ACCELERATED GROUND WATER MANAGEMENT
GEOPHYSICS PHASE
REPORT OF BIENNIUM 1983-85

TECHNICAL ANALYSIS UNIT
DIVISION OF WATERS
DEPARTMENT OF NATURAL RESOURCES
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ACCELERATED GROUNDWATER MANAGEMENT

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List of Figures

List of Appendices

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INTRODUCTION

Water supply investigations in much of Minnesota have been concerned primarily with defining the extent of glacial sands and gravels at the surface (sand plain aquifers). Studies have traditionally relied on test drilling to define the vertical and horizontal boundaries of these surficial water-bearing bodies; when these sands and gravels are buried within less permeable glacial drift, the cost of direct data acquisition by drilling becomes prohibitive. Attention has now been directed to developing indirect, geophysical methods for defining aquifer boundaries of the buried drift aquifers.

The Minnesota Department of Natural Resources (DNR) and the United States Geological Survey (USGS) have conducted a two-year cooperative program to test the applicability of electrical resistivity, shallow seismic reflection and shallow seismic refraction to water resources investigations in areas of glacial deposits. Funding was provided by the Legislative Commission on Minnesota Resources.

The successful application of geophysical methods depends upon contrasts in physical properties of the rocks or deposits being studied. The seismic methods rely on contrasts in the velocities of propagation of an energy wave; electrical resistivity methods rely on contrasts in the ability to pass electrical current. These tools have the potential of allowing vertical and horizontal mapping of subsurface units by surface exploration.

Sites chosen for the study this biennium are shown on Figure 1. These sites were chosen to test the geophysical tools in the range of geologic conditions in Minnesota. All areas considered for this research had previously been studied by the DNR and/or the USGS and so had good geologic control. The sites are: 1) Hastings (buried bedrock valley); 2) Sherburne County (basement determinations); 3) Marshall County (buried beach ridge); and 4) Swift County (outwash and buried drift aquifers).

In addition to the targeted study areas, we had several opportunities to perform technical assistance for other projects. Seismic work was done to assist Division of Minerals in their mineral potential program and for the Minnesota Geological Survey in depth to bedrock mapping in Olmsted and Winona Counties. Resistivity work was done at Moon Lake (Douglas County) to help define a subsurface sand channel believed to be contributing to the high lake level problem. Both geophysical tools were used to help define subsurface conditions at Division of Forestry pesticide disposal sites.

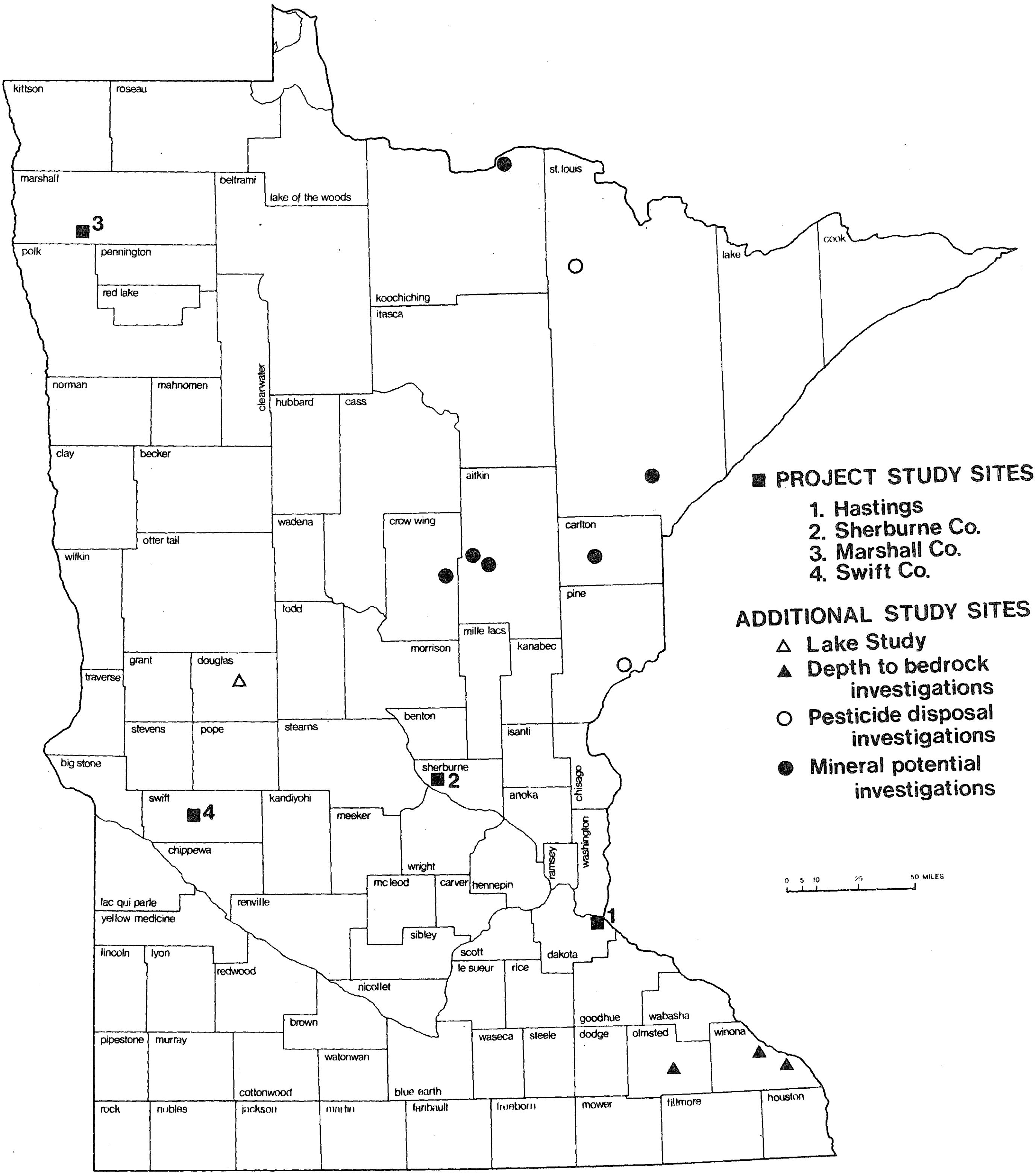


Figure 1. Geophysical Site Investigations

CONCLUSIONS

The geophysical methods of electrical resistivity and seismic refraction and reflection are useful in water resources investigations. In general, electrical resistivity has been found to be most useful for near-surface targets, while seismic techniques have worked best when exploring for deeper targets. The full range of application for shallow seismic reflection is just beginning to be realized. Preliminary work with this tool has concentrated on analytical techniques and equipment modifications. The outlook for improved reflection results is good.

Examples of near-surface features that have been successfully delineated with electrical resistivity include:

- near-surface beach ridges surrounded by clayey lake deposits;
- water table in relatively homogeneous sands;
- shallow bedrock;
- lateral boundaries of buried channel deposits.

Surface electrical resistivity methods can be employed to great advantage in the study of shallow groundwater contamination sites. Electrical resistivity can aid determination of the site geology, hydrology and, if the geology is sufficiently homogenous, the mapping of contaminant plumes.

Surface resistivity has not worked well in areas with complex geology, i.e. with many layers of alternating sands and clays or alternating layers with small electrical contrasts. Our cable system is not long enough for use in areas of thick drift (greater than 75 meters). We could build or purchase longer spread cables; however, laying out longer cables is very time-consuming, and crossing roads with cables is a problem.

Examples of subsurface interfaces which have been successfully detected by shallow seismic methods include:

- depth to water table (seismic refraction);
- depth to sand-till boundaries;
- depth to drift-bedrock boundaries;
- changes in the nature of bedrock surfaces.

Seismic exploration techniques work best when the target has reasonably sharp contacts such as sand-till and drift-bedrock boundaries, and when the targets are greater than 15 meters deep.

Seismic reflection is suitable for investigating deep targets, while electrical resistivity is best suited for near-surface targets. Thus, the two methods are complementary, and can be used effectively together.

RESULTS OF SITE SPECIFIC INVESTIGATIONS

HASTINGS

Hastings was the first site to be investigated with the seismic equipment and was chosen because of the known presence of a buried bedrock valley. It served a dual role, both as a geologically interesting region and as a stage upon which to develop skills as seismologists. Because this was our first field application of the geophysical equipment, it is not surprising that most conclusions about our work at this site arose from failures in our primary goal of identifying reflections. This experience was important later and led to more successful investigations at other sites.

The Hastings site was chosen because of the presence of both a near-ideal depth to the potential reflector (a till/sandstone boundary) and a favorable velocity-density contrast across this interface. We sought to trace the cross-section of a buried river channel, but could not adapt the field procedures to the rapidly changing reflector. The sub-surface characteristics of these channels remain tempting to shallow seismic investigations and may warrant a return visit.

SHERBURNE COUNTY

Two observation well sites in Sherburne County, the Gray Farm site and the Clear Lake site, were investigated. The Gray farm site was the most intensely studied. At the Gray Farm observation well, the water table was at a depth of 4.6 meters and bedrock (granite) at a depth of 27.1 meters. Both the great depth to the water table and relatively shallow depth to the reflector presented a challenge. Attempts to detect a reflection from the till/granite interface employed data collection techniques used by oil companies in deep seismic work. Although seismic refraction clearly defined both water table and bedrock, reflections were not seen. (Refraction cannot be used to define buried drift features due to its great dependence upon strong velocity-density contrast; further, this method requires an increasing velocity gradient with depth).

<u>Discussion of Gray Farm Site</u>

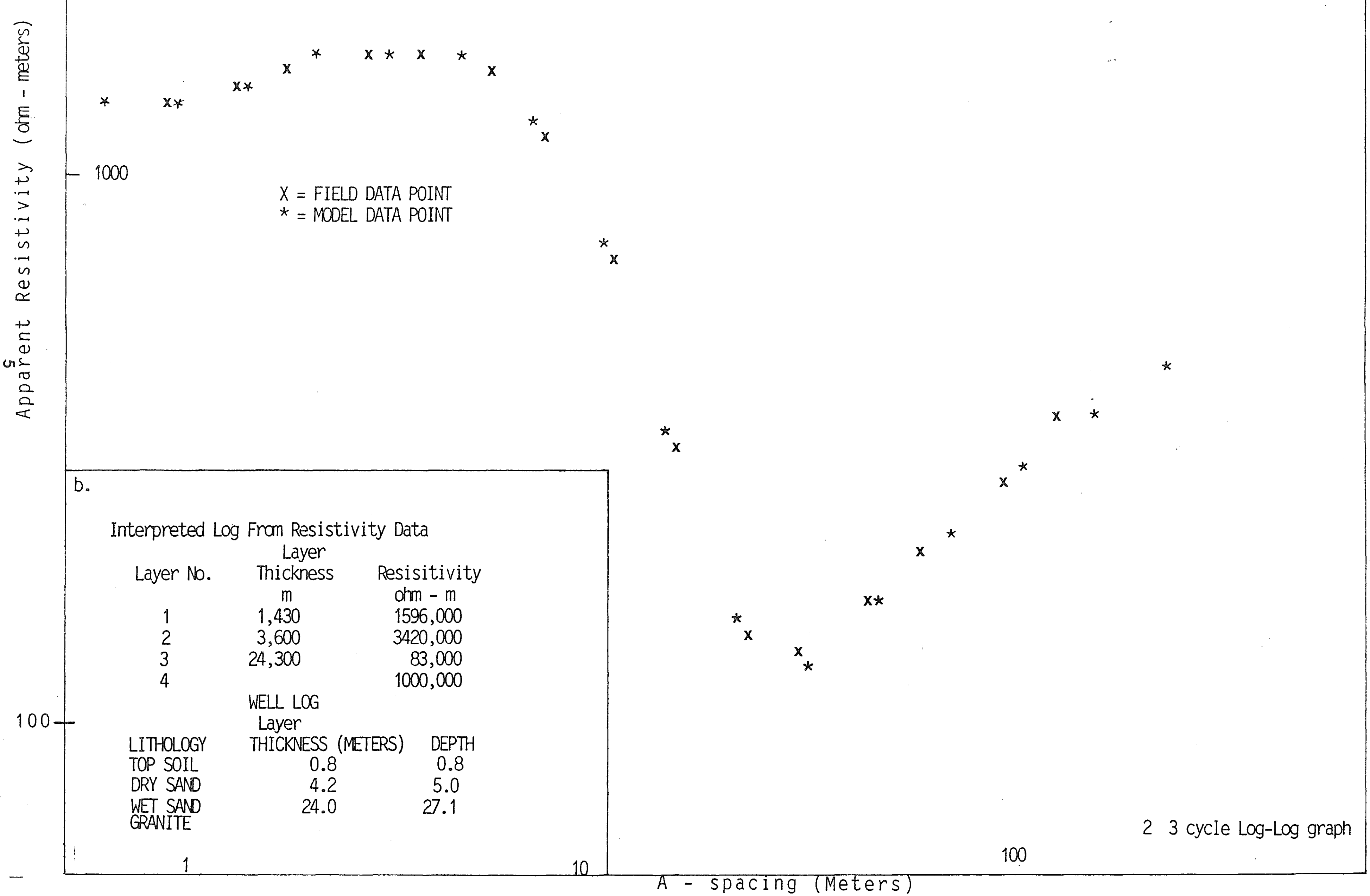
The Gray Farm site was also studied with electrical resistivity (ER). Four electrically distinct layers were present, with high electrical contrasts between layers and high resistivity bedrock at a depth of only 27.1 meters. This enabled surface ER and associated interpretive techniques to reasonably define the surface to bedrock geology including depth to the water table, (see Figure 2). A more thorough discussion of resistivity results is presented in Appendix A, "Assessment of Buried Aquifers in Minnesota Using Computer-Generated Wenner Electric Sounding Curves" (presented at February 1984 National Water Well Association Ground Water Conference).

Figure 2 Sherburne Co. Howard Gray Site

a.

VES Curve Matching Interpretation - Mooney & Orrellana

The following is a log-log plot of apparent resistivities vs. wenner a-spacings. The positive match between curves representing the field resistivity data and the model generated from this interpretation is shown in Fig. 2a.. The validity of this interpretation is corroborated by comparing model layer thicknesses to the well log data, fig. 2b.



b.

Interpreted Log From Resistivity Data

Layer No.	Layer Thickness m	Resisitivity ohm - m
1	1,430	1596,000
2	3,600	3420,000
3	24,300	83,000
4		1000,000

WELL LOG

LITHOLOGY	Layer THICKNESS (METERS)	DEPTH
TOP SOIL	0.8	0.8
DRY SAND	4.2	5.0
WET SAND	24.0	27.1
GRANITE		

Discussion of Clear Lake Site

A second site was investigated near the Clear Lake elementary school. It provided a valuable contrast to our results from the Gray farm site. Composition of earth material, composition of bedrock, terrain and depth to water table were similar to the first site, while depth to bedrock differed. Therefore, any anomalous results could be confidently ascribed to the change in depth of the reflector. We were successful in collecting reflections from the granite, and depth to bedrock was calculated to be 76.2 meters. The reflected signal was strong and stable, as expected for the nature of the till/granite interface.

MARSHALL COUNTY

A large, continuous buried beach ridge northeast of the City of Warren was the target site for both seismic and resistivity surveys. The location and geometry of these deposits was previously outlined by means of numerous test holes for a study which has been published in the U.S.G.S. Hydrologic Atlas No. 201.

A single seismic line was run across the aquifer. Reflections from three different interfaces were recorded, corresponding to the upper boundary and lower boundaries of the main sand unit and to the top of a second, deeper unit. The reflections lack continuity and so do not allow detailed depth calculations. The steep slope and lack of a sharp velocity-density contact in the till/sand interface has apparently reduced its suitability as a seismic reflection target. The result is a disjointed record that inadequately follows the changes in the buried drift boundary. Equipment failure precluded further work.

Two deposits were investigated by electrical methods. The first (Site A) is located at T155N, R47W, Sections 11 and 12 (see Figure 3) and the second (Site B) is located at T157N, R48W, Sections 21, 22 and 27, (see Figure 4). Thirty-six (36) soundings were run over sites A & B by a three person crew in four days using the Bison 2390 resistivity meter with the Bison Boss 2365 cable system. This system produces a type of Wenner curve.

