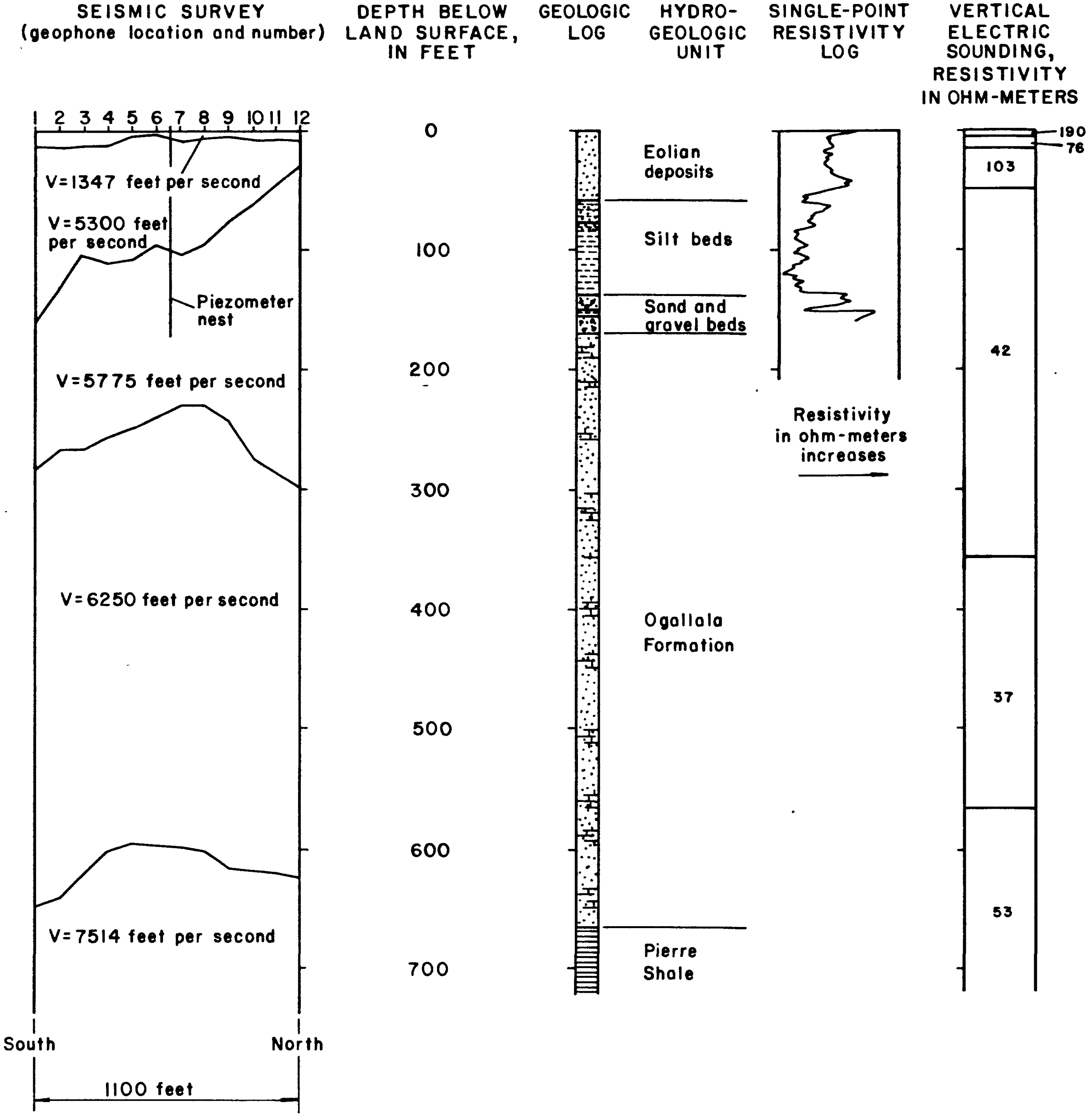


Figure 18.--Comparison of hydrogeologic data and interpretations of geophysical data at site adjacent to piezometer nest LLG-2.

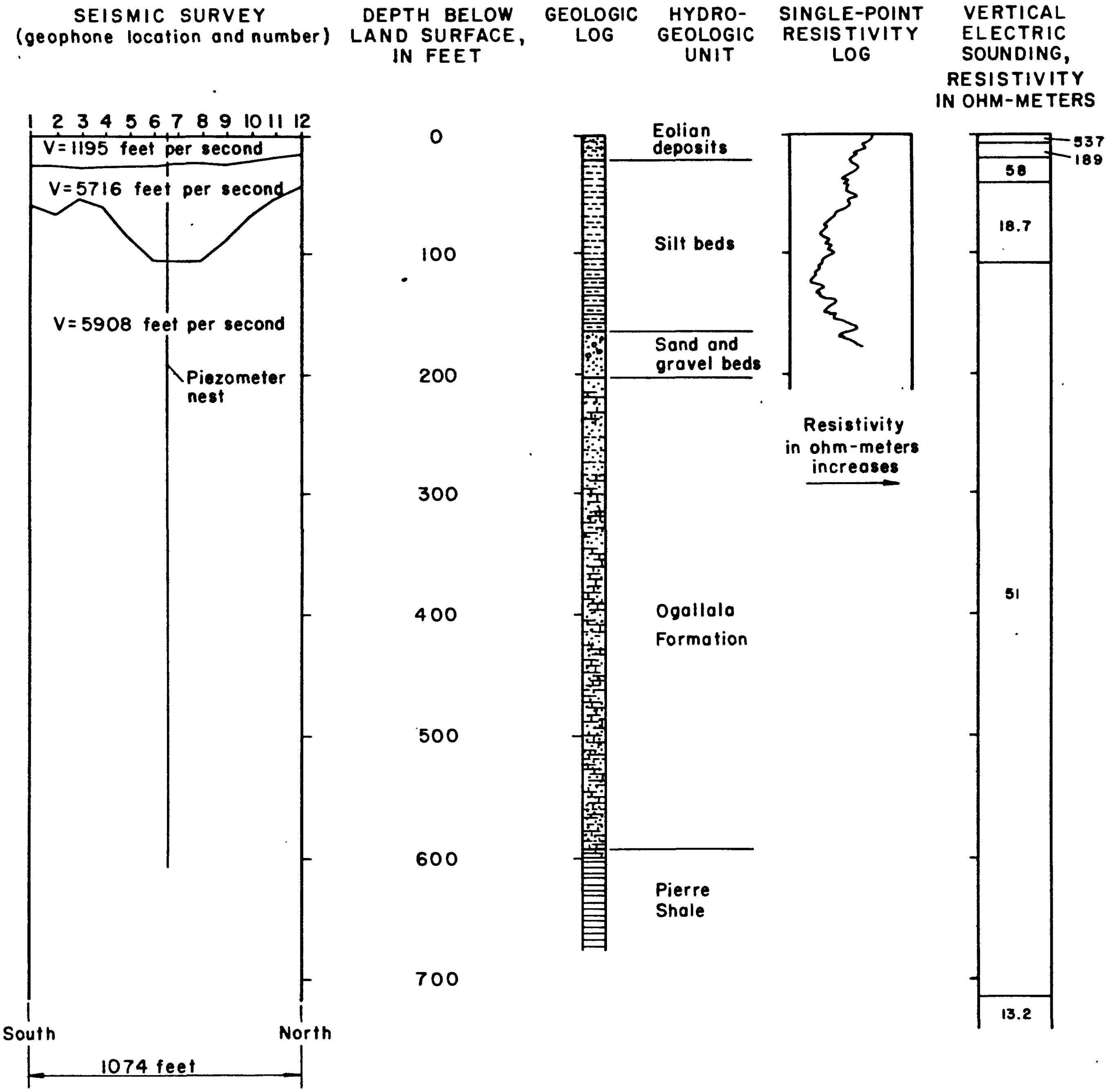


Figure 19.--Comparison of hydrogeologic data and interpretations of geophysical data at site adjacent to piezometer nest LLG-3.

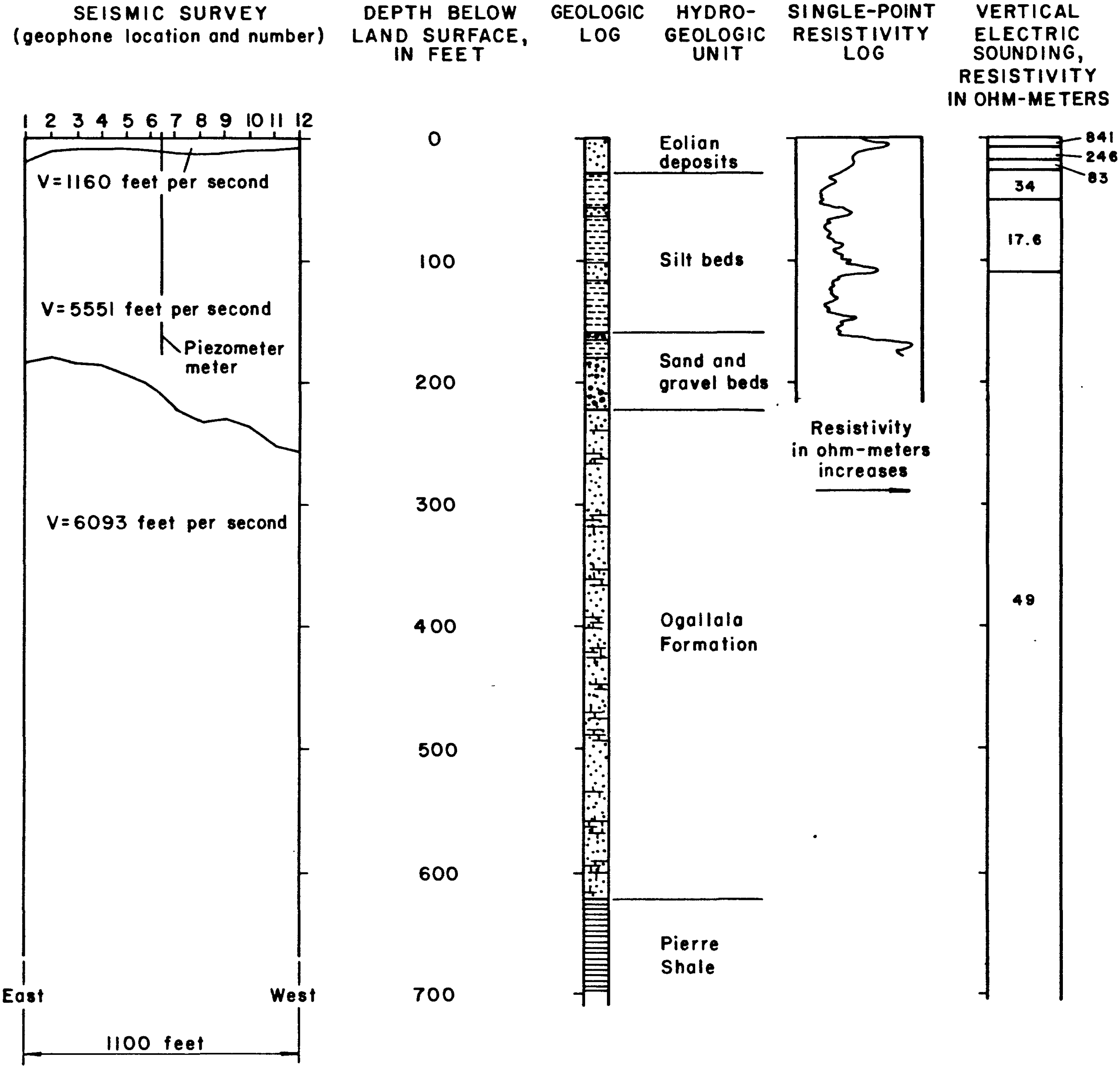


Figure 20.--Comparison of hydrogeologic data and interpretations of geophysical data at site adjacent to piezometer nest LLG-4.

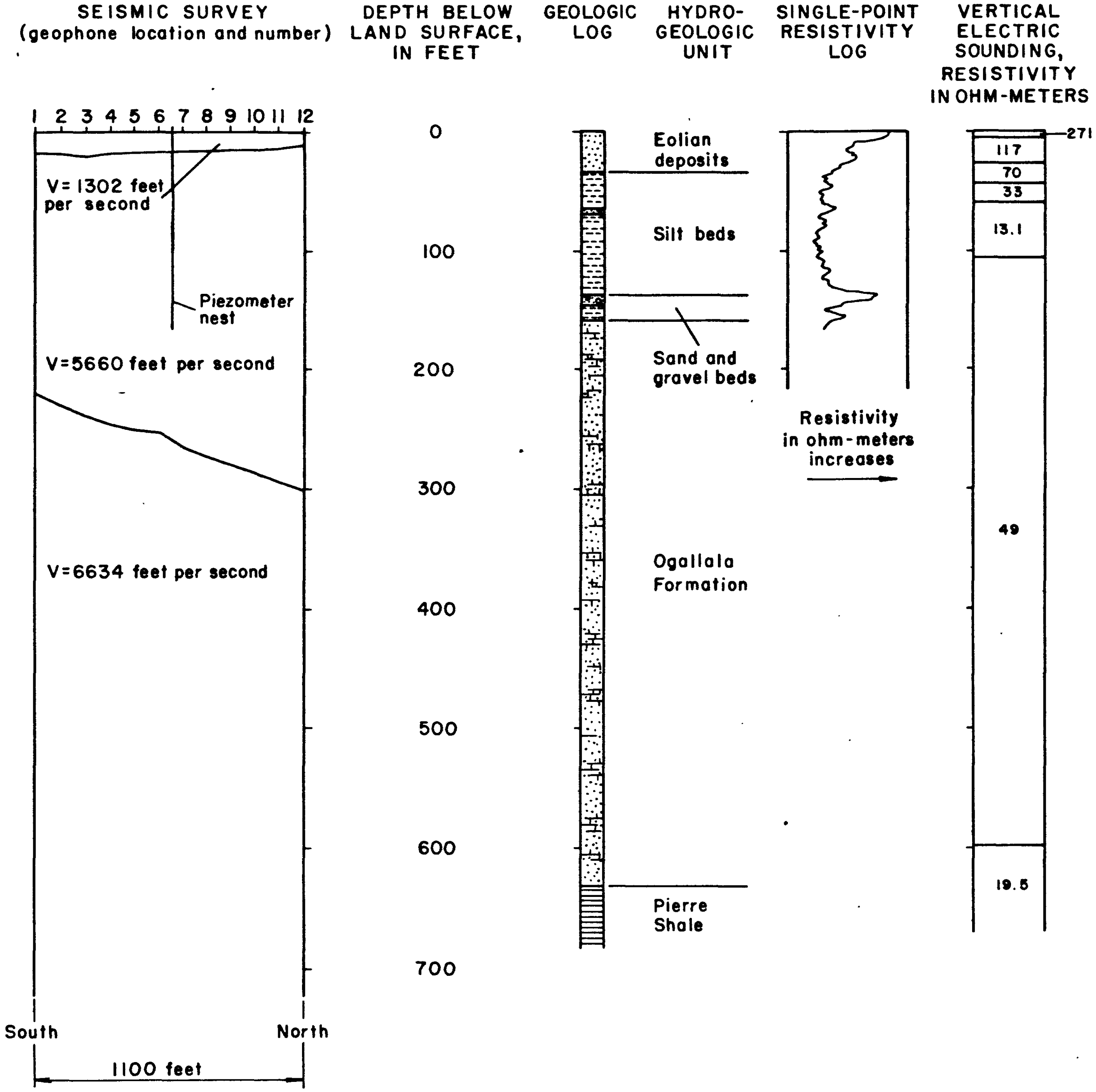


Figure 21.--Comparison of hydrogeologic data and interpretations of geophysical data at site adjacent to piezometer nest LLG-5.