Discussion of Site A

The target at Site A is characterized by a sand deposit of up to 12.2 meters in thickness overlain by up to 24.4 meters of till. Soundings at this site are not significantly different from soundings from an adjacent area where the buried sand layer is reportedly absent. This indicates that the electrical contrasts of the overlying till and buried sand layer may have been insufficient to allow detection. Alternatively the depth penetration may have been insufficient to reach the target.

Discussion of Site B

At this site a total of 24 soundings were run along four lines. The deposit of interest was intersected at several locations. Two of these lines correspond closely to cross sections generated by a series of test holes mentioned above (Figure 4). To minimize the effects of subsurface lateral variations on the electrical soundings all lines were layed out in a N-S direction, approximately parallel to the targeted deposit.

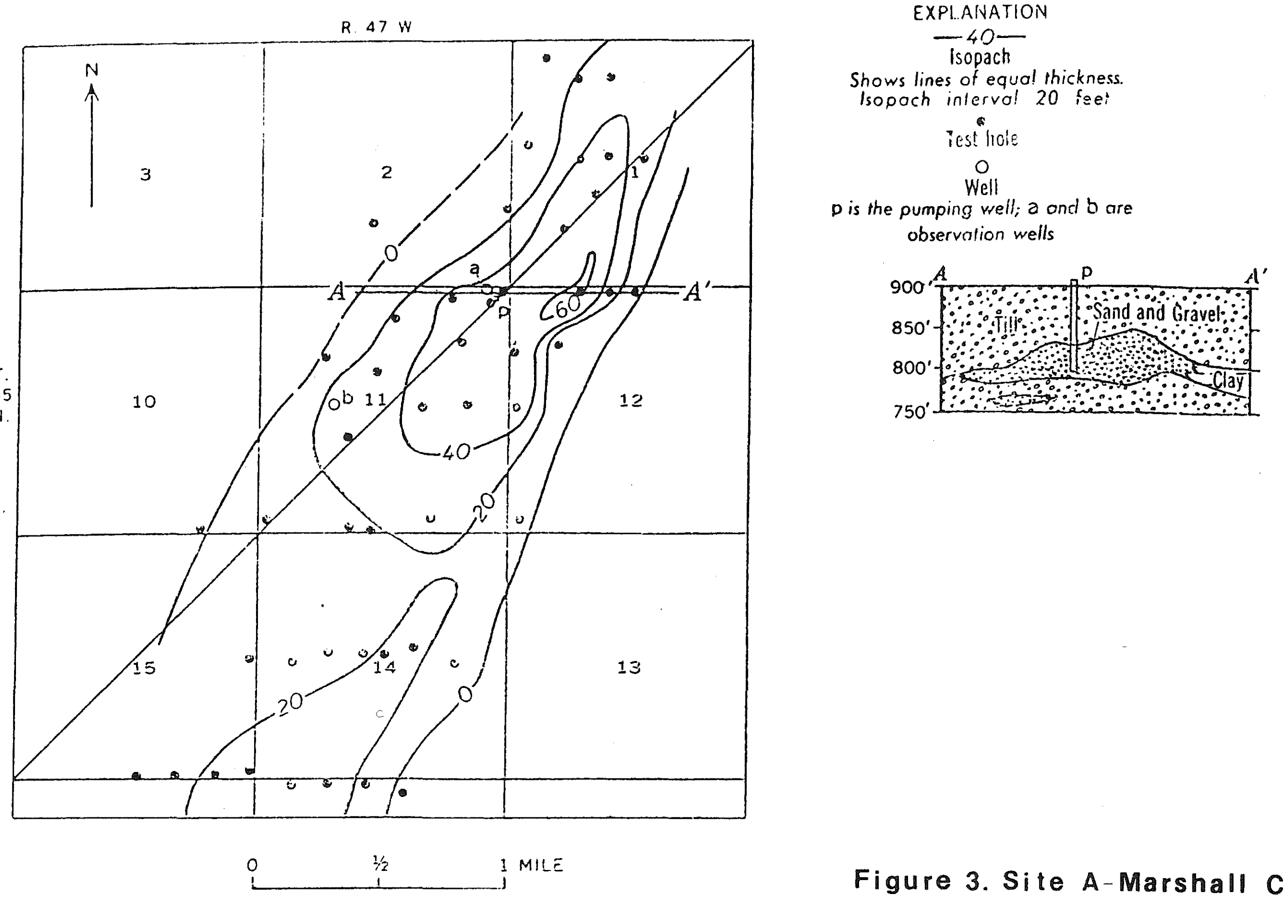


Figure 3. Site A-Marshall Co.

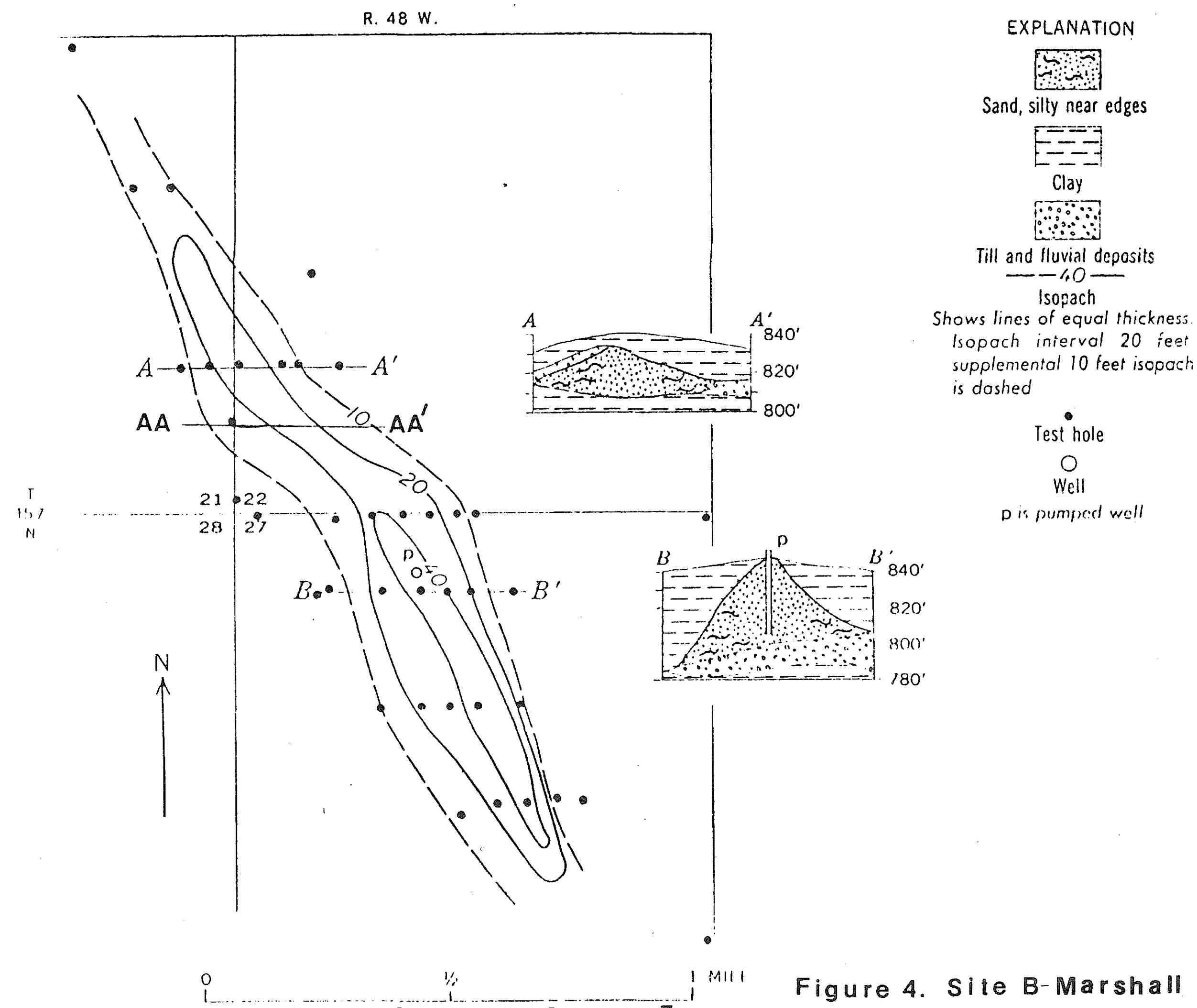


Figure 4. Site B-Marshall Co.

* Figures 3 and 4 from U.S.G.S. H.A. 201

Apparent resistivities for the various A-spacings were calculated. Two geoelectric psuedo-sections were generated by plotting apparent resistivities vs. A-spacing and drawing apparent resistivity isopachs. One geoelectric psuedo-section was generated along a line 183 meters south and parallel to line A-A', referred to as line AA-AA', and another along line B-B', (see Figure 4). Although precise quantification of this data requires further analysis some definitive characteristics of the buried deposit can be seen. Along AA-AA' (see Figure 5) there exists a zone of higher resistivity material, probably sand or sand and gravel. This is buried at some depth and is thickest near sounding #23. A similar but more pronounced and nearer surface feature can be seen at line B-B' (see Figure 6). The greatest apparent thickness is near sounding #4. Further analysis of sounding #4 was performed by auxiliary point curve matching for preliminary model development and model refinement. This model indicated a 9.8-meters-thick sand deposit starting immediately below the top soil layer. This agrees very well with the auger boring logs in the area.

SWIFT COUNTY

Several areas in Swift County in west-central Minnesota were chosen for demonstrating the effectiveness of geophysical methods in determining the geometry of buried drift aquifers. The areas surveyed were selected because the locations of the targeted aquifers had been previously defined in a groundwater modeling study by the U.S.G.S. based on well log information. Although the surficial aquifer does overlap one or more buried aquifers in many locations, we concentrated on areas where a particular aquifer was isolated to keep data interpretation manageable.

We conclude that resistivity surveys are suitable for mapping buried aquifers provided the aquifers are of sufficient size. However, no more than approximately 5 electrically different layers may be present, and well log information for calibration must be available.

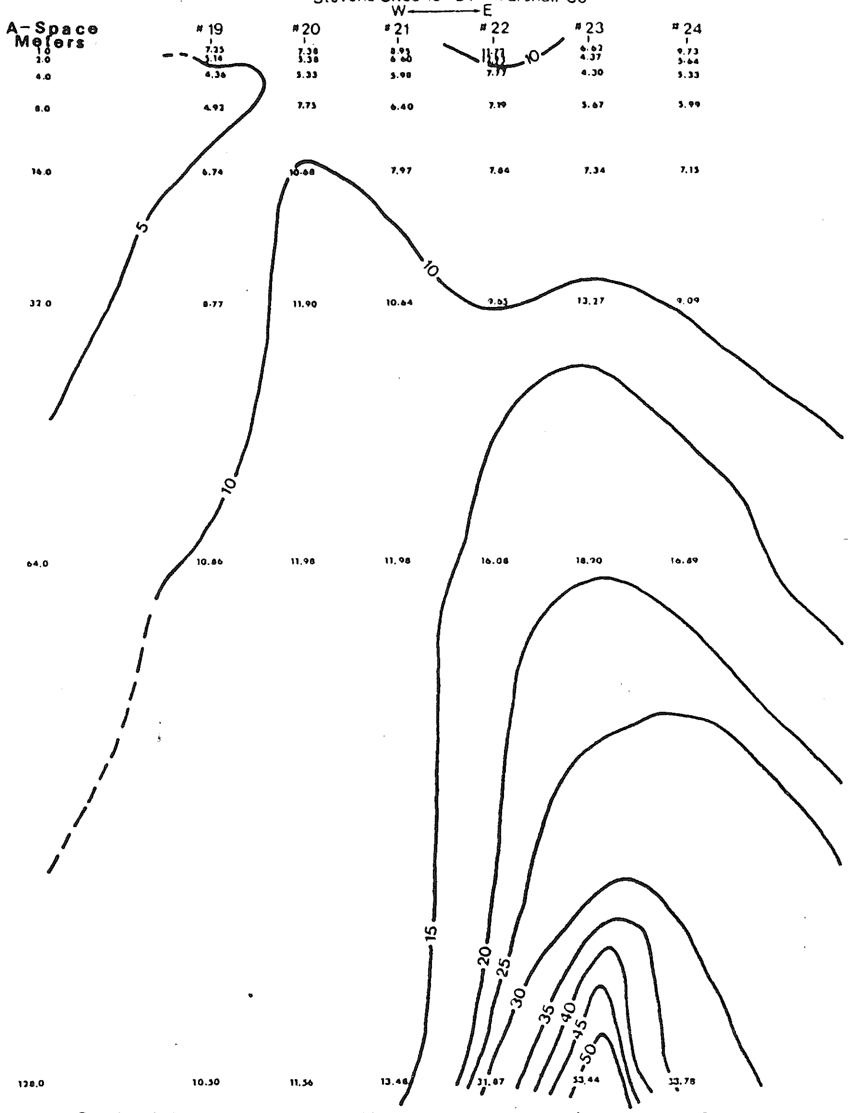
Seismic data from Swift County shows the importance of data processing. The waveform of Figure 7 is an example of raw data. The 12 traces correspond to records from 12 geophones that lie along a line. Time increases from left to right on the horizontal axis. The first significant deviation of each trace from the neutral setting occurs on line M-M'. The raw record does not always reveal reflections and so must be processed to highlight salient portions of the signal. Figure 8, a modified version of the original record, is the result of selective processing by the Geopro seismograph. First, digital filtering is employed to remove the low frequency large-amplitude portion of the signal that is not related to the reflected signal. Second, variable area display is employed to aid the eye in pattern recognition by darkening the upper portions of large-amplitude waveforms. Because of its reliance on slower wavepaths, reflection analysis requires an understanding of the entire wave-train. In Figure 8 two reflection patterns can be seen along lines N-N' and O-O'. From the location and time of these signals one can calculate the depth to the reflector. In the case of the reflection marked by line N-N', the reflector was found to be the lower boundary of a surficial aquifer at a depth of 51 feet.

The data used in this example came from the Swift County results which are given a more detailed analysis in a companion paper, "The Use of Seismic Reflection to Define Buried Drift Aquifers" (submitted to Society of Exploration Geophysicists for presentation at the annual meeting in the fall of 1985 and attached at Appendix B).

Figure 5.

Stevens Sites 19 24 – Marshall Co

W——E

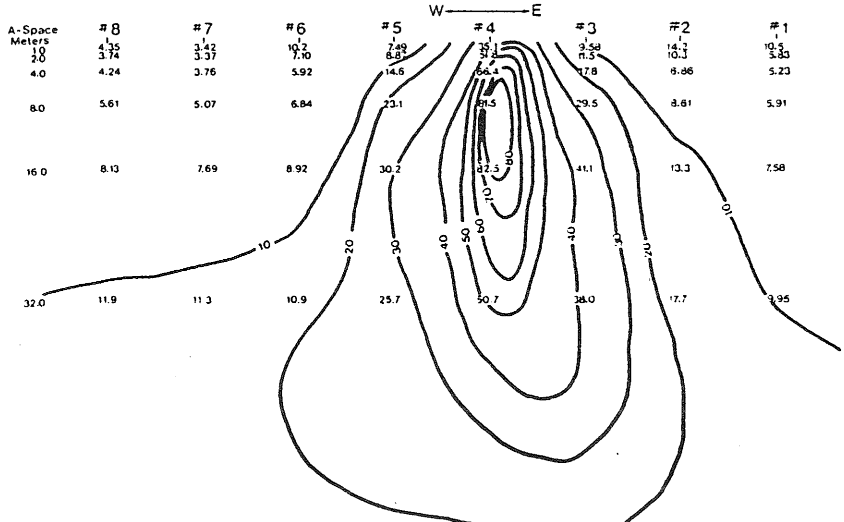


Geoelectric isopach parallel to and 600 feet south of Line A-A' H.A. 201 near Stephens - Marshall Co. MN. Units in ohms meters.

Figure 6.

Stevens Sites 1-8 — Marshall Co.

W——E



Geoelectric isopach along line BB' Area A-3 H.A. 201 near Stephens - Marshall Co. MN. Units in ohm meters.

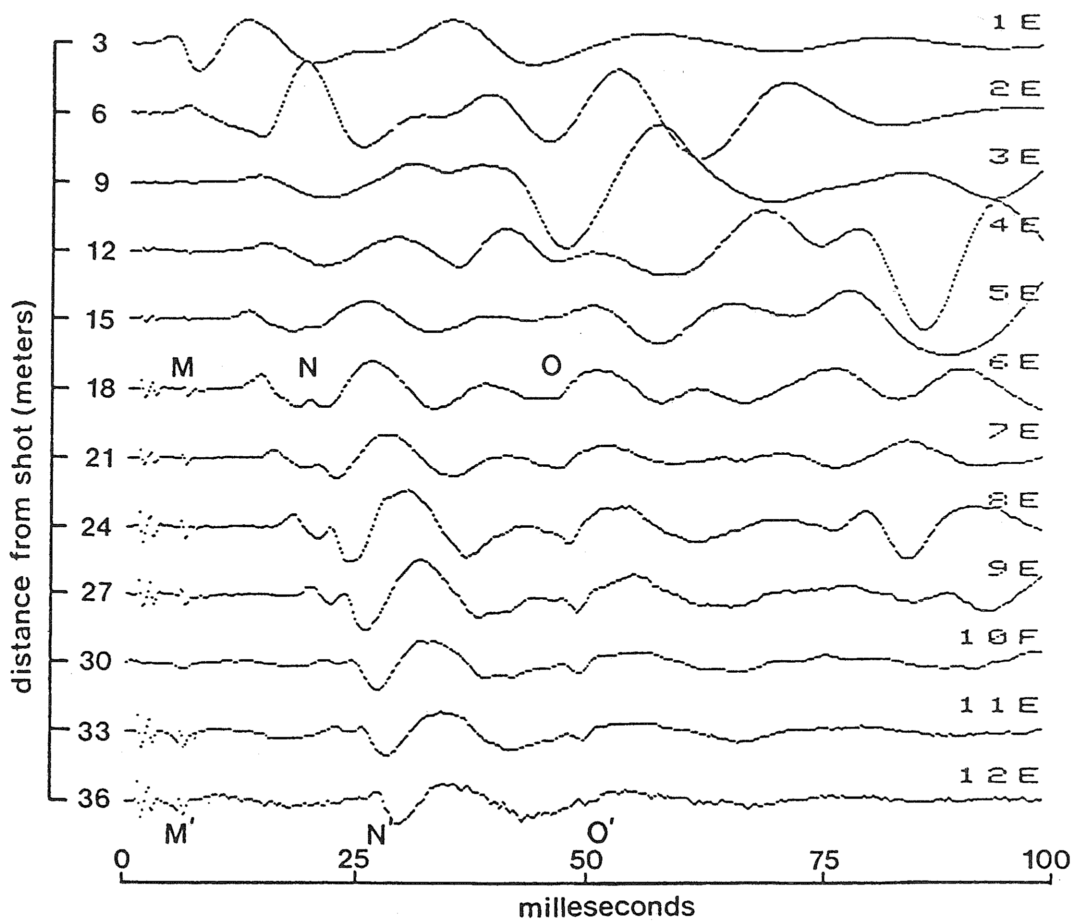


Figure 7, data set no.2; raw record. Swift Co., MN.

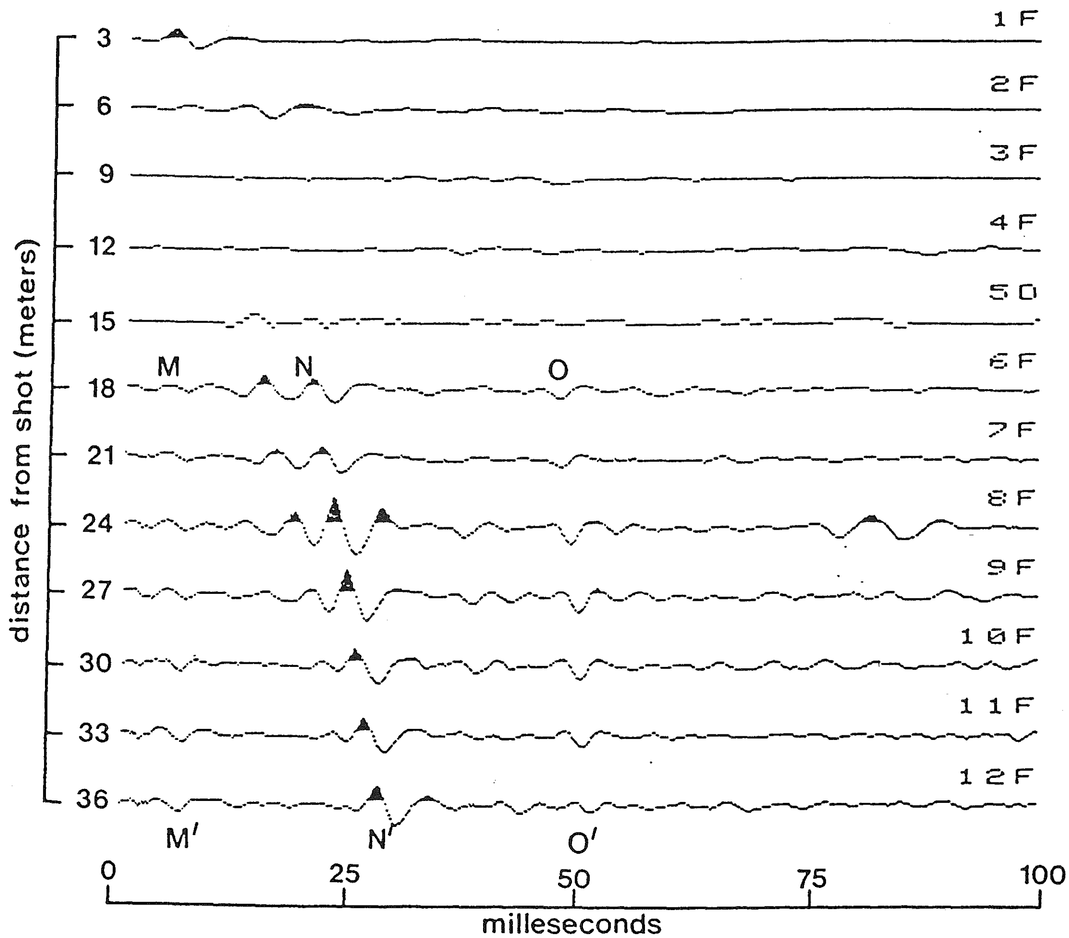


Figure 8, data set no. 2; processed record. Swift Co., MN.

APPENDIX A

ASSESSMENT OF BURIED AQUIFERS IN MINNESOTA USING COMPUTER-GENERATED WENNER ELECTRIC SOUNDING CURVES

By: Gilbert Gabanski
Joe Julik
Oulgout Bassou

Assessment of Buried Aquifers in Minnesota
Using Computer-Generated Wenner Electric Sounding Curves

by Gilbert Gabanski[1], Joe Julik[1], and Oulgout Bassou[2]

ABSTRACT

Aquifers buried in drift are becoming a primary source of water for users in the western third of Minnesota. These aquifers are irregular in shape and thickness, and the hydrologic data necessary to describe the ground water system is often lacking. Installation of high-capacity wells has resulted in well-interference problems. The areal extent and hydrologic parameters of these aquifers should be determined to establish ground water management plans. Drilling to obtain this information is prohibitively expensive, therefore electrical geophysical methods are used to obtain subsurface information and to act as a guide for selecting a limited number of drilling sites.

Resistivity models consisting of a series of layer thickness and true resistivity values were developed, in advance of the field work, from available hydrogeologic regional study data and from borehole data. Computer programs generated Wenner electric sounding curves for these models, and the sensitivity of the method was checked by varying the range of resistivity values and the configuration of layers. These model curves were used as a guide for the field investigations.

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Vertical electric soundings were collected in the field using the Barker Wenner offset electrode configuration. This configuration was found to be more effective than the standard Wenner electrode configuration. Data were interpreted in the field using a hand-held calculator program for curve matching analysis. Field curves were compared to the resistivity model curves to quickly assess the geology of the site. Interpretation in the field either confirmed the geologic model or indicated the need for more field data.

This approach was used to assist in the calibration of a ground water management model for Sherburne County, Minnesota. Geophysical estimation of depth to bedrock and thickness of the buried aquifer was done in the field and drilling was used to check conclusions. An area with an extensive surficial and buried drift aquifer system in Swift County, Minnesota will be studied in the next field season using this method.

INTRODUCTION

Since 1975 the Minnesota Department of Natural Resources, Division of Waters, has seen a two-fold increase in water appropriation permits for high-capacity water wells. Many of these wells produce from Quaternary buried outwash deposits located throughout most of western and central Minnesota. These aquifers are irregular in shape and thickness, and there is often very little hydrogeologic information available to describe the system. High capacity wells pumping from these aquifers have interfered with smaller capacity domestic wells. Increased public concern with ground water depletion, disputes between irrigators and non-irrigators, and a general ground water resource management problem have resulted from the proliferation of these high capacity wells. Budget constraints have limited hydrogeologic evaluation and resource management of the numerous buried outwash aquifers; in particular, drilling programs have become prohibitively expensive. Scattered well logs, and, in some cases, published regional studies are available and can be used in conjunction with other exploration methods to provide a base of hydrogeologic information for an area. One exploration method which might be used is electrical resistivity.

Vertical electrical sounding (VES) has been shown to be an effective exploration tool. However, when used as the sole source of hydrogeologic data for a large area, VES resistivity surveys are also expensive and inefficient (Merrick, 1977). Detailed mapping with VES requires a large number of sites. The time and money spent collecting and interpreting data at all the necessary sites might be more wisely invested in several test holes. Even a few "random" reconnaissance VES sites in a large area could produce little information at great expense. The problem becomes one of maximizing the use of available information before and while conducting field surveys. This can be accomplished by first developing resistivity models and computer-generated sounding curves for these models for the area in question. These are then used to evaluate the applicability of the VES method and the potential of producing cost effective results with it. This question is important wherever hydrogeologic information is required but where the budget is limited.

PURPOSE AND SCOPE

Use of the VES method to evaluate a large area in Sherburne County underlain by a buried outwash aquifer was the major objective of this study. We emphasized the use of a systematic planning process to decide whether to conduct a resistivity survey, to determine which parameters could be defined by the resistivity survey, and to use feedback from this systematic approach as field information was collected. This planning process consists of five steps:

1) to collect existing borehole data, published reports, and other information that could be used to describe the physical parameters of the study area,

2) to decide which parameters are not adequately defined,

3) to incorporate the existing information into resistivity models which represent earth models determined by the range of physical parameters,

4) to generate the sounding curves for these models with a computer program which determines apparent resistivity and electrode spacing for a specific geoelectric model,

5) to evaluate these model curves and to determine if selected parameters can be detected by the VES method.

For example, if depth to bedrock is important, the sounding curve will show if it is detectable and what electrode spacing for a given array is necessary to detect the depth.

The sensitivity of the method to small changes in the physical parameters is evaluated using additional models and sounding curves. For example, if a unit is to be detected in a resistivity survey, the minimum thickness and/or true resistivity contrast of a buried unit must increase with depth. If a particular unit is important, a clay layer for instance, then depth, thickness, and resistivity contrast are modeled to determine if the VES method will detect its presence. Field sites are selected in areas where the model predicts detection to be possible.

Field sounding curves are plotted and matched to model sounding curves during the collection of field data. Hand calculator programs can then be used to refine the model curve based on actual results. Large deviations from the expected model in a given area indicate a need for additional field data or drilling data.

DESCRIPTION OF STUDY SITE

Surficial and buried outwash aquifers were mapped by Lindholm (1980) near the city of Clear Lake, Sherburne County, Minnesota (Figure 1). The area is underlain by surficial and buried sands and gravels of variable thickness. The surficial outwash ranges in saturated thickness from 12 to 24 m. Buried outwash is found in two areas under semi-confining clay lenses with sand. The clay lenses are from 3 to 9 m thick, the underlying outwash is 15 to 33 m thick (Figure 2). The bedrock surface, which is not well defined, is irregular. As much as 55 m relief has been found in the general region. Lindholm (1980) also reported a till layer between the outwash and the bedrock; however, the presence of this till in the Clear Lake area is not well documented. Although the area has many high-capacity wells, few fully penetrate the aquifers and many of these wells lack detailed driller's logs.

In 1983 the decision was made to develop a ground water management model for the Clear Lake area because of the installation of additional high-capacity irrigation wells. All available borehole data and the information from Lindholm's (1980) report were compiled and used to form the physical basis of a numerical finite-difference model. Calibration and verification of the model could not proceed due to inadequate hydrogeologic information; in particular, depth to bedrock, saturated thickness and areal extent and thickness of the semi-confining beds were inadequately known. Budget constraints limited observation well drilling to three or four wells, thus site selection became critical. Field data from a concurrent VES survey in the same area (Bassou, 1984) had also become available for use in the site selection process.

METHODS

Resistivity Models

Resistivity models are geoelectric, layered-earth models composed of a number of layers of specified thickness and true resistivity value. Geoelectric models are not necessarily unique, several models may produce similar curves, thus a geoelectric model must represent a realistic earth model. One difficulty in developing a model which represents unconsolidated glacial deposits is the complexity und multitude of possible layers. These deposits consist of many sharply contrasting textural mixtures which may intergrade or interfinger unpredictably. The assignment of true resistivity values to selected layers is difficult. Naturally occurrring rocks and soil display a wide range of values. Keller and Frishknecht (1966, p. 40) give a resistivity range for granite as 500 to 2000 ohm-meters. Telford et al (1976, p. 450-457) cite resistivity for granite as 300 to 10^6 ohm-m; alluvium and sands as 10 to 8000 ohm-m; clays as 1 to 100 ohm-m; and wet clays as 20 ohm-m. Palacky and Jagodits (1975) give resistivities of gravels in the 1000 to 2000 ohm-m range; sands from 200 to 1000 ohm-m; and tills and clays from 10 to 200 ohm-m. McNeill (1980) cites a resistivity range for sandy soils as 500 to 1500 ohm-m; loose sands as 10^3 to 10^5 ohm-m; glacial till as 10 to 1500 ohm-m; and crystalline rocks as 10^3 to 10^6 ohm-m. Zohdy and Bisdorf (1979) investigated a buried outwash deposit near Moorhead, Minnesota, approximately 260 kilometers northwest of the Clear Lake site. The resistivity values from VES surveys and probable correlated lithologies served as a preliminary guide for selecting resistivity values for the Clear Lake models; however, the Clear Lake resistivity values for similar lithologies were later determined to be higher than the values selected from Zohdy and Bisdorf (1979). Obviously, field experience in an area or specific literature sources are necessary to reduce the range of possible resistivity values for use in a specific model.

The number of layers and their thickness range were initially determined from the inventory of borehole data and an evaluation of Lindholm's (1980) report. These were then modified by examining preliminary information as it became available from Bassou (1984).

A general four-layer model was selected (Table 1) with a thickness range (H) for layers 2 and 3 and true resistivity (R) ranges for all four layers. Bassou's (1984) data indicated that a thin soil layer was present and detectable by the VES method. The thickness of layer 1 was set as one meter because preliminary modeling indicated that small thickness variations in this layer would not result in major changes in the sounding curves. The thickness of layer 4, or the underlying half-space, is always infinite. The true resistivity for each layer was selected based on estimates from the literature, results from Zohdy and Bisdorf (1979) and preliminary results of field work by Bassou (1984).

Theoretical Wenner VES Curves

Theoretical Wenner VES curves were generated for a variety of resistivity models using the Fortran computer program RESIST (Davis, 1979 a,b; and Mooney, 1980). RESIST computes apparent resistivity values at six points of electrode spacing per log-cycle decade for a geoelectric model and a specified electrode array by solving the forward problem and using linear filter theory developed by Ghosh (1971 a,b) and Davis (1979 a). The basic model assumes that each layer is electrically homogeneous and isotropic. Ballantyne _et al_ (1981) offers a similar program for hand-held calculators.