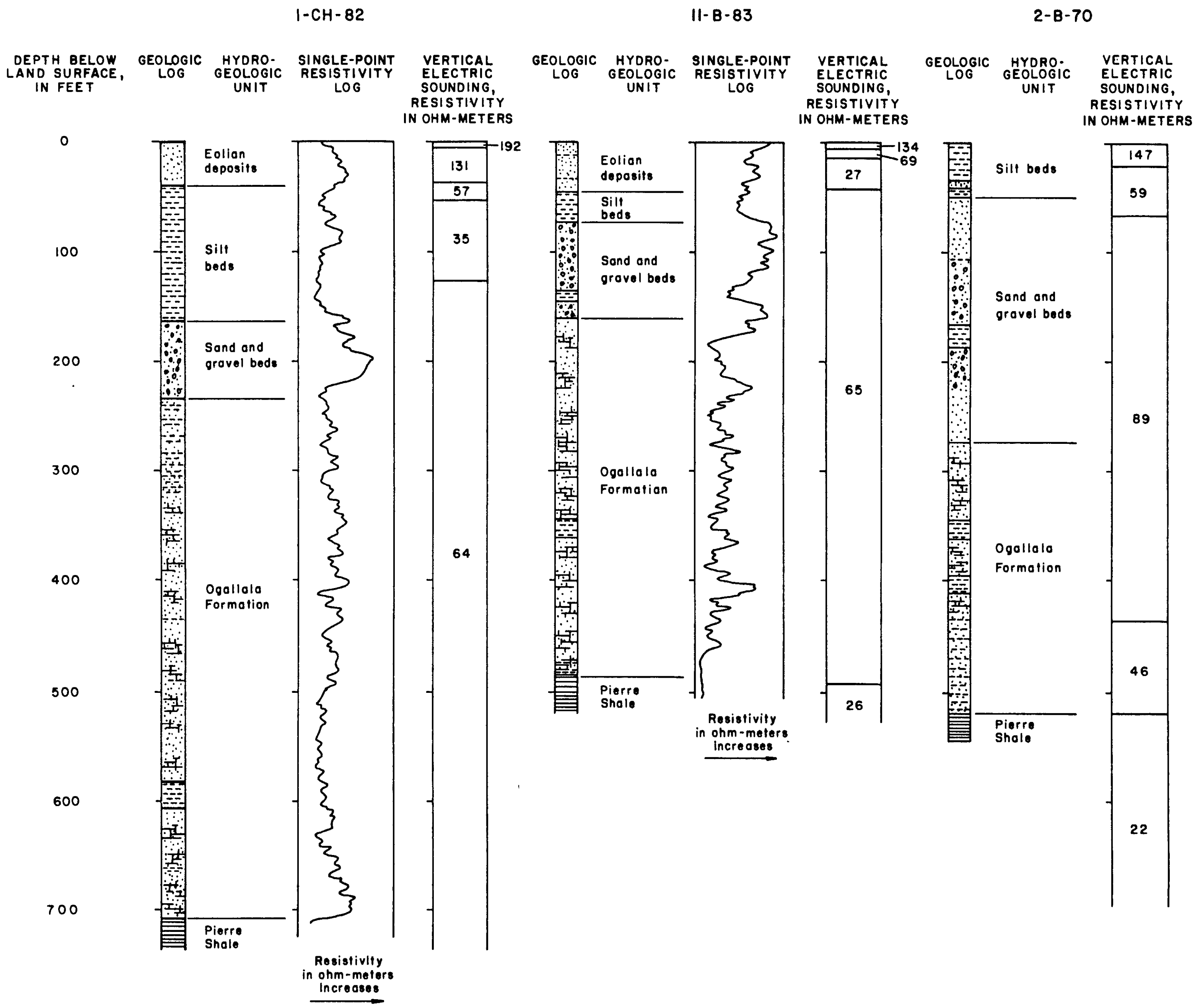


Figure 22.--Comparison of hydrogeologic data and interpretations of vertical electrical sounding data at sites adjacent to test holes 1-CH-82, 11-B-83, and 2-B-70.

Water Table

Both seismic surveys and vertical electrical soundings can be used to detect a geophysical horizon that can be correlated with the water table. Depths determined by either method, however, are approximations, because both methods measure the difference in the physical properties between saturated and unsaturated deposits, and this is a transitional phenomenon. The water table is that surface in an unconfined aquifer at which the pore pressure is atmospheric. Immediately above the water table is a zone called the capillary fringe, in which all or some of the pore spaces are filled with water that is under less than atmospheric pressure. This water is held above the water table by surface tension. The capillary fringe typically is saturated near the water table; but upward from the saturated part, only progressively smaller pores are filled, and the upper limit of the capillary fringe is indistinct. Generally, the thickness of the capillary fringe is greater in fine-grained deposits than in coarse-grained deposits. Thus the measurement of differences between the physical properties of saturated and unsaturated deposits, by geophysical methods, probably represents a change in physical properties that occurs in the capillary fringe and not the water table.

Seismic-refraction data indicate that significant contrasts exist between seismic velocities in the unsaturated and the saturated deposits. Within the study area, seismic velocities in unsaturated deposits ranged between 964 and 1,347 feet per second and velocities in the uppermost saturated deposits ranged between 3,491 and 5,716 feet per second. The distinct differences in the velocity ranges between unsaturated and saturated deposits made it possible to detect a velocity interface that was the approximate equivalent of the water table.

Analyses of the data from the two seismic surveys, in which the geophone spacings and shotpoint offsets were designed to obtain information on shallow velocity layers, provided estimates on the depth to the water table that correlated very well with hydrogeologic data. (See fig. 16.) Interpretation of data from the survey at the site adjacent to piezometer nest LLG-1, where shorter geophone spacings were used (spread 3), indicated a depth to the water table that was only 0.5 foot higher than the measured depth to water. For the survey made at the water-table site, the comparison of water-level depths is approximate; but the indicated depth to the water table determined by seismic methods is only 1.0 foot higher than the depth interpolated from hydrogeologic data.

As has been noted, accurate information on the depths to the velocity horizon that correlates with the water table was not expected from the five seismic surveys where a 100-foot geophone spacing was used. Interpretation of data from these surveys indicates depths to the velocity horizon between the saturated and unsaturated deposits were 5-15 feet greater than measured water levels. (See figs. 17-21.)

Data from vertical electrical soundings also provided reasonable estimates of the depth to the water table at five of the seven sites where comparisons to hydrogeologic data could be made. (See table 3.) At these five sites the difference between the actual and calculated depths were within about 1 foot. The calculated depths at the other two sites were 6.9 and 3.7 feet below the actual depth to the water table. Generally, the unsaturated deposits are much more resistive than the saturated deposits. Determining the water table from vertical electrical sounding data occasionally can be difficult if the water in the upper part of the aquifer contains a very small concentration of dissolved solids and thus has a very high resistivity. Within the study area, the resistivities of the unsaturated deposits ranged from 130 to 900 ohm-meters, and the resistivities of the uppermost saturated deposits generally were between 59 and 188 ohm-meters.

Table 3.--Comparison of water-level depths determined from hydrogeologic data and from vertical electrical sounding data

Site	Depth to water below land surface, in feet		Difference, in feet	Percent difference
	Hydro-geologic data	Vertical electrical sounding data		
LLG-1	7.0	13.9	6.9 lower	- 99
LLG-2	4.0	3.8	.2 higher	+ 5
LLG-3	3.0	6.7	3.7 lower	- 123
LLG-4	18.0	18.2	.2 higher	+ 1
LLG-5	5.0	5.3	.3 lower	- 6
2-B-70	([1])	----	---	---
1-CH-82	5.0	5.0	0	0
11-8-83	6.5	7.6	1.1 lower	- 17

[1] Sufficient data not available to estimate the depth to water at test hole 2-B-70.

Top of Silt Beds

Sufficient data are not available to determine if seismic-refraction surveying is a reliable method for obtaining information on the silt beds. None of the data from siesmic surveys in which 100-foot geophone spacings were used can be interpreted as representing velocity interfaces that definitely can be correlated with the top of the silt beds. However, the velocity interfaces that occur at depths of about 100 feet near piezometer nests LLG-2 and LLG-3 (figs. 18 and 19) correlate well with the depths at which geologic logs indicate the silt beds become very clayey. Available data indicate that such very clayey zones do not occur in the vicinities of the other piezometer nests.