The theoretical Wenner VES curves consisted of various combinations of thicknesses and true resistivity values; models A, B, C, and D as shown in Figure 3 and 4. All of the curves were four-layer models of the KH type where $R1 < R2 > R3 < R4$. Figure 3 shows four VES curves generated by keeping true resistivity (R) constant and varying the thickness (H) of layers 2 and 3. Curves shifted vertically and horizontally when a layer thickness was increased. If depth to bedrock is to be determined, then the minimum field electrode spacing for a Wenner configuration can be evaluated by comparing the VES curves for model A and D.

Figure 4 shows an example of Wenner VES curves where layer thickness (H) is held constant and the true resistivity (R) of layers 3 and 4 is varied. These curves illustrate the dominating influence of the true resistivity for layer 3 compared to that of layer 4. This can be seen by comparing curves for models A to C and B to D (Figure 4).

The shape of the curves was dominated by the true resistivity contrast of layer 3 to the other layers. In the Clear Lake area layer 3 of the four-layer geoelectric model did not realistically model the surficial and buried outwash found. The presence of additional layers, including a confining unit, was evaluated by dividing layer 3 into three separate layers, thus creating a six-layer model (Table 2). The sensitivity of the computer-generated Wenner VES curves to variations in the thickness and true resistivity could then be evaluated.

In Table 2, the thickness and true resistivity of layers 1, 2, and 6 were kept constant. True resistivity contrasts between layers 3 and 5 to layer 4 were kept constant while the thickness of layers 3 and 5 were varied in relation to layer 4. Figures 5, 6, 7, and 8 show examples of theoretical Wenner VES curves for true resistivity contrasts of 15, 3, 2, and 1.5 times between layers 3 and 5 to layer 4. The departure of model H2, H3, and H4 from Model H1 is presented as a percentage. Field measurement accuracy is assumed to be 2 to 5 percent (Merrick, p. 93, 1977), thus a shift in a curve by 5 percent was used as a measure of the capability of detecting the confining unit. For example, in Figure 5 (true resistivity contrast 15 times), any thickness change would be detected. On the other hand, Figure 7 (true resistivity contrast 2 times) represents conditions where the thickness of the confining unit (layer 4) would have to increase to approximately one-third that of the upper or lower layers before it could be detected.

Field Electrode Configuration

A comprehensive review of the various types of electrode configurations available and used for VES exploration has been compiled by Whitely (1973). Each configuration has advantages and unique features which make it applicable to certain problems and less useful for others. Near surface lateral resistivity variations are one type of problem encountered in VES exploration in areas underlain by Quaternary deposits. The variations will distort the sounding curve and usually the distortion is difficult to interpret and correct. The Schlumberger configuration has commonly been used instead of the Wenner configuration for this problem because it is less sensitive to undetected lateral variations in resistivity (Mooney, 1980). Yet the Schlumberger method is costly if adequate field crew are used and slow (though not as slow as the Wenner configuration) if an adequate crew is not available.

A variation on the Wenner configuration has been developed (Barker, 1981). The Barker Wenner offset sounding array with a multicore cable is designed to eliminate problems from lateral effects, to improve accuracy of the measured results, and to reduce time and personnel requirements. The method employs a basic five electrode Wenner array, as shown in Figure 9. The resistance from RD1 and RD2 are averaged to provide the offset Wenner resistance RD. The five electrode array spacing is doubled for each new measurement with the center electrode common to all spacings. Two pairs of multicore cables with fixed electrode positions are spread from the center. Nineteen fixed electrode positions are used to measure 8 Wenner spacings and calculate an additional 8 Wenner spacings resulting in a 16 point Wenner sounding curve. The calculated intermediate Wenner spacing points are not spurious interpretations but the result of various readings from the different configurations and spacings. The configuration for measuring RA, RB, and RC resistances are from the tripotential method of checking for lateral resistivity variations (Barker, 1979; Carpenter, 1955; and Carpenter and Habberjam, 1956). The tripotential method uses the relationship:

$$RA = RB + RC$$

as an observation error check. Differences greater than 10% indicate either instrument errors of measurement or the presence of sources or sinks within the earth. This error calculation provides a reliable check on field data as measurements are taken.

Two additional error measurements, the offset error and lateral error are also calculated. The offset error measures the effects of subsurface lateral resistivity variations by comparing RD1 and RD2 resistances. The lateral error is another measure of the effects of lateral resistivity variations but uses resistances measured at two different spacings. Additional information on all three error measurement methods is found in Barker (1981).

Field Data Collection

Field work was conducted with a Bison Model 2390 Resistivity System[3] and a Bison Model 2365 Offset Sounding System[3]. The multicore cable has electrode hook-ups spaced at metric intervals so all spacings and resistivity values are in metric units. Bassou (1984) used the Bison Model 2350

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[3] The use of a brand name in this report is for descriptive purposes only and does not constitute endorsement by the Minnesota DNR-DOW.

Resistivity System and both the Wenner and Schlumberger methods. The Wenner offset sounding method was found to be more efficient and reliable than the standard Wenner or Schlumberger methods.

RESULTS AND DISCUSSION

A total of 47 soundings were made using the standard Wenner and Schlumberger methods and 15 soundings were made with the Barker Wenner offset method. An example of the field data from site C10 (Figure 1) and the data form for the Barker method are shown in Table 3. The error calculations are within recommended limits (Barker, 1981) except the lateral error for the 16 meter spacing. Site C10 was selected for a sounding because its location is near the buried outwash boundaries; and because a log for a nearby well indicated that the depth to bedrock should exceed 46 m.

After the field data from C10 were collected and plotted, model curves from the four-layer model were compared to the field curve. The differences between the field and model curves indicated that the top of the bedrock was obviously closer than expected. Estimates of layer thickness and true resitivities were used to generate modified model curves from a calculator program (Ballantyne et al, 1981). Variations in thickness and true resistivity which would shift the model curve closer to the field curve were tried. Figure 10 shows the field curve plot and the graph points for a four layer model. This model was later modified by using RESIST. The field curve did not indicate the presence of a confining unit but the decision was made to install an observation well nearby in order to verify the interpretation. The generalized log for the observation well, drilled 50 m west of sounding C10 (Figure 1), is shown in Figure 10. The actual depth to bedrock and to the water table were closely matched by the four-layer model.

The VES curves for sites within the buried outwash area do not indicate the presence of a confining or semi-confining unit. Two additional observation wells (Figure 1) were drilled. The logs of these wells indicate alternating layers with textures consisting of sand and gravel, sandy clay, and silty sand. The true resistivity contrast of these layers is probably not sufficient given their relative thicknesses to be reflected as detectable changes in the sounding curves. The high true resistivity values for the unsaturated zone also mask the smaller contrast between the layers in the saturated zone. Modeling the changes in the VES curves will require additional work and, most likely, more reliable estimates of true resistivity values.

The sounding curve interpretations have supplied information for other physical parameters. The depth to bedrock is very irregular and varies in altitude from 240 to 270 m, and the saturated thickness varies from 30 to 61 m. Most of this information was determined in the field from matching model curves to field curves and using the calculator program to refine the model. In areas where the field curve did not reflect the anticipated model, more time was spent refining the model and sometimes taking additional soundings nearby.

The Barker Wenner offset method was more efficient for a two person crew than the standard Wenner and Schlumberger methods. More data points for each sounding site were available and the reliability checks on the field data were useful. On occasion, when the observation error was outside the recommended limits, inspection of the cables and electrodes solved the problem. Several sounding sites had unusually high lateral errors which were reduced by rotating the array 90 degrees to avoid crossing the area with lateral variations. More work is necessary in order to quantify the information found in the error analysis.

CONCLUSIONS

The development of resistivity models and computer-generated sounding curves prior to conducting field investigations for a given area is a valid approach for evaluating the effectiveness and capabilities of the VES method. By generating the theoretical VES curves for the resistivity models, the user can decide if various physical parameters can be determined and how to conduct the field study in a manner which maximizes the available information for the area. Field interpretation is also improved by comparing the field curves to the model curves and by using hand-held calculator programs to refine the initial model. Field costs are then reduced by prior planning and on-going evaluation of the data. On-site decisions can then be made to collect additional information or to move to the next site.

Buried outwash deposits near the Clear Lake area, Minnesota, were investigated by using this planning approach. Four- and six-layer resistivity models were used to generate a multitude of sounding curves. These curves were used to determine parameters to be investigated and to site field locations. The Barker Wenner offset sounding array used to collect field data provided improved accuracy of measured results and information on lateral variations. On-site interpretation of the field curves by comparison to model curves assisted in planning additional field work. Observation wells drilled to confirm the interpreted geology indicated that the confining zone was irregular in areal extent and thickness and composed of alternating layers at variable depths.

The planning process is very useful for determining if resistivity mapping is possible and cost-effective, especially when resource managers request information about an area with inadequate hydrogeologic map coverage. This methodology will be used as a guide for additional work in larger buried outwash deposits in Swift County, Minnesota.

ACKNOWLEDGEMENTS

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Oulgout Bassou is a graduate student in hydrogeology at the University of Minnesota, Department of Geology and Geophysics. He has an engineering degree from the School of Mineral and Metallurgy Industry in Rabat, Morocco.

Figure 1. Clear Lake, Sherburne County, Minnesota. Map showing locations for high-capacity wells, observation wells, soundings, and cross section. Dashed lines outline general area underlain by buried outwash. Modified from Lindholm (1980).

Figure 2. Generalized cross section. See Figure 1 for location.

Table 1. Four layer resistivity model showing the range of thickness and true resistivity parameters and their interpretation for buried outwash area near Clear Lake.

Figure 3. Examples of Wenner electric sounding curves with constant R and variable H from the four layer model (Table 1).

Figure 4. Examples of Wenner electric sounding curves with constant H and variable R from the four layer model (Table 1).

Table 2. Six layer resistivity model with interpretation. Model is an expansion of four layer model and is used for determining the response in Wenner sounding curves to changes in thickness and true resistivity.

Figure 5. Sensitivity response of Wenner sounding curves for six layer model (Table 2) with resistivity contrast of 15x between r3 , r5 and r4. Percentages show the departures from model H1 for thickness changes in h3, h4, and h5.

Figure 6. Sensitivity response of Wenner sounding curves for six layer model (Table 2) with resistivity contrast of 3x between r3 , r5 and r4. Percentages show the departures from model H1 for thickness changes in h3, h4, and h5.

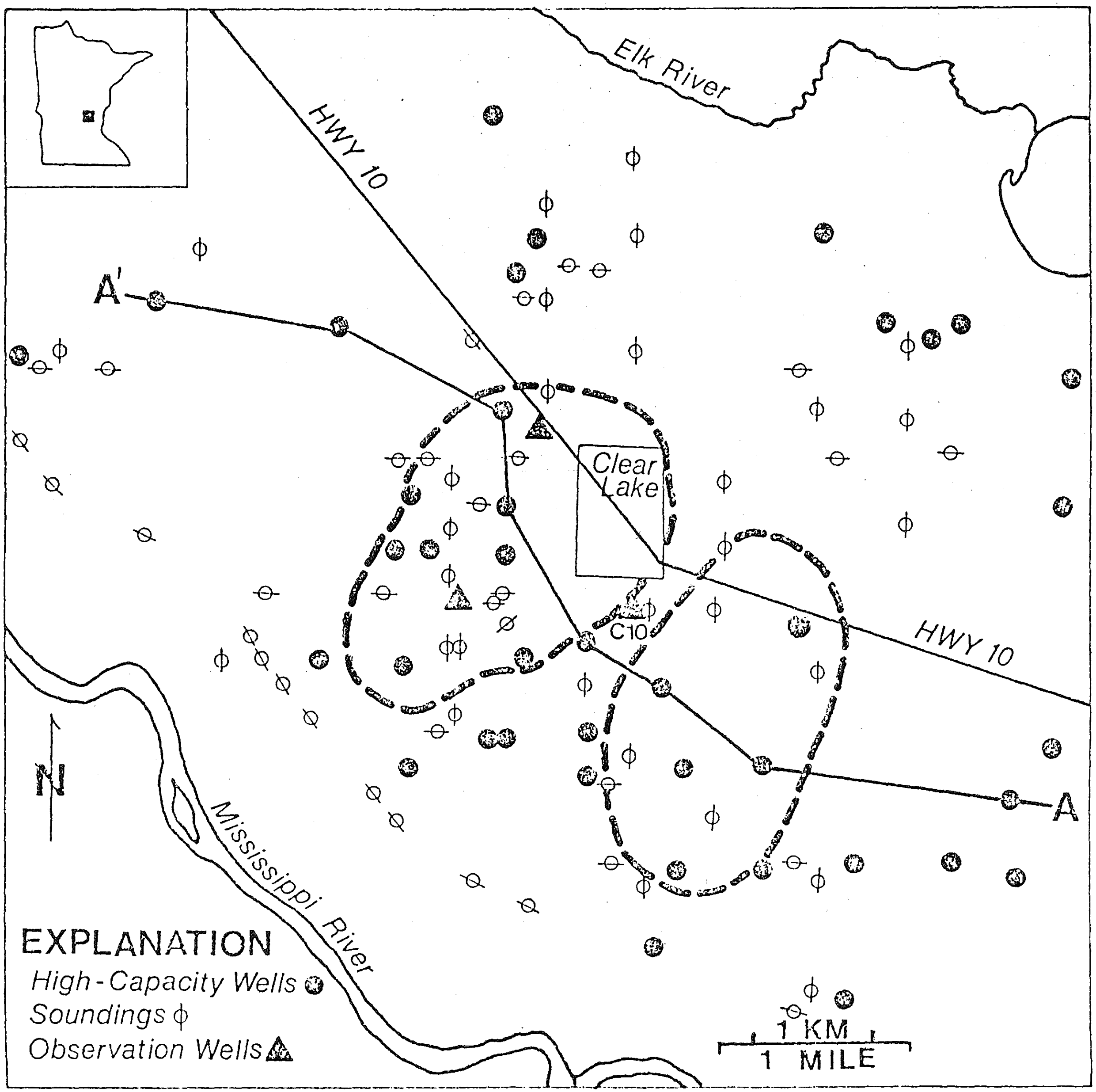
Figure 7. Sensitivity response of Wenner sounding curves for six layer model (Table 2) with resistivity contrast of 2x between r3 , r5 and r4. Percentages show the departures from model H1 for thickness changes in h3, h4, and h5.

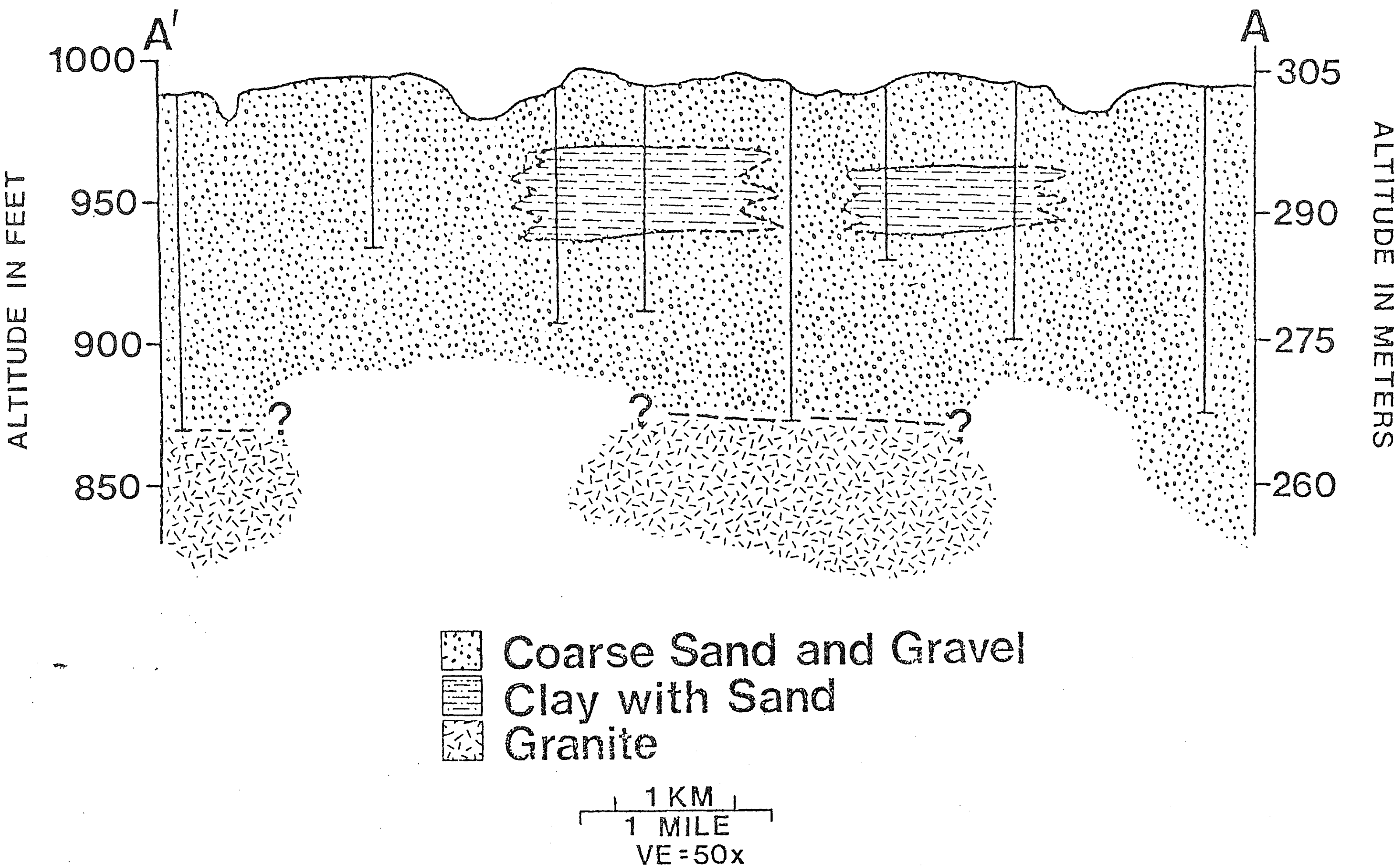
Figure 8. Sensitivity response of Wenner sounding curves for six layer model (Table 2) with resistivity contrast of 1.5x between r3 , r5 and r4. Percentages show the departures from model H1 for thickness changes in h3, h4, and h5.

Figure 9. Barker offset Wenner sounding electrode configuration. Observed spacing resistances are used to calculate additional spacing resistances. No readings were recorded for the 0.5 spacing and for RA, RB, and RC at the 1.0 spacing. C = current probe; P = potential probe. Modified from Barker (1981).

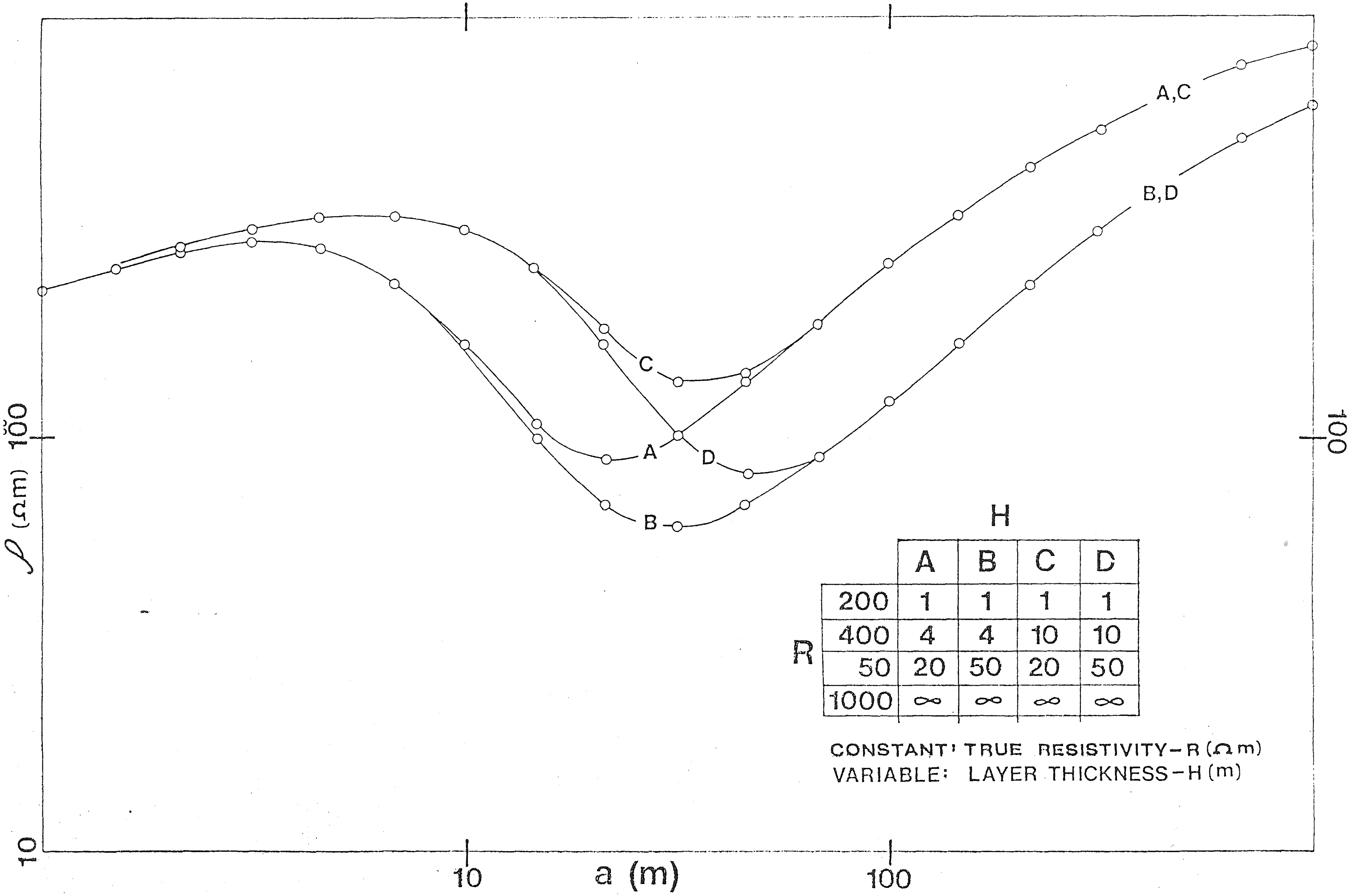
Table 3. Barker offset Wenner sounding data sheet for site C10 (Figure 1). See text for explanation of observed, offset, and lateral errors.

Figure 10. Field data curve (see Table 3) and four layer model curve for sounding site C10. Four layer model was generated from hand-calculator program and then modified with RESIST. Driller's log for observation well, located 50 meters west of C10, is shown for comparison.

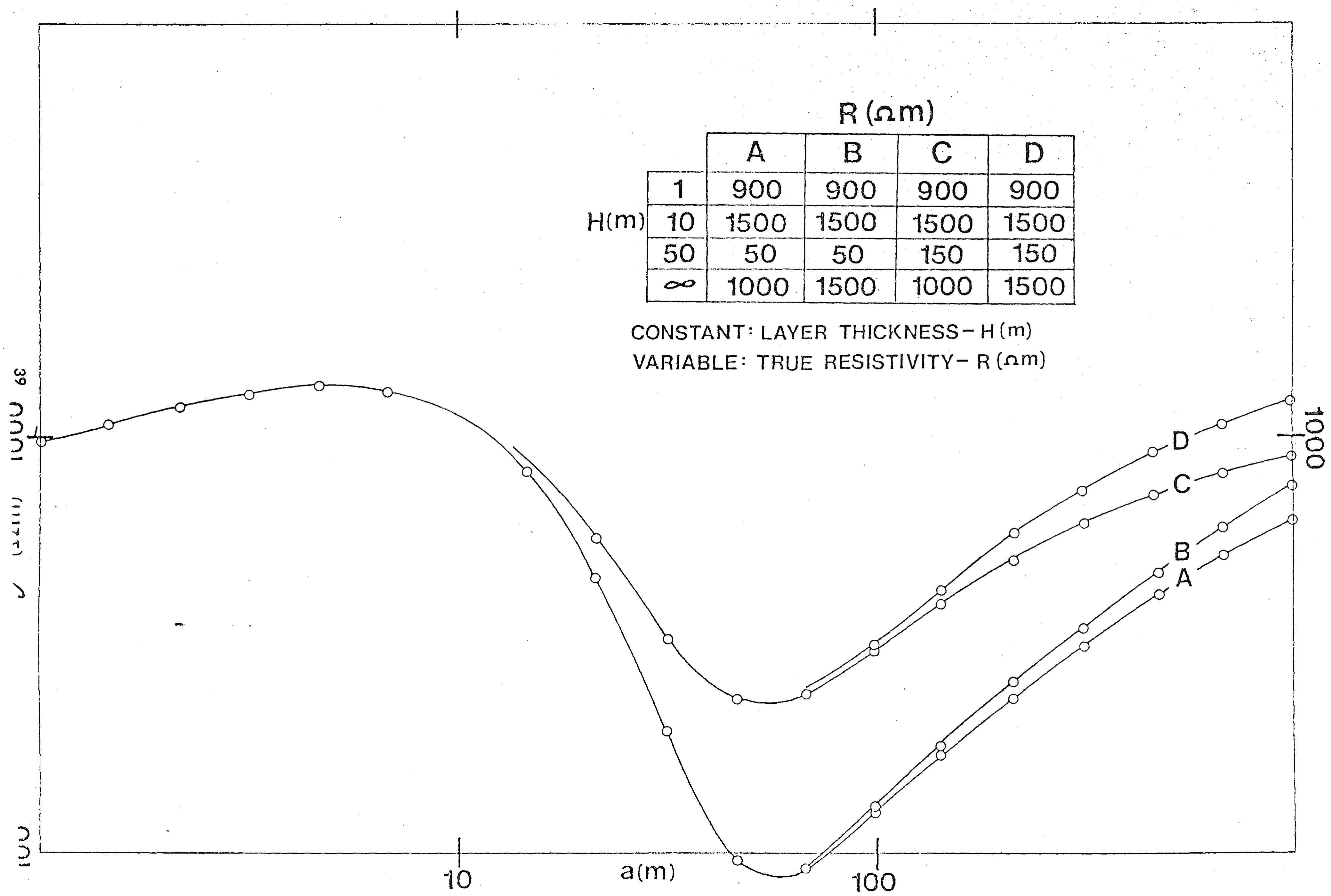

Elk River
HWY 10
HWY 10
A'
A
Clear Lake
C10
N
Mississippi River
EXPLANATION
High-Capacity Wells
Soundings
Observation Wells
1 KM
1 MILE


A'
A
1000
950
900
850
ALTITUDE IN FEET
305
290
275
260
ALTITUDE IN METERS
?
?
?
Coarse Sand and Gravel
Clay with Sand
Granite
1 KM
1 MILE
VE = 50x

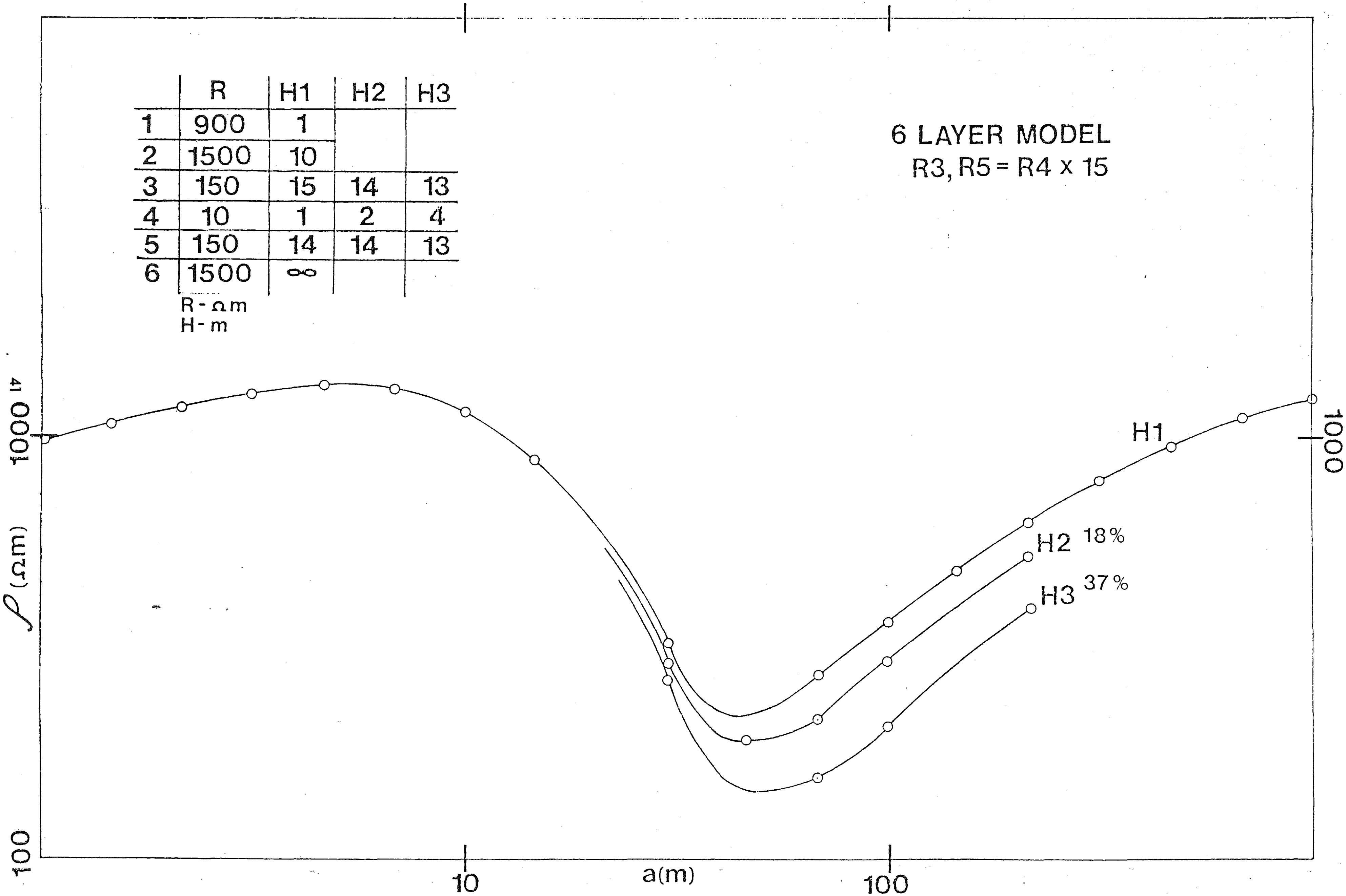
LAYER NO.	Thickness H(m)	True Resistivity R(Ωm)	Interpretation
1	1	200-900	Soil
2	4-10	400-1500	Unsaturated Zone
3	20-50	50-150	Aquifer Zone
4	∞	1000-1500	Bedrock