Data from the two seismic surveys designed to provide information on the shallow beds are inadequate for making any conclusions on the suitability of the seismic method for detecting the top of the silt beds. Because of the short geophone spacings and the small shotpoint-offset distances used at the water-table site, the only velocity interface detected was the one between the unsaturated and saturated deposits. Data from the survey adjacent to piezometer nest LLG-1 provides some indication that the method detected the top of the silt beds at depths ranging from 30 to 34 feet beneath geophones 8 through 12 (fig. 16). Because of the geometry of shotpoint offsets used, no seismic information is available near piezometer nest LLG-1 to confirm the validity of this interpretation.

Data from most of the vertical electrical soundings can be correlated with the top of the silt beds. At all of the sounding sites (figs. 17-22), except those adjacent to piezometer nest LLG-1 and test hole 2-B-70, distinct changes in resistivities occur within 10 feet of the actual top of the silt beds. The comparison of vertical electrical soundings and hydrogeologic data is summarized in table 4. In the vicinity of piezometer nest LLG-1, the upper part of the silt beds is very sandy (fig. 17), but this probably was not detected because the electrical properties of the silt beds are similar to the overlying eolian deposits. However, the thicker silt beds that occur at 68 feet below the land surface at this location probably can be correlated with a geoelectric horizon that occurs at about 78 feet below the land surface (15 percent difference in depths). Available data indicate that the depths to the water table and the top of silt beds are about the same in the vicinity of test hole 2-B-70, and valid comparisons of hydrogeologic and vertical electrical sounding data for shallow horizons cannot be made at this site.

Deposits overlying the silt beds generally have resistivities that range from about 70 to 246 ohm-meters, and deposits below the top of the silt beds generally have resistivities that range from 33 to 83 ohm-meters. This difference in the ranges probably is due to differences in porosity and in water quality that occur between the beds.

Table 4.--Comparison of depths below land surface to the top of the silt beds determined from hydrogeologic data and from vertical electrical sounding data

Site	Depth to top of silt beds, in feet: Hydro-geologic data	Depth to top of silt beds, in feet: Vertical electrical sounding data	Difference, in feet	Percent difference
LLG-1	30	78	48 lower	[1]-160
LLG-2	57	48	9 higher	+ 16
LLG-3	20	18	2 higher	+ 10
LLG-4	28	26	2 higher	+ 7
LLG-5	35	43	8 lower	- 23
2-B-70	—	—	---------	---
1-CH-82	40	38	2 higher	+ 5
11-8-83	46	42	4 higher	+ 9

[1] Upper part of the silt beds is very sandy and contains interbedded sand layers.

Top of Sand and Gravel Beds

Neither seismic surveys nor vertical electric soundings yielded data that could be interpreted as pertaining to the top of the sand and gravel beds.

Top of Ogallala Formation

Seismic surveys at sites adjacent to all of the piezometer nests, except the one near piezometer nest LLG-3, indicated that a velocity interface occurs in the upper part of the Ogallala Formation. The interface ranges between 5 and 60 feet below the top of the formation. This change in seismic velocities cannot be correlated to the top of the Ogallala with any surety, because hydrogeologic data indicate that velocity inversions probably occur within the overlying Quaternary deposits, and because the seismic velocities below the interface are even greater than those known to occur in the clayey basal part of the Ogallala. Data from vertical electrical soundings indicate there are no differences in resistivities between the Ogallala and the overlying sand and gravel deposits.

Top of Pierre Shale

The seismic refraction method is not suitable for detecting the top of the Pierre Shale, because hydrogeologic data indicate that velocity inversions may occur in both the Tertiary and Quaternary deposits that overlie the Pierre, and because there is not a significant contrast between seismic velocities in the Ogallala Formation and in the Pierre Shale.

Analyses of data from vertical electrical soundings did not result in interpretations that consistently could be correlated with depth to the top of the shale (table 5). Changes in resistivities, from values credible for the Ogallala Formation to values credible for the Pierre, occurred at depths that correlated reasonably well with hydrogeologic data at sites adjacent to piezometer nests LLG-1 and LLG-5, and test hole 11-B-83. At the other sounding sites, little or no correlation between hydrogeologic data and vertical electrial sounding data was evident.

As noted in the discussion on interpretation of electrical-resistivity data (p. 20), the method was relatively insensitive to the depths and resistivities of the deeper beds. This insensitivity was not expected, because available borehole geophysical data indicate significant differences occur between resistivities that are characteristic of the Pierre Shale and those that are characteristic of the Ogallala Formation, and because an AB electrode spacing of 1,768 meters normally is adequate for measuring the resistivity of geoelectric layers at the depth at which the Pierre occurs. However, with the data that are available, it can only be concluded that longer electrode spacings should have been used in making vertical electrical soundings. The need for longer electrode spacings probably is due to the fact that most of the beds overlying the Pierre have relatively high resistivities because the water in them has a small concentration of dissolved solids.

Table 5.--Comparison of depths below land surface to the top of the Pierre Shale determined from hydrogeologic data and from vertical electrical sounding data

Site	Depth to top of Pierre Shale, in feet: Hydrogeologic data	Depth to top of Pierre Shale, in feet: Vertical electrical sounding data	Difference, in feet	Percent difference
LLG-1	582	635	53 lower	- 9
LLG-2	665	1,205	540 lower	- 81
LLG-3	590	874	284 lower	- 48
LLG-4	620	1,283	663 lower	-107
LLG-5	630	600	30 higher	+ 5
2-B-70	520	686	[1]146 lower	- 28
1-CH-82	710	842	132 lower	- 19
11-8-83	490	492	2 lower	- 0.4

[1] Corrected for difference in elevation between sounding point and test hole.

EVALUATION OF METHODS

As stated previously, the purpose of this study is to provide an evaluation of the effectiveness and the potential usefulness of seismic-refraction and electrical-resistivity methods for obtaining data that could be used in hydrogeologic investigations of the Nebraska Sand Hills region. The evaluation of the effectiveness of the geophysical methods is semiquantitative, and the evaluation of the potential usefulness is qualitative. Because of the many variables that are beyond the scope of this study, only a generalized evaluation has been made of the potential cost efficiencies that might result from the use of surface geophysical methods.

Effectiveness

Two factors were considered in evaluating the effectiveness of geophysical methods as a means of collecting hydrogeologic data. These factors are the reliability of the methods and how accurately the interpreted geophysical data correlate with hydrogeologic data. The reliability of the geophysical methods was assessed by ascertaining how consistently each method was able to detect geophysical horizons that correlated with hydrogeologic horizons at the test sites, and by determining that, if a geophysical layer was not detected at a given test site, whether it could be correctly assumed the correlatable hydrogeologic layer was not present.

Accuracy is a relative term, because some error is inherent in any measurement. An accurate measurement can be defined as one that conforms, within an acceptable limit of error, to a defined standard. For evaluations made in this study, the depths to selected hydrogeologic horizons, as determined from available hydrogeologic data, were used as the standards for comparison with values determined by geophysical methods. Acceptable limits of error vary with the depths at which the selected hydrogeologic horizons usually occur and with the degree of detail commonly shown on interpretive maps of individual horizons. The following are the acceptable limits of error used in evaluating the accuracy of depths determined by interpretation of geophysical data from the study area:

Water table--------------------10 percent, or 20 percent if
depth is less than 25 feet.

Top of silt beds---------------10 percent.

Top of sand and gravel beds----10 percent.

Top of Ogallala Formation------5 percent, or 10 percent if
depth is less than 125 feet.

Top of Pierre Shale------------5 percent.

The comparisons of data from seismic surveys and vertical electrical soundings with existing hydrogeologic data indicate that both geophysical methods are effective for collecting some types of data that could be used to supplement hydrogeologic data normally collected in water-level measurement and test-drilling programs. A summary of the effectiveness of seismic-refraction and electrical-resistivity methods for detecting geophysical horizons that correlate well with the selected hydrogeologic horizons is given in table 6. The geophysical horizons that can be detected most reliably and accurately are the velocity and geoelectric horizons that are correlatable with the water table and the geoelectric horizon that can be correlated with the top of the silt beds.

A geoelectric horizon that correlated with the top of the Pierre Shale was detected at all of the sites where vertical electrical soundings were made. However, the methods used to interpret field data are relatively insensitive to the depths and resistivities of the Pierre. An analysis of available data indicates that by modifying field procedures used in making vertical electrical soundings, it should be possible to more accurately determine the depth to the top of the geoelectric horizon that correlates with the top of the Pierre Shale.

Table 6.--Effectiveness of seismic-refraction and electrical-resistivity method for detecting geophysical horizons that correlate with selected hydrogeologic horizons

Hydrogeologic horizon	Seismic-refraction method	Electrical-resistivity method
Water table	Very reliable detection of correlatable velocity horizon. Accuracy is very good if shotpoint offsets and geophone spacings are designed for detection of shallow velocity layers.	Very reliable detection of correlatable geoelectric horizon. Accuracy generally good but may be affected by variations in water quality.
Top of silt beds	No reliable detection of correlatable velocity horizon; but detection of velocity layer that correlates with top of very clayey silt beds was reliable. Accuracy good for detection of very clayey silts.	Very reliable detection of correlatable geoelectric horizon. Accuracy generally is adequate, but variable because of differences in water quality.
Top of sand and gravel beds	No reliable detection of correlatable velocity horizon.	No reliable detection of correlatable geoelectric horizon.
Top of Ogallala Formation	No reliable detection of correlatable velocity horizon.	Reliable detection of correlatable geoelectric horizon.
Top of Pierre Shale	No reliable detection of correlatable velocity horizon.	Reliable detection of correlatable geoelectric horizon. Accuracy poor, but probably can be improved by modifying field methods.

Reliable information on the depth to the water table that is accurate enough for use in most hydrogeologic investigations can be obtained through the use of either seismic surveys or vertical electrical soundings. However, seismic surveys offer some distinct advantages over vertical electrical soundings. Included in these advantages are the following:

1. Seismic surveys can be made with a two-person crew, whereas vertical electrical soundings are best made with three-person crews.

2. Seismic surveys probably can be made somewhat faster than vertical electrical soundings.

3. Data from almost all seismic surveys could be treated as a two-layer problem, and a preliminary interpretation of data could be made in the field to determine if the data are reasonable.

4. Data from seismic surveys probably are more accurate, because measured differences between the physical properties of saturated and unsaturated deposits are not affected by variations in water quality that may occur in the upper part of the saturated zone.

Comparisons of vertical electrical sounding data with hydrogeologic data indicate that reliable and reasonably accurate detection of a geoelectric horizon that correlates with the top of the silt beds is possible. Two hydrogeologic conditions, however, may significantly affect the reliability of data from vertical electrical soundings. These conditions are where the top of the silt beds and the water table are at about the same depth, and where the upper part of the silt beds is very sandy. Comparison of seismic-survey data with hydrogeologic data indicates only the tops of the uppermost, relatively dense deposits, such as very clayey silts, can be correlated reliably and accurately with seismic horizons.

Usefulness

Although data collected through the use of geophysical methods might improve the reliability and accuracy of most hydrogeologic interpretations, such data probably could only be used in conjunction with, or to supplement data collected by traditional methods. The objectives of each hydrogeologic investigation need to be reviewed to determine if additional data are needed that could be collected by using geophysical methods. In this evaluation of the potential usefulness of geophysical methods, some of the problems that were encountered in the collection and interpretation of hydrogeologic data in the Sand Hills region are described, and how the use of surface-geophysical methods to collect supplemental data might alleviate these problems is discussed.

In many parts of the Sand Hills region, it is difficult to find wells in which representative water levels can be measured, and usually it is too costly to install an adequate number of observation wells. Thus, hydrogeologic interpretations in these areas commonly are made with insufficient or nonrepresentative data. Use of surface-geophysical methods would allow investigators to collect additional water-level information at locations where it is needed, with the only restriction being that of obtaining permission for access to the locations.

Most of the problems encountered in the collection and interpretation of water-level data in the region occur in three types of areas. These are: upland areas where virtually no wells exist in which water levels can be measured; border areas between uplands and natural discharge areas where there are few wells in which water levels can be measured; and areas where measured water levels may not be representative of the water table or the desired potentiometric surface.

Upland areas, where it is difficult to find wells in which water levels can be measured, range in size from less than 10 square miles to more than 1,000 square miles. In these areas most domestic and stock wells are sealed to prevent pollution, and there are no irrigation wells in which water-level measurements can be made. Because the direction of ground-water movement in these areas is somewhat predictable and the gradient of the water table is usually slight, reasonable interpretations of the configuration of the water table usually can be made with few data for regional or statewide interpretive studies. But for more detailed studies of smaller areas, such as a county or a drainage basin, inadequate water-level data may seriously limit the accuracy of hydrogeologic interpretations.

Border areas between uplands and major natural discharge areas, such as perennial streams and hay meadows, usually are linear areas 1 to 3 miles wide, where large changes in the altitude of the water table occur within relatively short distances. Commmonly, it is possible to obtain reliable information on the altitude of the water table in both the uplands and in the natural discharge areas, but it is extremely difficult to obtain any data for use in defining the configuration of the water table in areas where the gradient of the water table is often the steepest. This potential for making large errors in defining the configuration of the water table is a major concern in making hydrogeologic interpretations, because the configuration of the water table in these border areas is an important facet in the accurate evaluation of stream-aquifer interrelationships.

A common but usually unrecognized problem encountered in the collection of water-level data in the Sand Hills region is that some of the data may not be representative of the water table or the potentiometric surface of that part of the aquifer being studied. Nonrepresentative water levels usually result from localized variations in hydrogeologic conditions, differences in well-completion practices, and/or differences in well depths. The occurrence of nonrepresentative water levels is common in areas where the aquifer is unconfined and there are large vertical variations in static head.

These vertical variations in static head result from movement of ground water from recharge areas to discharge areas (Freeze and Cherry, 1979; Lohman, 1972; and Toth, 1963). A recharge area can be defined as that part of a drainage basin in which the net saturated flow of ground water is away from the water table; and a discharge area is that part of a drainage basin in which the net saturated flow is toward the water table. Thus, in a recharge area, the static head, as determined by water-level measurements in tightly cased wells, will decrease with depth. Conversely, cased wells near streams and other natural discharge areas reach water with greater static head as depth increases, and wells open at moderate depths generally will flow at the land surface.

Use of nonrepresentative water-level data, if unrecognized as such, may result in making incorrect hydrogeologic interpretations. For example, calculated values of aquifer thicknesses might be too large in a discharge area or too small in a recharge area; the occurrence of perched ground water might be postulated in recharge areas; and the presence of confining beds might be postulated in discharge areas. Either seismic-refraction surveys or vertical electrical soundings could be used to verify depths to the top of the water table, and thus help insure that correct aquifer thicknesses are calculated. Vertical electrical soundings also probably could be used to determine whether or not confining beds are present and if there are unsaturated deposits beneath postulated occurrences of perched ground water.

Information on the extent and thickness of the silt beds may be essential in adequately defining the hydrogeologic system in the Sand Hills region, but very little information is available for use in making hydrogeologic interpretations. Information about distinct lithologic units that are important sources of water, such as the sand and gravel beds or the Ogallala Formation, usually can be derived from driller's logs as well as from geologic logs for test holes. However, the silt beds generally are difficult to define even with detailed test-hole data. Vertical electrical soundings could be used as a method for obtaining additional information on the lateral extent and depths to the top of the silt beds. Test-hole data probably need to be used in conjunction with vertical electrical soundings, because variations in water quality may significantly affect resistivity values.

Few data are available on depths to the top of the Pierre Shale, because none of the water wells in the Sand Hills region penetrates the entire thickness of the aquifer, and because of the expense involved in drilling test holes to the top of the Pierre. If, by modification of field procedures used in making vertical electrical soundings, it is possible to obtain more accurate data on the depth to the geoelectric horizon that correlates with the top of the Pierre Shale, the accuracy of the hydrogeologic interpretations could be improved.

Cost Efficiency

Based on the limited field work that was done for this study, the following two generalizations can be made about factors affecting determinations of cost efficiencies:

1. If seismic-refraction surveys are used to obtain data for use in defining the configuraton of the water table, the time and personnel requirements probably would be about the same as those needed for scheduling and measuring water levels in areas where there are wells.

2. Time and personnel requirements for using vertical electrical soundings to obtain subsurface data on lithologic boundaries probably are about one-third of those needed for test-drilling operations.