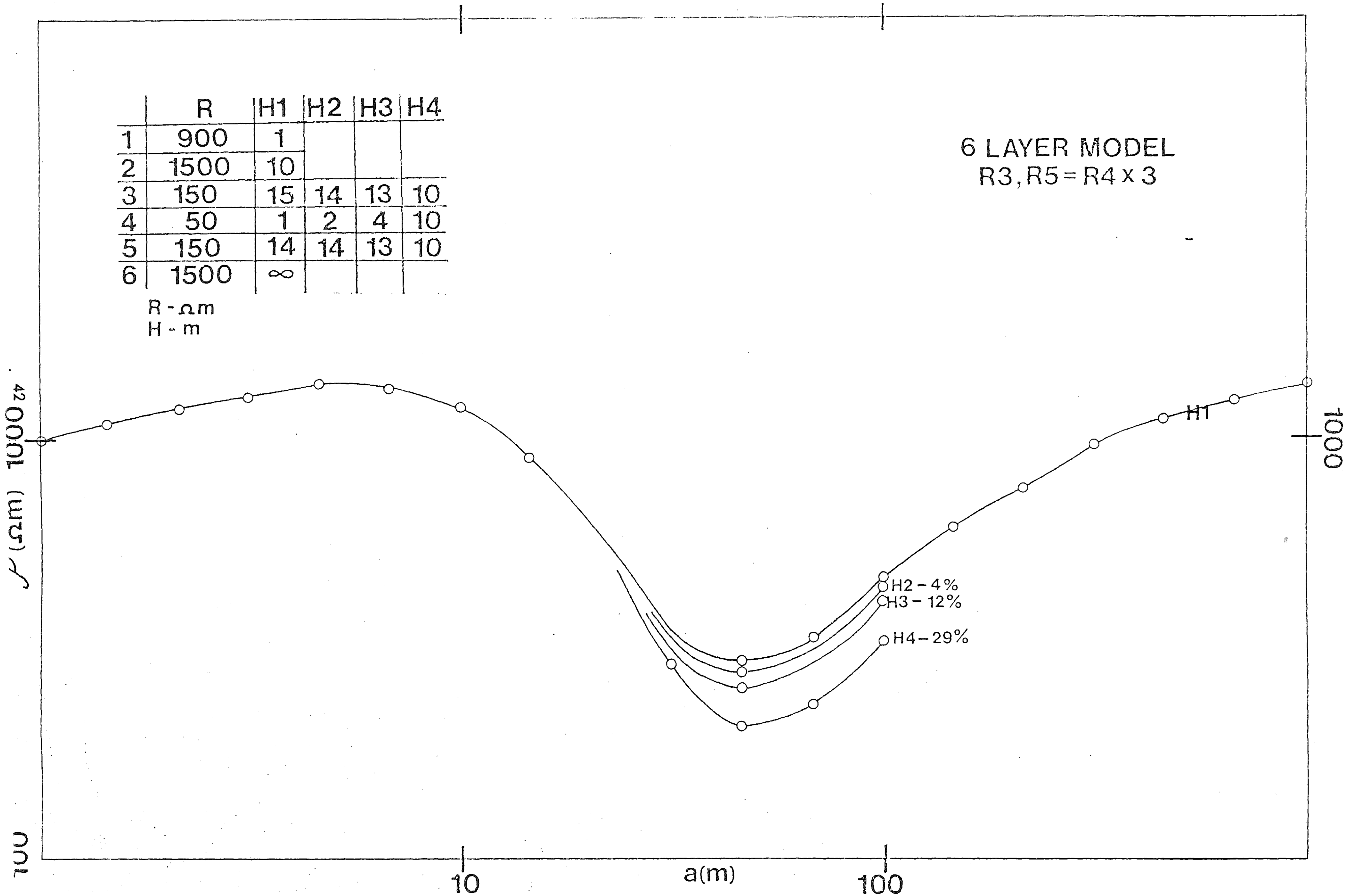
	H			
R	A	B	C	D
200	1	1	1	1
400	4	4	10	10
50	20	50	20	50
1000	∞	∞	∞	∞


R (Ωm)
A
B
C
D
1
900
900
900
900
H(m)
10
1500
1500
1500
1500
50
50
50
150
150
∞
1000
1500
1000
1500
CONSTANT: LAYER THICKNESS - H (m)
VARIABLE: TRUE RESISTIVITY - R (Ωm)
D
C
B
A
1000
10
a(m)
100

LAYER NO.	Thickness H(m)	True Resistivity R(Ωm)	Interpretation
1	1	900	Soil
2	10	1500	Unsaturated Zone
3	h3	r3	Aquifer
4	h4	r4	Confining Zone
5	h5	r5	Aquifer
6	∞	1500	Bedrock

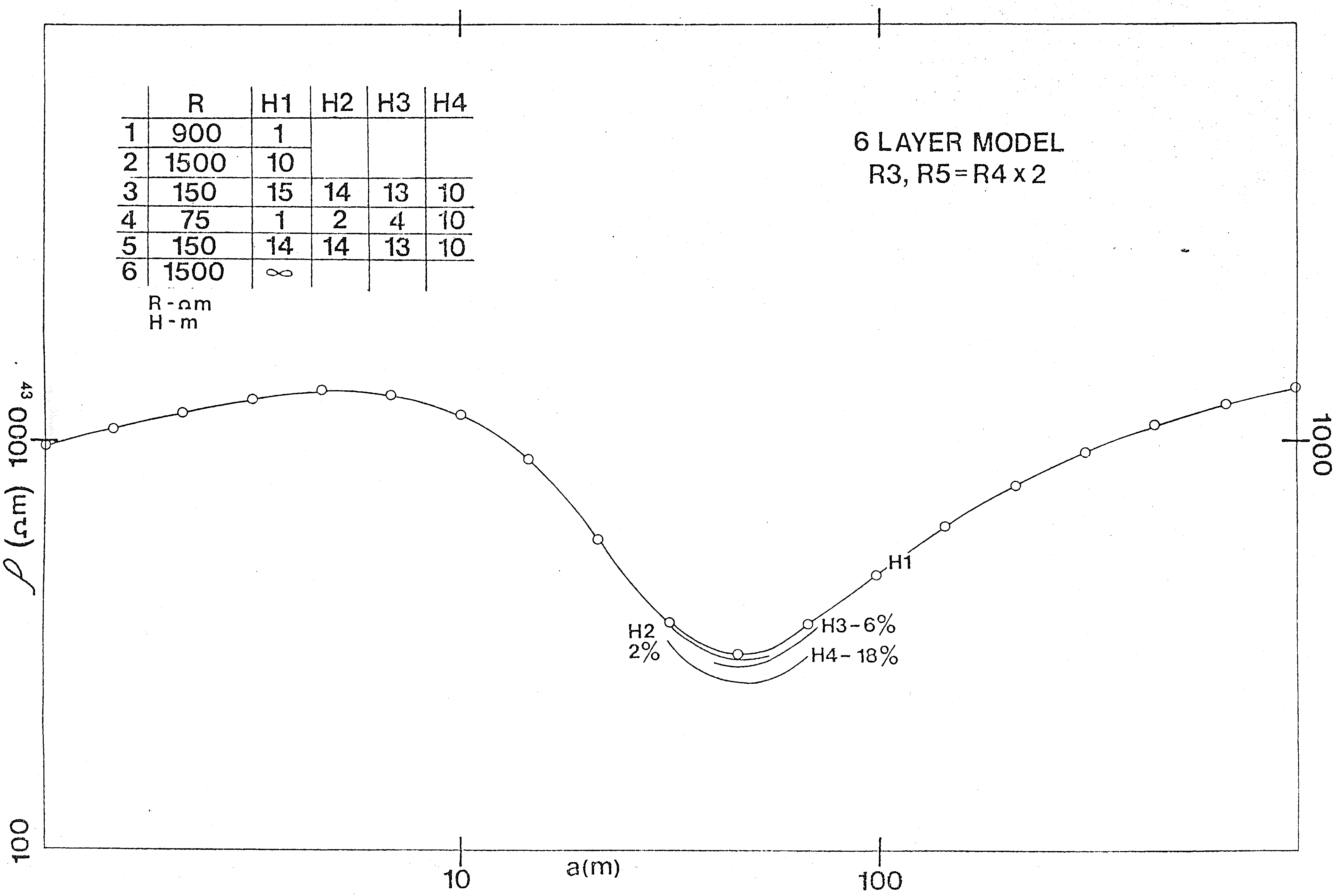


	R	H1	H2	H3
1	900	1		
2	1500	10		
3	150	15	14	13
4	10	1	2	4
5	150	14	14	13
6	1500	∞		

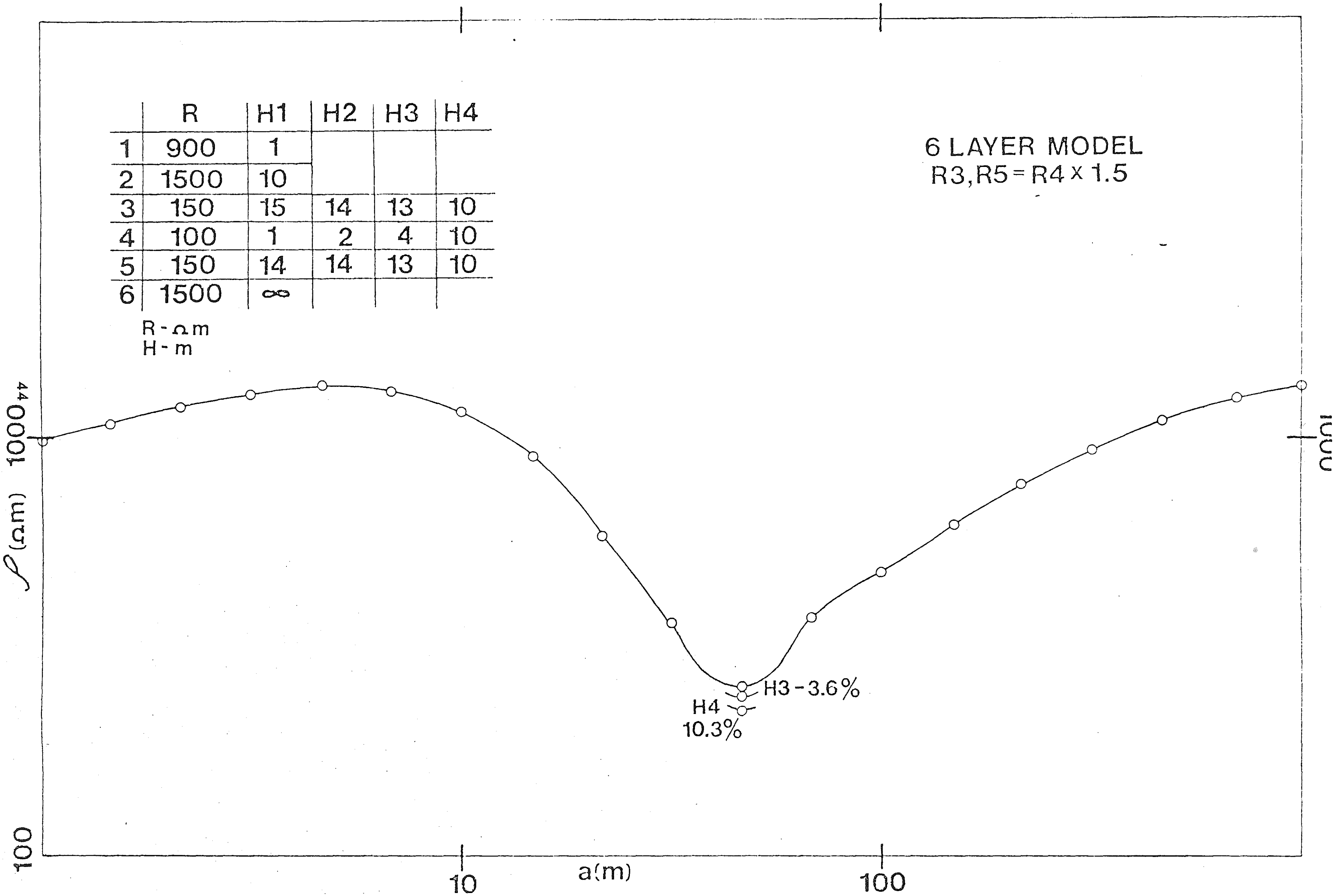


	R	H1	H2	H3	H4
1	900	1			
2	1500	10			
3	150	15	14	13	10
4	50	1	2	4	10
5	150	14	14	13	10
6	1500	∞			

R - Ωm
H - m
6 LAYER MODEL
R3, R5 = R4 x 3
ρ (Ωm)
1000
100
H1
H2 - 4%
H3 - 12%
H4 - 29%
a(m)
10
100
1000



	R	H1	H2	H3	H4
1	900	1			
2	1500	10			
3	150	15	14	13	10
4	75	1	2	4	10
5	150	14	14	13	10
6	1500	∞			



	R	H1	H2	H3	H4
1	900	1			
2	1500	10			
3	150	15	14	13	10
4	100	1	2	4	10
5	150	14	14	13	10
6	1500	∞			

FIVE ELECTRODE ARRAY

CONFIGURATION	1	2	3	4	5	
	C	P		P	C	R_A
	C	C		P	P	R_B
	C	P		C	P	R_C
	C	P	P	C		R_{D1} R_D
		C	P	P	C	R_{D2}

$$R_A > R_C > R_{D1} = R_{D2} >> R_B$$

$$R_A = R_B + R_C$$

OBSERVED: ½, 1, 2, 4, 8, 16, 32, 64 (128)

CALCULATED: 1.5, 3, 6, 12, 24, 48, 96, 128 (256)

DIVISION OF WATERS

RESISTIVITY SURVEY

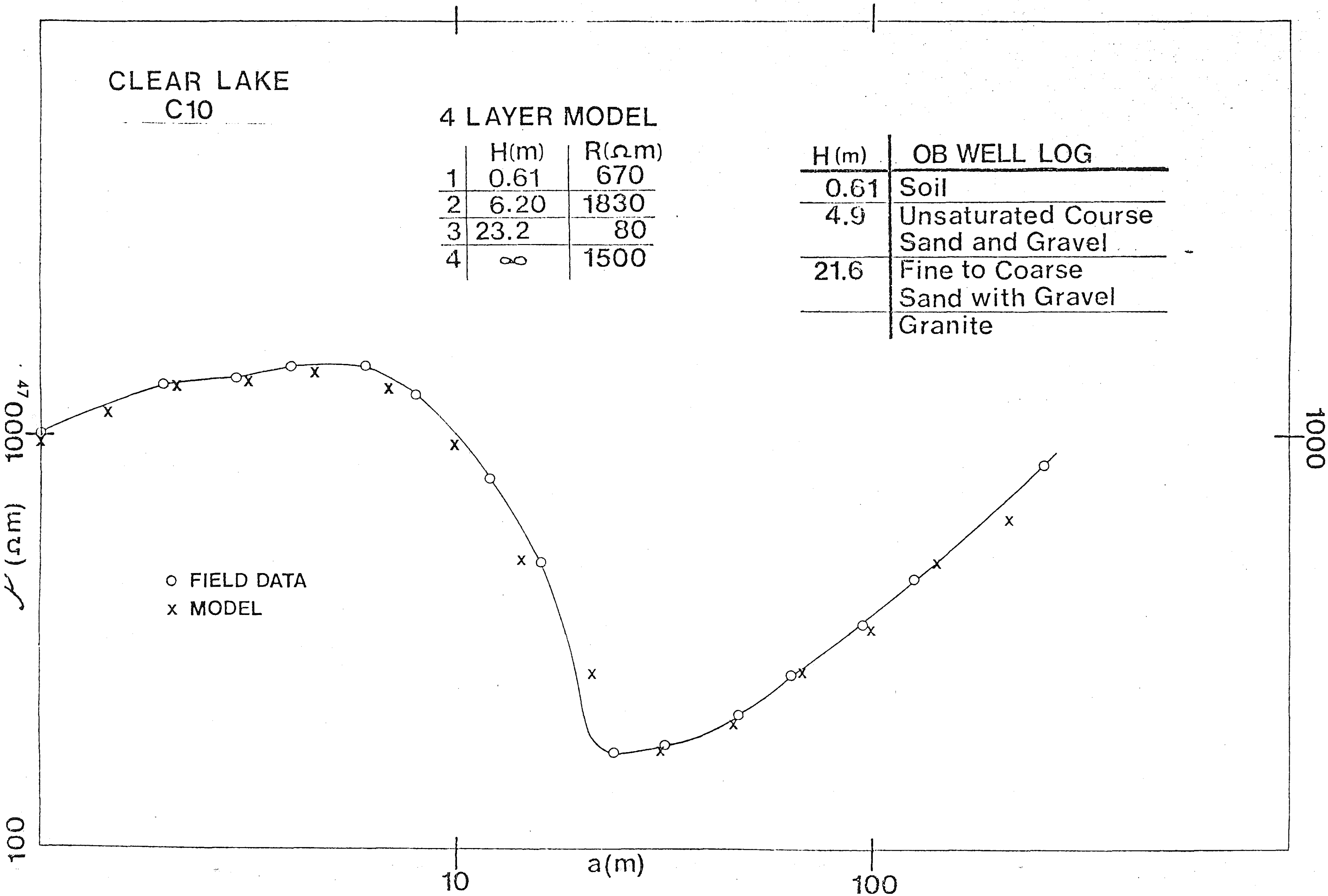
JOB I.D. CLEAR LAKE	LOCATION 34-29-18ACB N	DATE 10-20-83