CONCLUSIONS

Results of the study indicate that seismic-refraction surveys and vertical electrical soundings can provide reliable and accurate data that could improve interpretations of the hydrogeology in the Nebraska Sand Hills region, especially if they are used in conjunction with established techniques of test drilling and water-level measuring. Seismic-refraction surveys are best suited for determining the depth to the water table; however, vertical electrical soundings also provide reliable and accurate data. Distribution of lithologic variations within the water-bearing deposits could not be determined with seismic surveys, and could be determined only to a limited extent with vertical electrical soundings. An analysis of available hydrogeologic data indicates that, with some refinement or modification of data collection or interpretation techniques, vertical electrical soundings might yield more useful data.

Seismic surveys were made at six sites. At all of the sites, the large contrast in seismic velocities that exists between the unsaturated and saturated deposits was detected. In areas where the water table was near the land surface, the best results were obtained when 5- or 10-foot geophone spacings were used and the shotpoints were offset from the geophone line by 5 feet. When larger offsets were used, the critical distance usually was less than the distance between the shotpoint and the first geophone; and the depth to the water table could be only approximated. Data from the seismic surveys indicate that some differences in seismic velocities exist in the saturated deposits, but the differences are slight and cannot be considered reliable for determining depths to mappable hydrogeologic units. The data also indicate that seismic velocities in the silt beds are faster than most, if not all, of the velocities occurring in the underlying sand and gravel beds and in the Ogallala Formation, causing a velocity inversion. Thus, depths to all of the beds underlying the silt beds cannot accurately be determined with available data by seismic-refraction methods.

Vertical electrical soundings provide reliable data on the depth to the water table and to the top of the silt beds, and thus provide information on the thickness of the saturated eolian deposits that overlie the silt beds. The accuracy of depth determinations made with vertical electrical soundings is affected by variations in water quality caused by differences in local flow systems occurring within the aquifer. Thus, data from test holes need to be used for control when vertical electrical soundings are used to collect hydrogeologic data in the Sand Hills region. Data from vertical electrical soundings were erratic pertaining to tops of the sand and gravel beds, the Ogallala Formation, and the top of the Pierre Shale. Because borehole geophysical logs indicate that marked differences occur at the top of these three hydrogeologic horizons, it is probable that refinement or modification of data-collection and interpretation techniques would make it possible to collect more useful hydrogeologic data with vertical electrical soundings.

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Table 7. -- Summary of data from seismic-refraction surveys

Seismic Survey at site adjacent to piezometer nest LLG-1: Spread 1 of 3, geophone line centered on piezometer nest. The locations of geophones were approximately the same in both spreads 1 and 2; and data from both of the spreads were combined for interpretations.

Shotpoint data:

Shot-point number	Altitude, in feet	Distance and direction from geophone number 1, in feet	Depth of shot, in feet
1 *	2,206	1,110 north	4.0
2	2,206	20 south	4.0
3 **	2,206	1,400 north	4.0
4	2,206	1,115 north	4.0

* Data from shot number 1 was not usable.
** Data from shot number 3 was of marginal value and was not used for interpretations.

Geophone data:

Geophone number	Altitude, in feet	Distance and direction from geophone number 1, in feet	First arrival times, in milliseconds	
			Shot 2	Shot 4
1	2,212	0	10	215
2	2,211	100 north	40	195
3	2,210	200 north	57	176
4	2,208	300 north	77	160
5	2,207	400 north	93	139
6	2,206	500 north	110	120
7	2,206	600 north	130	102
8	2,207	700 north	150	85
9	2,207	800 north	170	67
10	2,208	900 north	185	50
11	2,208	1,000 north	200	34
12	2,208	1,100 north	222	12

Seismic survey at site adjacent to piezometer nest LLG-1: Spread 2 of 3, geophone line centered on piezometer nest. See note under spread 1.

Shotpoint data:

Shot-point number	Altitude, in feet	Distance and direction from geophone number 1, in feet	Depth of shot, in feet
1	2,195	2,200 south	2.5
2	2,225	3,300 north	5.0

Geophone data:

Geophone number	Altitude, in feet	Distance and direction from geophone number 1, in feet	First arrival times, in milliseconds	
			Shot 1	Shot 2
1	2,212	0	400	587
2	2,211	100 north	418	574
3	2,210	200 north	435	555
4	2,208	300 north	455	539
5	2,207	400 north	470	524
6	2,206	500 north	487	509
7	2,206	600 north	502	490
8	2,207	700 north	522	475
9	2,207	800 north	540	455
10	2,208	900 north	555	440
11	2,208	1,000 north	570	425
12	2,208	1,100 north	587	405

Table 7. -- Summary of data from seismic-refraction surveys --Continued

Seismic survey at site adjacent to piezometer nest LLG-1: Spread 3 of 3, geophones 1 and 2 centered on piezometer nest.

Shotpoint data:

Shot-point number	Altitude, in feet	Distance and direction from geophone number 1, in feet	Depth of shot in feet
1	2,212	5 north	2.0
2	2,212	180 south	2.0

Geophone data:

Geophone number	Altitude, in feet	Distance and direction from geophone number 1, in feet	First arrival times, in milliseconds	
			Shot 1	Shot 2
1	2,212	0	8	47
2	2,212	5 south	12	46
3	2,212	10 south	16	45
4	2,212	15 south	19	45
5	2,212	35 south	23	42
6	2,212	55 south	27	38
7	2,212	75 south	30	35
8	2,212	95 south	34	32
9	2,212	115 south	39	29
10	2,212	135 south	42	23
11	2,212	155 south	45	19
12	2,212	175 south	50	6

Seismic survey at site adjacent to piezometer nest LLG-2: Spread 1 of 1, geophone line centered on piezometer nest.

Shotpoint data:

Shot-point number	Altitude, in feet	Distance and direction from geophone number 1, in feet	Depth of shot, in feet
1	2,170	20 south	4.0
2	2,170	1,100 south	5.0
3	2,174	2,200 south	4.0
4	2,168	1,120 north	3.5
5	2,170	2,200 north, 24 west	4.5
6	2,167	3,105 north, 24 west	3.0

Geophone data:

Geophone number	Altitude, in feet	Distance and direction from geophone number 1, in feet	First arrival times, in milliseconds					
			Shot 1	Shot 2	Shot 3	Shot 4	Shot 5	Shot 6
1	2,170	0	18	212	401	214	401	538
2	2,171	100 north	38	232	418	198	386	528
3	2,170	200 north	56	248	434	180	370	512
4	2,169	300 north	74	265	450	162	351	495
5	2,168	400 north	89	282	466	142	330	476
6	2,168	500 north	107	300	480	122	312	462
7	2,168	600 north	132	318	500	105	299	447
8	2,168	700 north	151	338	517	88	280	433
9	2,168	800 north	167	352	532	68	265	413
10	2,168	900 north	184	368	548	52	248	396
11	2,168	1,000 north	201	387	562	32	228	386 *
12	2,168	1,100 north	219	402	576	13	211	370 *

* Geophone not functioning, extrapolated value.

Table 7. -- Summary of data from seismic-refraction surveys --Continued

Seismic survey at site adjacent to piezometer nest LLG-3: Spead 1 of 1, geophone line centered on piezometer nest.

Shotpoint data:

Shot-point number	Altitude, in feet	Distance and direction from geophone number 1, in feet	Depth of shot, in feet
1	2,230	20 south	3.0
2	2,230	1,100 south	4.5
3	2,229	1,093 north, 190 west	3.0
4	2,211	2,129 north, 462 west	3.0

Geophone data:

Geophone number	Altitude, in feet	Distance and direction from geophone number 1, in feet	First arrival times, in milliseconds			
			Shot 1	Shot 2	Shot 3	Shot 4
1	2,233	0	21	223	225	404
2	2,232	100 north	55	253	206	387
3	2,232	200 north	73	269	194	371
4	2,232	300 north	90	285	171	352
5	2,238	400 north	110	302	155	340
6	2,243	498 north, 8 west	130	323	140	326
7	2,238	592 north, 37 west	146	337	120	300
8	2,236	689 north, 66 west	160	352	99	285
9	2,238	787 north, 96 west	182	370	80	270
10	2,232	883 north, 126 west	198	382	59	250
11	2,231	979 north, 155 west	214	400	40	225
12	2,229	1,074 north, 184 west	227	411	15	210

Seismic survey at site adjacent to piezometer nest LLG-4: Spread 1 of 1, geophone line centered on piezometer nest.

Shotpoint data:

Shot-point number	Altitude, in feet	Distance and direction from geophone number 1, in feet	Depth of shot, in feet
1	2,266	20 east-northeast	6.0
2	2,251	1,120 west-southwest	3.5
3	2,286	1,078 east-northeast, 116 south-southeast	6.0
4	2,249	2,200 west-southwest	3.0

Geophone data:

Geophone number	Altitude, in feet	Distance and direction from geophone number 1, in feet	First arrival times, in milliseconds			
			Shot 1	Shot 2	Shot 3	Shot 4
1	2,266	0	16	225	239	402
2	2,256	100 west-southwest	37	204	252	382
3	2,251	200 west-southwest	55	185	271	365
4	2,254	300 west-southwest	74	168	285	345
5	2,253	400 west-southwest	93	151	300	330
6	2,251	500 west-southwest	111	132	320	313
7	2,256	600 west-southwest	129	117	340	299
8	2,258	700 west-southwest	147	99	359	281
9	2,253	800 west-southwest	165	75	370	261
10	2,250	900 west-southwest	180	55	385	244
11	2,255	1,000 west-southwest	200	40	405	221
12	2,251	1,100 west-southwest	215	20	420	203

Table 7. -- Summary of data from seismic-refraction surveys --Continued

Seismic survey at site adjacent to piezometer nest LLG-5: Spread 1 of 1, geophone line centered on piezometer nest.

Shotpoint data:

Shot-point number	Altitude, in feet	Distance and direction from geophone number 1, in feet	Depth of shot, in in feet
1	2,177	20 south	2.0
2	2,183	1,110 south	2.0
3 *	2,183	2,200 south	3.0
4	2,183	2,200 south, 20 west	3.0
5	2,176	1,100 north	3.0
6	2,174	2,200 north	3.0
7 **	2,174	3,300 north	5.0
8	2,174	3,300 north	5.0

* Data from shot 3 was not usable.
** Data from shot 7 was of marginal value, and was stacked with data from shot 8 to provide better resolution.

Geophone data:

Geophone number	Altitude, in feet	Distance and direction from geophone number 1, in feet	First arrival times, in milliseconds Shot 1	Shot 2	Shot 4	Shot 5	Shot 6	Shot 7+8
1	2,177	0	16	229	405	213	400	585
2	2,177	100 north	38	250	420	200	386	571
3	2,178	200 north	53	267	440	185	369	555
4	2,179	300 north	74	284	453	165	349	539
5	2,180	400 north	92	302	472	142	334	523
6	2,178	500 north	108	320	487	126	317	508
7	2,179	600 north	126	335	504	110	298	490
8	2,179	700 north	146	352	520	91	282	470
9	2,177	800 north	164	369	545	73	263	454
10	2,176	900 north	180	385	565	52	243	436
11	2,176	1,000 north	200	400	583	35	223	420 *
12	2,176	1,100 north	215	414	595	15	205	402 *

* Geophone not functioning, extrapolated value.

Seismic survey at water-table site: Spread 1 of 1.

Shotpoint data:

Shot-point number	Altitude, in feet	Distance and direction from geophone number 1, in feet	Depth of shot, in feet
1	2,160	5 southeast	3.5
2	2,160	115 northwest	3.5

Geophone data:

Geophone number	Altitude, in feet	Distance and direction from geophone number 1, in feet	First arrival times, in milliseconds Shot 1	Shot 2
1	2,160	0	6	66.5
2	2,160	10 northwest	14	64.5
3	2,160	20 northwest	25	62.5
4	2,160	30 northwest	33	60
5	2,160	40 northwest	41	59
6	2,160	50 northwest	48	57
7	2,160	60 northwest	54	52
8	2,160	70 northwest	56	42
9	2,160	80 northwest	58	33
10	2,160	90 northwest	60	25
11	2,160	100 northwest	63	17
12	2,160	110 northwest	65	10

Table 8. Summary of data from vertical electrical soundings made adjacent to piezometer nests and test holes [$\overline{AB}$/2=distance between current electrodes divided by 2; $\overline{MN}$=distance between potential electrodes; ΔV=difference in electrical potential; and I=electric current]

Vertical electrical sounding at site adjacent to piezometer nest LLG-1: Sounding made along road west of piezometer nest, electrode line oriented north-south.

$\overline{AB}$/2, in meters	$\overline{MN}$, in meters	ΔV, in millivolts	I, in milliamperes
1.00	0.3	7,370	300
1.47	.3	2,805	250
2.15	.3	1,540	300
3.16	.3	759	300
4.64	.3	330	300
---	---	---	---
10.0	1.0	225	500
14.7	1.0	49	300
---	---	---	---
31.6	3.0	13.8	200
46.4	3.0	3.9	150
---	---	---	---
100	10.0	1.9	150
147	10.0	.83	130
---	---	---	---
316	30.0	.17	180
464	30.0	.22	180
---	---	---	---
---	---	---	---

$\overline{AB}$/2, in meters	$\overline{MN}$, in meters	ΔV, in millivolts	I, in milliamperes
---	---	---	---
---	---	---	---
---	---	---	---
3.16	1.0	2,420	300
4.64	1.0	847	250
6.81	1.0	352	300
10.0	3.0	682	500
14.7	3.0	154	300
21.5	3.0	39	200
31.6	10.0	49	200
46.4	10.0	14.4	150
68.1	10.0	6.3	200
100	30.0	8.4	200
147	30.0	2.6	130
215	30.0	1.3	140
316	100	2.4	200
464	100	.72	170
681	100	.44	170
884	100	.33	300

Vertical electrical sounding at site adjacent to piezometer nest LLG-2: Sounding made along road east of the piezometer nest, electrode line oriented north-south.

$\overline{AB}$/2, in meters	$\overline{MN}$, in meters	ΔV, in millivolts	I, in milliamperes
1.00	0.3	6,380	440
1.47	0.3	3,135	400
2.15	0.3	968	300
3.16	0.3	352	300
4.64	0.3	176	400
---	---	---	---
10.0	1.0	110	400
14.7	1.0	53	400
---	---	---	---
31.6	3.0	16.5	250
46.4	3.0	10.7	400
---	---	---	---
100	10.0	8.4	600
147	10.0	3.2	500
---	---	---	---
316	30.0	1.9	500
---	---	---	---
---	---	---	---
---	---	---	---

$\overline{AB}$/2, in meters	$\overline{MN}$, in meters	ΔV, in millivolts	I, in milliamperes
---	---	---	---
---	---	---	---
---	---	---	---
3.16	1.0	1,199	300
4.64	1.0	451	300
6.81	1.0	187	300
10.0	3.0	330	400
14.7	3.0	154	400
21.5	3.0	51	300
31.6	10.0	115	500
46.4	10.0	36	400
68.1	10.0	8.5	250
100	30.0	27	700
147	30.0	9.6	500
215	30.0	4.4	500
316	100	6.4	500
464	100	2.9	600
681	100	1.3	700
884	100	.83	800

Table 8. -- Summary of data from vertical electrical soundings made adjacent to peizometer nests and test holes -- Continued

Vertical electrical sounding at site adjacent to piezometer nest LLG-3. Electrode line oriented north-south.

$\overline{AB}$/2, in meters	$\overline{MN}$, in meters	ΔV, in millivolts	I, in milliamperes	$\overline{AB}$/2, in meters	$\overline{MN}$, in meters	ΔV, in millivolts	I, in milliamperes
1.00	0.3	11,000	300	---	---	---	---
1.47	0.3	5,610	300	---	---	---	---
2.15	0.3	2,860	300	---	---	---	---
3.16	0.3	1,210	300	3.16	1.0	3,630	300
4.64	0.3	528	300	4.64	1.0	1,540	300
---	---	---	---	6.81	1.0	451	250
10.0	1.0	105	220	10.0	3.0	325	220
14.7	1.0	28	220	14.7	3.0	86	220
---	---	---	---	21.5	3.0	19.3	220
31.6	3.0	5.5	200	31.6	10.0	20	220
46.4	3.0	2.5	200	46.4	10.0	7.7	200
---	---	---	---	68.1	10.0	3.0	150
100	10.0	1.7	150	100	30.0	5.1	150
147	10.0	.88	150	147	30.0	2.7	150
---	---	---	---	215	30.0	1.9	200
316	30.0	.88	200	316	100	3.6	250
464	30.0	.44	250	464	100	1.1	200
---	---	---	---	681	100	.55	300
---	---	---	---	884	100	.33	300

Vertical electrical sounding at site adjacent to piezometer nest LLG-4: Electrode line oriented approximately east-west; however, location is in an area of sand-dune topography, which made it difficult to maintain straight-line orientation of the electrode line.