FIELD DATA	FREQUENCY SETTING 3.33	SURVEY NO. C10

SPACING (METERS)	RA	RC	RD_1	RD_2	RB	COMMENTS
0.5						
1			163.4	162.0		
2	149.2	140.4	107.0	104.4	8.83	
4	77.0	70.8	58.3	58.9	6.25	
8	28.1	26.2	24.8	25.0	1.89	
16	4.9	4.73	4.66	5.0	0.15	
32	1.29	1.23	0.84	0.92	0.06	
64	0.97	0.94	0.665	0.635	0.03	
128	0.865	0.83	0.535	0.57	0.04	

OUTPUT DATA

METERS	WENNER RESISTIVITY	+5 - -5 OBSERVED ERROR	<20% OFFSET ERROR	<50% LATERAL ERROR
0.5				
1.0	1022		0.86	
1.5				
2.0	1328	-0.02	2.45	-18.4
3.0	1383			
4.0	1473	-0.06	-1.02	2.01
6.0	1477			
8.0	1252	0.03	-0.8	46.2
12.0	792			
16.0	485	0.40	-7.04	52.7
24.0	168			
32.0	177	0.0	-9.09	-7.69
48.0	204			
64.0	261	0.0	-4.61	-4.97
96.0	345			
128.0	444	-0.58	-6.33	
256.0	893			
	R.M.S. ERROR	0.269	5.02	29.8


CLEAR LAKE
C10
4 LAYER MODEL
H(m) R(Ωm)
1 0.61 670
2 6.20 1830
3 23.2 80
4 ∞ 1500
H (m) OB WELL LOG
0.61 Soil
4.9 Unsaturated Course Sand and Gravel
21.6 Fine to Coarse Sand with Gravel
Granite
o FIELD DATA
x MODEL
ρ (Ωm)
1000
100
1000
a(m)
10
100

APPENDIX B

THE USE OF SEISMIC REFLECTION TO DEFINE BURIED DRIFT AQUIFERS

By: Andrew R. Streitz

ABSTRACT

Shallow seismic reflection methods can be used to define buried drift aquifers, which are important sources of water in western Minnesota. Working from a well log, three outwash boundaries were isolated that gave promise of returning reflections. Theoretical constraints limiting the usefulness of this geophysical tool were partially overcome through a combination of new equipment and changed field strategies. Data were collected and processed on a 12 channel signal processing seismograph. Signals were analyzed to identify coherent waveforms and separate other arrivals (e.g. direct wave, ground-coupled air wave, ground roll, etc.) from reflections. Observed reflections were also compared to theoretical characteristics to confirm identification. Velocities were developed from refraction data and applied to reflection arrival times to calculate depths. Three reflections were observed, with good correlation to the three interfaces chosen as probable reflectors. The physical nature of the different interfaces appeared to affect the frequency content and waveform 'signature' of the reflections. Shallow seismic reflection can be applied to other types of drift investigations.

INTRODUCTION

Water supply problems in much of western Minnesota have concerned definition of the extent of glacial sands and gravels buried in the drift. Traditionally, studies have relied on test drilling to define the vertical and horizontal boundaries of water-bearing bodies. The cost of obtaining this information directly by test drilling has become prohibitive; thus, attention is being focused on indirect, geophysical methods for defining aquifer boundaries.

To test the applicability of geophysical tools to water resources investigations in glacial terrane, the Minnesota Department of Natural Resources (DNR) and the U.S. Geological Survey (USGS) began a 2-year cooperative program using electrical resistivity, shallow seismic refraction and shallow seismic reflection. Funding was provided in part by a special appropriation from the Legislative Commission on Minnesota Resources (LCMR).

A primary area for investigation is the western third of the State where irrigated agriculture is of prime economic importance. Water for irrigation, as well as domestic usage, generally is withdrawn from buried drift aquifers. Surficial aquifers, where they exist, are not capable of sustaining additional high yields and are more vulnerable to contamination. Surface water supplies are not adequate for high capacity pumpage except during times of flood flow which does not coincide with crop irrigation demand. Future groundwater development needed to support economic growth will thus have to come from buried drift aquifers.

One of the areas chosen for investigation during the 2 year "experiment" is in Swift County, T 121N, R 42W, S 17 ABB. This area has been studied previously by the USGS and the DNR. Test hole data revealed the presence of two buried drift aquifers separated by a thick sequence of clay.

GEOLOGY

The geology of this area consists of Quaternary age glacial deposits directly overlying Precambrian crystalline rock. These glacial deposits are made up of alternating layers of till (clay, sand and rock fragments) and outwash sands and gravels.[1]

[1]"Appraisal of the Surficial Aquifers in the Pomme de Terre and Chippewa River Valleys, Western Minnesota." USGS Water Resource Investigations Report 84-4086, page 7.

At the site of interest, this general description has been clarified by the observation well log which reveals the geologic column from surface soils to basement granite. (Figure 1). This log describes units of glacial drift on the basis of particle type, size and color (this is illustrated in Figure 1 by dotted lines). Careful inspection suggests that a looser grouping of similar units will produce a simpler, though still accurate, geologic model (represented by heavy solid lines).

Extending from the surface to a depth of 15.5 meters is a layer of sand and gravel which grades to sand in the lower two-thirds of the unit. This sand overlies a sequence of clay 25 meters thick, which itself overlies another 15.2 meters of sand. Below this second unit of sand lies a 15.2 meter zone of weathered granite. At a depth of 72.6 meters, granitic basement begins. The three interfaces of interest are the first sand/clay boundary at a depth of 15.5 meters (the shallow reflector), the clay/sand boundary at 40.5 meters (the intermediate reflector) and the sand/weathered granite division at a depth of 57.3 meters (deep reflector).

The rationale for grouping the units as described in the log into simpler and larger units lies in the need to tie the geologic column to possible targets for shallow seismic reflection. Theoretically, every interface (representing a velocity-density contrast) is capable of reflecting energy and of appearing in the seismic record. Taking into account associated matters of unit thickness and signal wave length, we determined that the probability for reflections was highest for the interfaces at 15.5, 40.5 and 57.3 meters.

The first two selected interfaces have sharp geologic contacts, while the third (the sand/weathered granite boundary) is of an entirely different nature. A geologic interpretation shows a rough gradient of material, from heavily weathered granite to "fresh" rock, from fine particles to boulders. Further, this chaotic weathering pattern varies laterally so that this interface could best be visualized as an uneven series of velocity steps stretching from the sand/weathered granite interface toward the basement, each representing a credible reflection target.

FIELD STRATEGY

Three technical obstacles have slowed application of shallow seismic reflection to buried drift investigations: 1) strong velocity-density contrast between adjacent units are frequently lacking, 2) reflections from thin units can only be generated by a sufficiently high-frequency signal, and 3) the information-rich, high frequency portion of the signal must be separated from the large amplitude, dominant frequency. To overcome these problems, it is necessary to combine equipment changes with new parameter selections. The sensitivity of the equipment to high frequency information is increased by reducing the effect of large amplitude, low frequency signals which swamp the seismograph's dynamic range. This is accomplished through the use of front-end, high pass analog filters and higher natural frequency geophones.

The higher natural frequency together with the analog filter does not respond to frequencies below 40 Hz, and burial of the sensor (encased within the waterproof marsh casing) cuts down on wind and traffic noise. Placing the sensor as little as two feet underground yields an important gain in the high frequency loss of the signal in the low velocity, unsaturated, near surface material. Boosting the dominant frequency of the source wave involves exchanging a 16 lb. sledge hammer for a modified 12 gauge pipe gun. Post-collection digital filtering, including both high-pass and low-pass filters, isolates favorable signals.

The central piece of equipment, the Bison Instruments Geopro, a 12 channel signal processing seismograph, is used both for collection and signal processing. Field data are digitally stored on a B&K recorder; auxiliary equipment includes cables, 12 8 Hz. surface geophones, 12 40 Hz. Marsh-case geophones, a 16 lb. hammer and the modified 12 gauge.[2]

The field strategy for data collection includes reflection and refraction profiles on two lines ranging west and north of the observation well. Each of the two lines is anchored by a preliminary 24-trace multichannel spread, designed to provide velocity information for observed reflections. Takeouts and offsets are both 3 meters, thus the maximum offset provided by either of these lines is 72 meters. Applying a generalization that depth of penetration is approximately one-fourth of the offset, such a line provides information only to a depth of 18 meters. A penetration of 18 meters is only one-third the depth of the geologic column. This offset is sufficient in this case because of log control for comparison with the geophysical data, and because the velocity-density contrast between units is small enough to allow for an assumption of a constant velocity throughout the drift. Good agreement between initial profiles

[2]Use of specific brands of equipment should in no way be construed as an endorsement by the State of Minnesota.

and the well log lends confidence to the velocity assumptions based on the refraction data.

At 36 meter intervals, 12 trace multichannel profiles are run for two-thirds of a kilometer. With maximum offsets of 36 meters, these lines are shot with shorter sweeps to concentrate on early arrivals and to monitor changes in the water table (which force changes in the velocity model). These profiles are laid out to provide 3 meters continuous coverage from the first shot point.

Data Set #1, the initial 24 trace refraction profile of the northern line, is presented as Figure 2. This version of the data has been digitally filtered and displayed with variable area. First arrivals have been plotted on a time-distance plot (Figure 3). Parameter settings included gains of 42-78 db., a 192 millisecond (MS) sweep and a 75 Hz. high-pass analog filter.

Data Set #2, represents a line 360 meters north of the first data set's shot point. This 12 trace line appears as Figures 4 and 5. The former shows raw data while the latter has been processed (both with variable area and high pass digital filtering). Parameters were similar to those in Data Set #1, except that the sweep was shortened to 96 MS.

ANALYSIS

The refraction profile in Data Set #1 defines a two layer velocity model. The upper layer has a velocity of 470 M/S, and the lower a velocity of 1857 M/S. Combined with the cross-over from Figure 3, a depth can be calculated at 4.1 meters. As a first step in correlating the well log with seismic data, the lower velocity can be tied to the unsaturated zone, the interface (defined by the velocity-density contrast) ascribed to the water table and the higher velocity represents the saturated drift. Through the use of:

$$V_{RMS} = \left(\frac{\Sigma d_i V_i}{\Sigma d_i / V_i} \right)^{1/2} \qquad \text{equation a,}$$

this simple model can develop root-mean-squared velocities for specific depths, namely our three target interfaces.

Analysis of reflection data must begin with a strong argument supporting the selection of a waveform as a reflection. The criteria that are used to identify these reflections include: high dominant frequency, high amplitude, large apparent velocity (as observed on the multichannel spread) and separation the waveform from interference with other arrivals. Figure 2 reveals a reflection with these characteristics. Along line K-K', the arrivals are isolated from other events, benefit from high-pass digital filtering, display a steep slope and have sufficient amplitude to stand clear of background noise. However, the waveform signature is not coherent and initial motions of the waveforms across traces 13-24 do not describe a smooth parabola.

Data Set #2 displays two reflections which meet the stated requirements. Figures 4 and 5 reveal reflections along lines N-N' and O-O'. Comparisons between the two reflection waveforms are instructive; the shallower reflection has a lower apparent velocity, higher dominant frequency and suffers from near-interference with first breaks. The first two observations follow from the physical nature of reflections, while the third, which consists of interference with direct and refracted arrivals, demonstrates depth limitations in shallow seismic work. In contrast to the deep reflection, these two shallow reflections have unique waveform signatures whose initial motions describe smooth parabolas.

Other recognized waveforms are important and they can be removed from consideration as possible reflections. Figure 2 has two recognizable patterns: 1) electronic noise (from "cross-talk" between the geophone and trigger cables) along line J-J', and 2) ground-coupled air wave labeled L-L'. Figures 4 and 5 both show electronic noise along line M-M'.

RESULTS

It is now possible to correlate the three interfaces of the well log with the three reflections isolated from the field data. Reasons for assigning root-mean-squared velocities to the interfaces were outlined above. These velocities can be combined with reflection arrival times and offsets to calculate depths through:

$$D = \left(\frac{T^2 V^2 - X^2}{4} \right)^{1/2} \qquad \text{equation b.}$$

The reflection of Data Set #1 (using a velocity calculated from equation a, of 1640 meters/second) yields depths of 53-54 meters. A check on the accuracy of this calculation (beyond its favorable comparison to the geologic log's depth of 57.3 meters for the sand/weathered granite interface) is the percent agreement of the various depths generated from the observed reflections. This percentage represents deviation from the best fit parabola of a velocity to observed reflections. For a velocity of 1640 M/S the percent agreement is 97%. The calculated velocity is therefore a good choice, but does not explain the discrepancy between calculated depths and the depth taken from the well log. The explanation may lie in the nature of the reflector with its uneven grading of weathered granite. Interference from delayed arrivals and changing reflector depths could cause phase shifts in initial motions and create reflection wave trains of varying length.

The remaining two reflections are dealt with in a similar fashion. From a calculated velocity of 1475 M/S, the shallow reflection produces depths of 14.9 to 16 meters. The intermediate reflection generates depths of 39.6 meters to 40.8 meters from a calculated velocity of 1677 M/S. This last velocity is higher than the root-mean-squared velocity at the 57.3 meter interface because of a decrease in the depth of the water table at the site of Data Set #2. These depths show very good agreement with the two shallow interfaces of the geologic column (e.g. 15.5 and 40.5 meters). This greater precision over Data Set #1, is due to the nature of the reflectors. The poorly defined nature of the sand/weathered granite interface blurs the seismic record, while the sharp contrast of the clay/outwash interfaces produces sharp, coherent reflections. The depth calculations of the two shallow reflections benefit both from unambiguous first motions and from a more accurate velocity model. The velocity model used in this work predictably introduces a certain amount of error at greater depths.

COMMENTS

Reflection as a tool for investigating buried drift features requires further development to increase precision in varied environments. Interpretation of data remains a difficult process which, if mastered, can help in tracing confining layers in ground water contamination studies, resource development and engineering investigations.

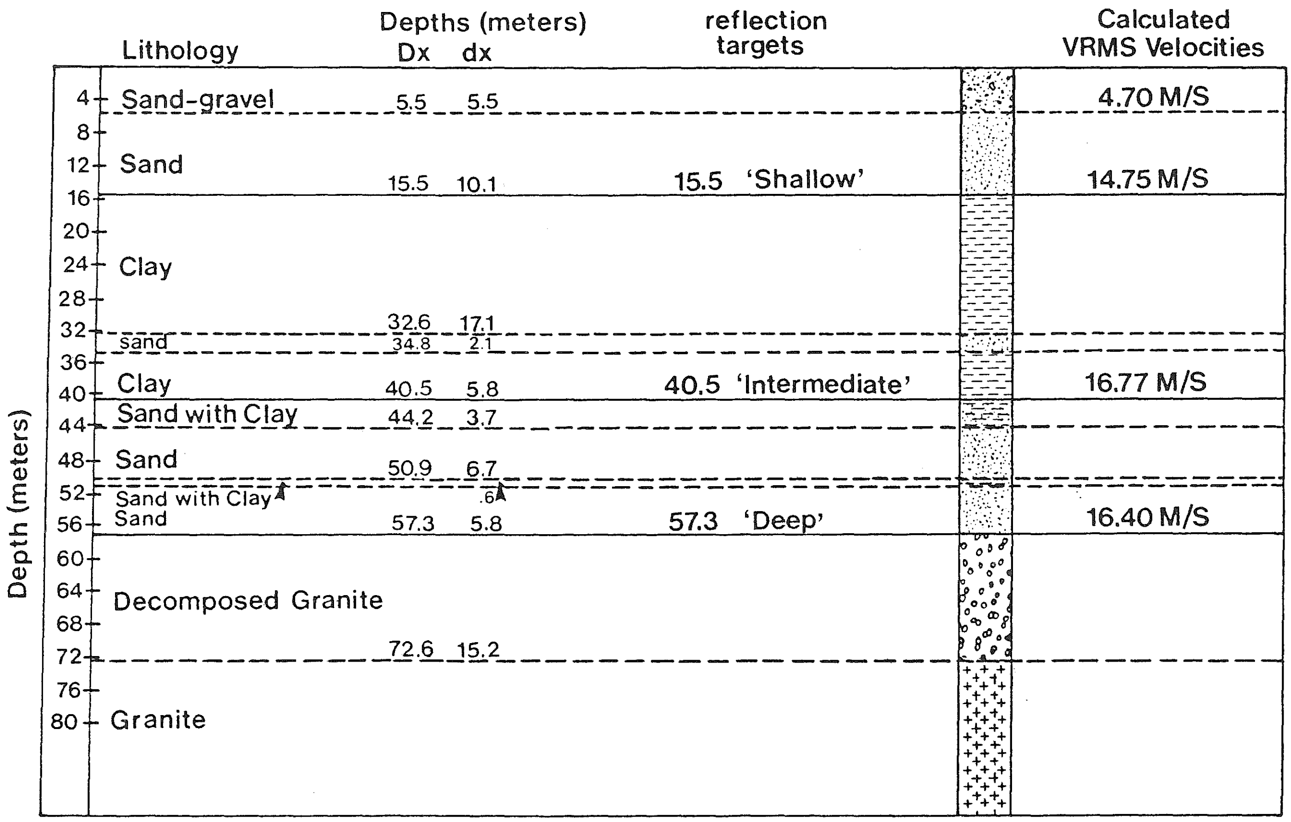


Figure 1. Pomme de Terre Well Log, Swift Co., Minnesota (121.42.17 ABBB)

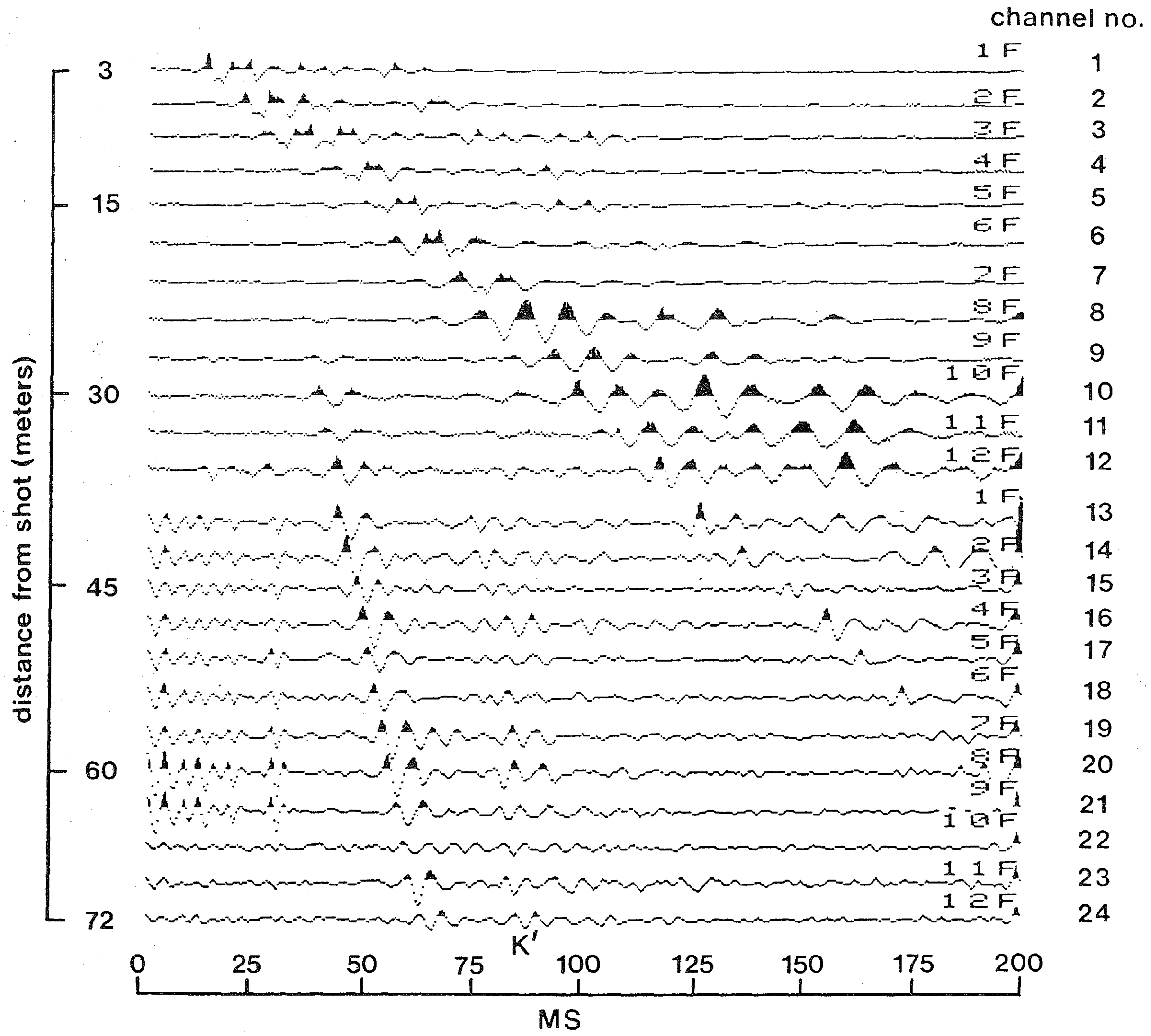


Figure 2, data set no.1; Swift Co., MN.

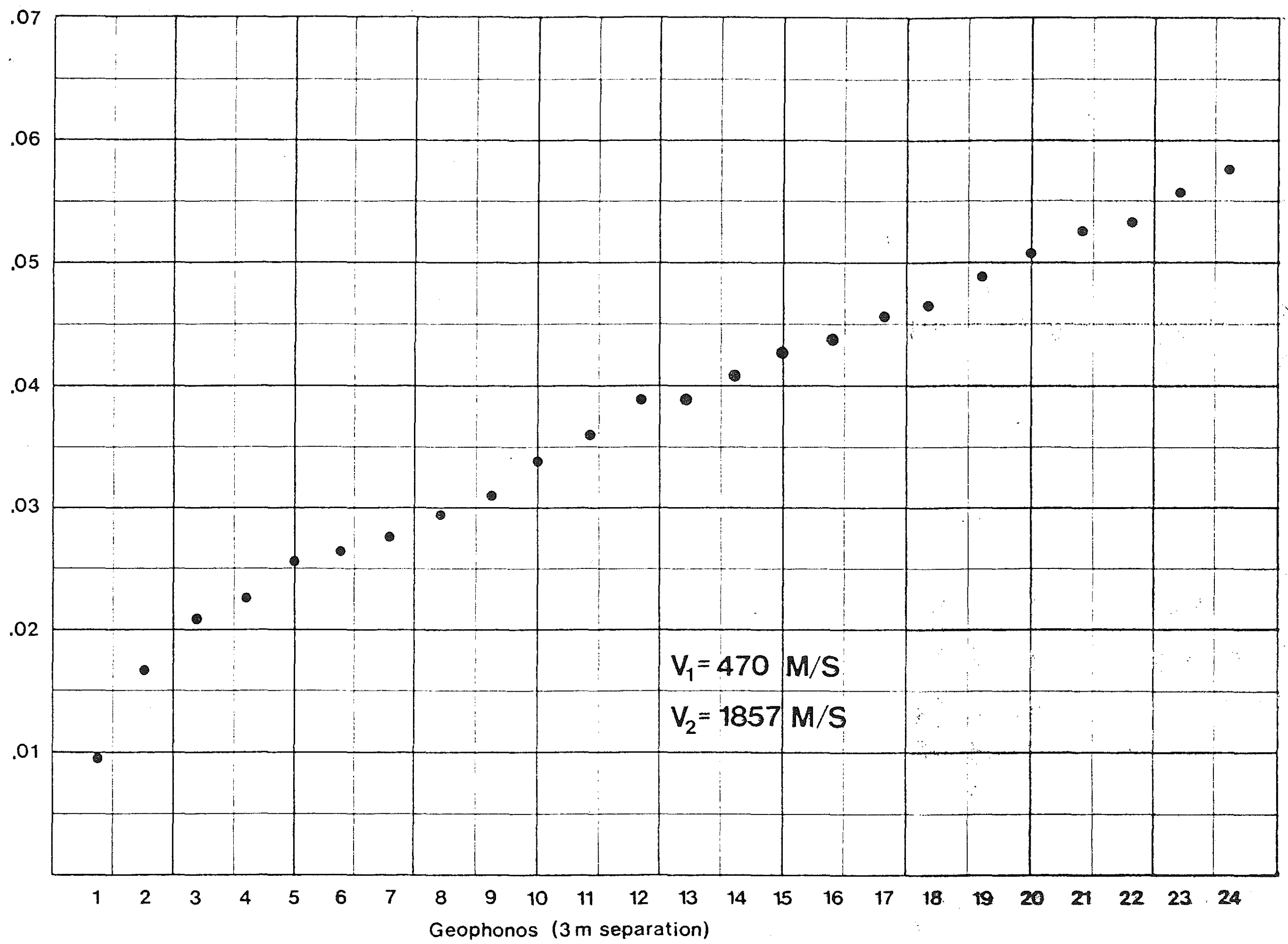


Figure 3. Time-distance Plot, data Set 1; Swift Co., MN.

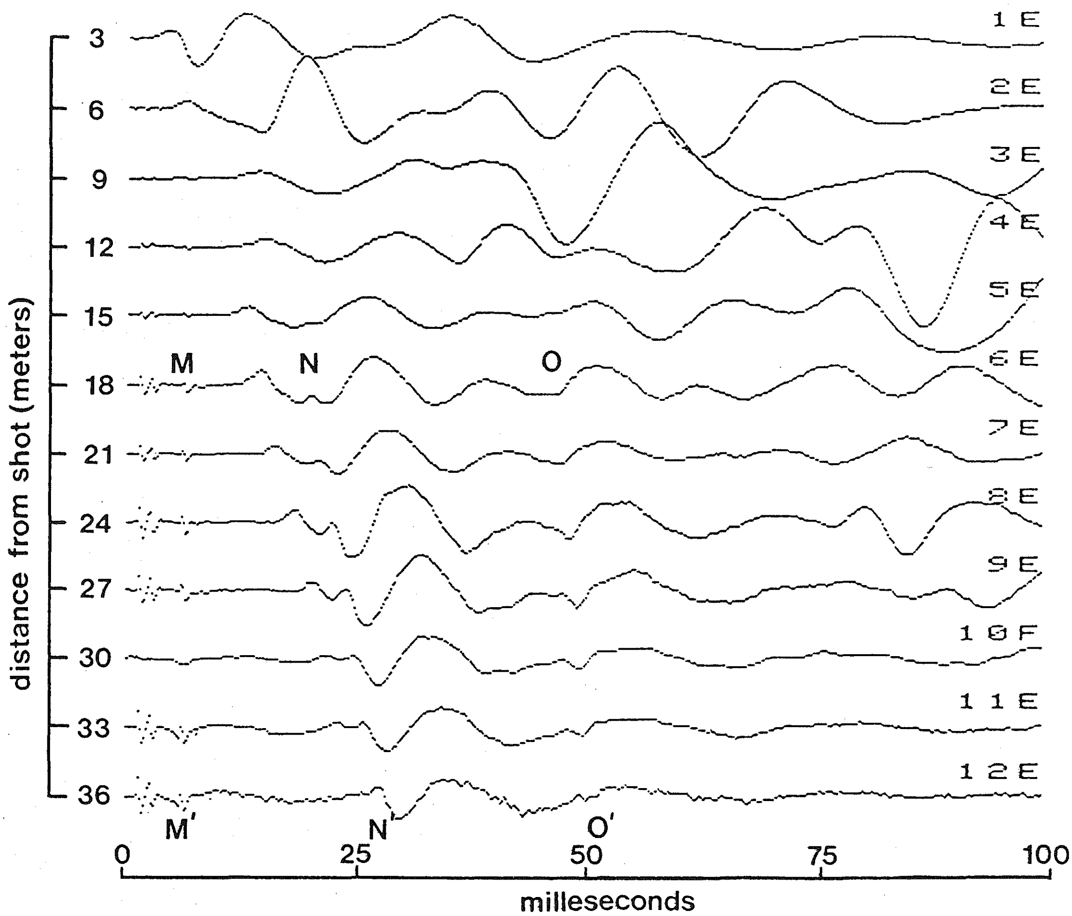


Figure 4, data set no.2; raw record. Swift Co., MN.

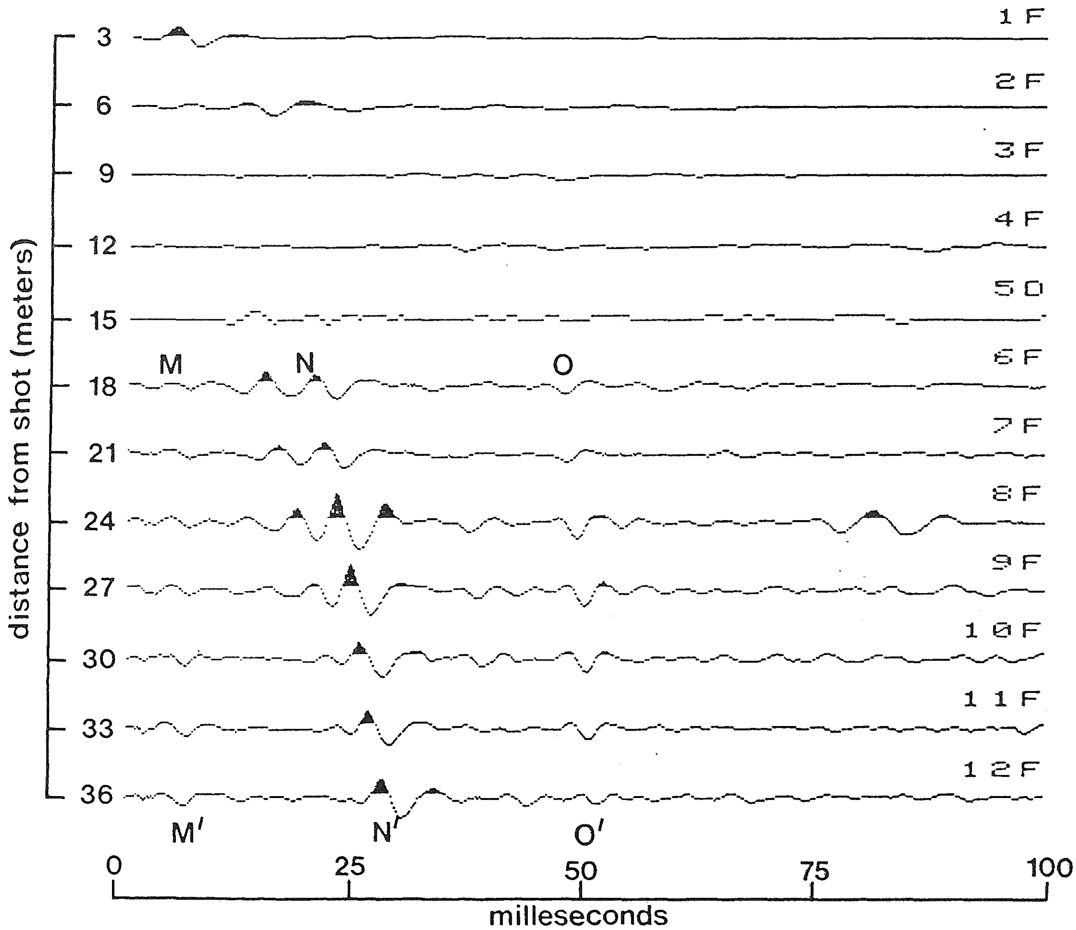


Figure 5, data set no. 2; processed record. Swift Co., MN.