$\overline{AB}$/2, in meters	$\overline{MN}$, in meters	ΔV, in millivolts	I, in milliamperes	$\overline{AB}$/2, in meters	$\overline{MN}$, in meters	ΔV, in millivolts	I, in milliamperes
1.00	0.3	4,290	60	---	---	---	---
1.47	0.3	2,530	70	---	---	---	---
2.15	0.3	946	60	---	---	---	---
3.16	0.3	418	70	3.16	1.0	1,485	70
4.64	0.3	182	70	4.64	1.0	528	70
---	---	---	--	6.81	1.0	182	80
10.0	1.0	36	60	10.0	3.0	127	60
14.7	1.0	6.7	50	14.7	3.0	26	60
---	---	---	--	21.5	3.0	4.7	50
31.6	3.0	1.5	60	31.6	10.0	6.8	70
46.4	3.0	.88	80	46.4	10.0	3.2	80
---	---	---	--	68.1	10.0	.99	50
100	10.0	.55	50	100	30.0	1.5	50
147	10.0	.39	70	147	30.0	.99	60
---	---	---	--	215	30.0	.66	70
316	30.0	.11	70 *	---	---	---	---
464	30.0	1.7	80	464	100	.44	70
---	---	---	--	681	100	.22	90
---	---	---	--	884	100	.11	100

* Error in field measurements, not used in analysis of data.

Table 8. -- Summary of data from vertical electrical soundings made adjacent to piezometer nests and test holes -- Continued

Vertical electrical sounding at site adjacent to piezometer nest LLG-5: Sounding made along road east of piezometer nest, electrode line oriented north-south.

$\overline{AB}/2$, in meters	$\overline{MN}$, in meters	ΔV, in millivolts	I, in milliamperes
1.00	0.3	7,920	390
1.47	0.3	4,180	390
2.15	0.3	1,870	395
3.16	0.3	880	400
4.64	0.3	418	500
---	---	---	---
10.0	1.0	154	400
14.7	1.0	53	400
---	---	---	---
31.6	3.0	14.9	400
46.4	3.0	5.0	400
---	---	---	---
100	10.0	3.1	300
147	10.0	1.7	300
---	---	---	---
316	30.0	1.8	500
464	30.0	.88	600
---	---	---	---
---	---	---	---

$\overline{AB}/2$, in meters	$\overline{MN}$, in meters	ΔV, in millivolts	I, in milliamperes
---	---	---	---
---	---	---	---
---	---	---	---
3.16	1.0	2,640	400
4.64	1.0	1,320	500
6.81	1.0	539	500
10.0	3.0	440	400
14.7	3.0	154	400
21.5	3.0	49	400
31.6	10.0	52	400
46.4	10.0	17.6	400
68.1	10.0	2.9	300 *
100	30.0	10.1	300
147	30.0	5.2	300
215	30.0	4.1	500
316	100	6.2	500
464	100	2.9	600
681	100	.39	200
884	100	.22	200

* Error in field measurements, not used in analysis of data.

Vertical electrical sounding at site adjacent to test hole 2-B-70: Sounding point was approximately 400 feet south and 20 feet higher than test hole location. Sounding made along road west of test hole location, electrode line oriented north-south.

$\overline{AB}/2$, in meters	$\overline{MN}$, in meters	ΔV, in millivolts	I, in milliamperes
1.00	0.3	704	300 *
1.47	0.3	693	400 *
2.15	0.3	99	200 *
3.16	0.3	64	300 *
4.64	0.3	41	220 *
---	---	---	---
10.0	1.0	52	150
14.7	1.0	55	400
---	---	---	---
31.6	3.0	23	400
46.4	3.0	15.4	600
---	---	---	---
100	10.0	4.7	200
147	10.0	8.9	800
---	---	---	---
316	30.0	2.8	500
464	30.0	1.3	600
---	---	---	---
---	---	---	---

* Error in field measurements, not used in analysis of data.

$\overline{AB}/2$, in meters	$\overline{MN}$, in meters	ΔV, in millivolts	I, in milliamperes
---	---	---	---
---	---	---	---
---	---	---	---
3.16	1.0	1,430	300
4.64	1.0	396	190
6.81	1.0	281	300
10.0	3.0	187	150
14.7	3.0	138	300
21.5	3.0	47	300
31.6	10.0	92	400
46.4	10.0	50	500
68.1	10.0	13.2	300
100	30.0	17.4	250
147	30.0	26	800
215	30.0	8.8	600
316	100	11.6	600
464	100	3.2	500
681	100	.88	500
884	100	.66	600

Table 8. -- Summary of data from vertical electrical soundings made adjacent to piezometer nests and test holes -- Continued

Vertical electrical sounding at site adjacent to test hole 1-CH-82: Sounding made along road east of test-hole location, electrode line oriented north-south.

$\overline{AB}/2$, in meters	$\overline{MN}$, in meters	ΔV, in millivolts	I, in milliamperes
1.00	0.3	11,550	800
1.47	0.3	6,655	800
2.15	0.3	2,475	700
3.16	0.3	1,111	700
4.64	0.3	473	700
---	---	---	---
10.0	1.0	331	800
14.7	1.0	160	900
---	---	---	---
31.6	3.0	54	800
46.4	3.0	16.0	800
---	---	---	---
100	10.0	9.1	600
147	10.0	6.1	800
---	---	---	---
316	30.0	4.7	900
464	30.0	1.7	800
---	---	---	---
---	---	---	---

$\overline{AB}/2$, in meters	$\overline{MN}$, in meters	ΔV, in millivolts	I, in milliamperes
---	---	---	---
---	---	---	---
---	---	---	---
3.16	1.0	4,125	700
4.64	1.0	1,650	700
6.81	1.0	803	800
10.0	3.0	1,023	800
14.7	3.0	473	900
21.5	3.0	174	900
31.6	10.0	187	800
46.4	10.0	65	800
68.1	10.0	10.7	300
100	30.0	29	600
147	30.0	18.5	800
215	30.0	4.6	400
316	100	6.6	900 *
464	100	5.1	800
681	100	.94	400
884	100	.94	800

* Error in field measurements, not used in analysis of data.

Vertical electrical sounding at site adjacent to test hole 11-B-83: Sounding made along road east of test-hole location, electrode lines oriented north-south.

AB/2, in meters	MN, in meters	ΔV, in millivolts	I, in milliamperes
1.00	0.3	11,550	900
1.47	0.3	3,960	600
2.15	0.3	1,870	700
3.16	0.3	1,089	800
4.64	0.3	407	700
---	---	---	---
10.0	1.0	59	400
14.7	1.0	33	500
---	---	---	---
31.6	3.0	21	500
46.4	3.0	11.3	500
---	---	---	---
100	10.0	9.9	500
147	10.0	5.9	700
---	---	---	---
316	30.0	2.8	700
464	30.0	1.2	1,000
---	---	---	---
---	---	---	---

AB/2, in meters	MN, in meters	ΔV, in millivolts	I, in milliamperes
---	---	---	---
---	---	---	---
---	---	---	---
3.16	1.0	2,970	800
4.64	1.0	946	600
6.81	1.0	176	400
10.0	3.0	152	400
14.7	3.0	88	500
21.5	3.0	34	400
31.6	10.0	73	500
46.4	10.0	39	500
68.1	10.0	19.8	500
100.	30.0	40	600
147	30.0	18.2	700
215	30.0	8.5	700
316	100	10.2	700
464	100	4.3	1,000
681	100	1.1	1,000
884	100	.55	600