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REPORT OF INVESTIGATION NO. 77

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## FOREWORD

This report was prepared by the North Dakota Geological Survey, Grand Forks, North Dakota under USBM Contract number J0275010. The contract was initiated under the Advanced Mining Technology Program, subsequently the Minerals Environmental Technology Program. It was administered under the technical direction of Denver Mining Research Center with Michael Bailey, W. W. Watts, Jr., and Tim Hackett acting as Technical Project Officers. Darlene Wilson was the contract administrator for the Bureau of Mines. This report is a summary of the work recently completed as a part of this contract during the period October 1, 1979 to June, 1982. This report was submitted by the authors on November 30, 1982.

## ABSTRACT

Earth resistivity surveys using the Wenner electrode configuration were made in unmined areas and reclaimed spoils at three surface lignite mines in western North Dakota. The study sites were the Center, Indian Head, and Falkirk Mines. Automatic interpretation of the curves was accomplished with the method of Zohdy and Bisdorf (1975). Overburden materials become more homogeneous with respect to resistivity during the mining and reclamation process. The spoils curves show localized heterogeneities probably related to discontinuous moisture content variations in the spoils. Consistent resistivity differences in spoils occur between mines with overburdens of different mineralogic compositions. Groundwater chemical composition in terms of total-dissolved-solids (TDS) is inversely correlated ($r=-0.61$) with apparent resistivity at the 80-foot spacing from a survey centered at a piezometer screened near the base of the spoils. Better inverse correlation is probably prevented by high variability in TDS within the spoils groundwater. A useful predictive relationship may be the plot of mean apparent resistivity at the 80-foot spacing for an entire mine against mean TDS for all wells in spoils at that mine. Data from more mines are needed to test the hypothesis.

## EXECUTIVE SUMMARY

This study used earth resistivity techniques to investigate subsurface conditions in reclaimed surface lignite mine spoils in North Dakota. The surveys were made in unmined materials at three lignite mines (Center, Indian Head, and Falkirk) and in reclaimed spoils at two mines (Center and Indian Head). Earth resistivity methods are based on the varying ability of subsurface materials to conduct electrical current. Resistivity is an indirect technique which results in subsurface layering configurations that are not unique and must be interpreted with the assistance of some other type of information. Existing test holes in unmined areas were used as subsurface control points to calibrate the resistivity data. The advantages of earth resistivity are its low cost and its ability to predict conditions between test-hole data points.

In unmined areas the techniques used were successful in detecting subsurface layers when layers of contrasting resistivity occurred near the surface. Material such as sand, with high resistivity, could be distinguished from clay, with low resistivity. At study sites where the materials were relatively uniform, such as the Indian Head Mine, the techniques used could not differentiate the subsurface layers.

Mixing of materials during mining and reclamation produces resistivity curves indicating more homogeneous overall conditions than the unmined areas. At the same time, however, the curves indicate localized variations in the spoils which may be the result of variations in moisture content or mineral content.

The spoils at the Center and Indian Head Mines showed a consistent difference in resistivity. This appears to be a reflection of the hydrogeochemical environments in the spoils at the two mines. Groundwater chemistry is related to the mineral composition of the spoils. The resistivity surveys show an inverse correlation between the measured resistivity value and the total-dissolved-solids content of groundwater from wells at points where resistivity surveys are made.

At the Indian Head Mine, a mine with clayey overburden, low resistivity in the lower part of the spoils near the water table is a reflection of chemical reactions between the spoils minerals and infiltrating water which produce groundwater with high total-dissolved-solids content. The majority of resistivity surveys at the Center Mine, a mine with sandy overburden, indicate relatively high resistivity near the base of the spoils. Groundwater quality in spoils at the Center Mine study site is characterized by much lower TDS than at the Indian Head site. One area within the Center Mine spoils had low resistivity near the base of the spoils. This area also had the highest total-dissolved-solids content in spoils groundwater at the mine.

Resistivity could therefore be used as a tool for evaluating groundwater degradation following mining and reclamation. The higher the resistivity of the overburden materials, the better the quality of groundwater below reclaimed spoils that can be expected.

## INTRODUCTION

Reclamation of surface lignite mines creates new and different hydrogeologic environments relative to premining conditions. A major disruption of the groundwater system results from the removal of lignite beds and redistribution of overburden. Prior to mining, lignite beds often function as zones of lateral groundwater flow because of the high fracture-controlled hydraulic conductivity of the beds. Overburden sediments transmit water vertically or laterally depending on the texture of the materials and stratigraphy and topography of the site. As overburden materials are redeposited and contoured over mined areas, major physical and chemical changes occur in the material (Moran et al., 1978; Groenewold et al., 1980). Although lithologic and stratigraphic variations in spoils do exist, reclaimed spoils are generally less heterogeneous than their premining counterparts.

Non-lithologic heterogeneity in spoils is induced, however, by differences in stockpiling position during mining and by the season and type of earthmoving equipment used during spoils contouring (Groenewold and Rehm, 1980). For example, spoils materials which occupy the valley positions in the spoils landscape prior to contouring commonly have higher hydraulic conductivity than materials in the ridge positions of the spoils landscape. Materials contoured by dozers in winter have particularly high hydraulic conductivity because large frozen blocks of material are pushed into spoils valleys and improperly compacted. These conditions lead to subsequent subsidence of winter-contoured spoils. In addition, such areas may control saturated and unsaturated movement of groundwater through the spoils.

The geochemical environment of the spoils is highly altered from the premining state (Groenewold et al., 1980; Groenewold et al., 1981). The principal change is the exposure to atmospheric conditions of unoxidized sediment and the subsequent entrapment of oxygen in the reclaimed spoils. In undisturbed conditions, free oxygen in the soil zone is depleted by oxidation of organic matter. In the reclaimed spoils, the entrapped oxygen reacts with soil minerals such as pyrite. Oxidation of pyrite can potentially generate large amounts of sulfate ($SO_4^{2-}$), an ion which can travel great distances in groundwater. Sulfate concentrations greater than 10,000 mg/L have been detected in spoils groundwater at the Indian Head Mine in western North Dakota (Groenewold et al., 1981).

Sodium is another ion which can reach high concentrations in spoils groundwater. Sodium is released to infiltrating waters mainly by cation exchange reactions where sodium adsorbed on clay mineral surfaces is exchanged for calcium and magnesium in the groundwater. Sodium concentrations in spoils groundwater can therefore be elevated because exchangeable calcium and magnesium concentrations are increased by carbonate-mineral dissolution. Carbonate-mineral dissolution exceeds normal $CO_2$-controlled levels primarily because of elevated hydrogen ion concentrations resulting from the pyrite dissolution reaction.

The purpose of this project was to investigate and compare reclaimed spoils areas with adjacent undisturbed settings using earth resistivity techniques. Earth resistivity techniques have been found useful in several types of subsurface studies. Using one of the techniques, the resistivity and thicknesses of subsurface layers can be determined where layers contrast in resistivity. Another major application involves determining changes in groundwater quality usually associated with contamination of some type. If spoils resistivity varies in a systematic and detectable fashion, the resistivity patterns could be related to the physical and chemical variables affecting reclamation. Periodic resistivity surveys could then be used to determine initial postmining subsurface spoils conditions and, later, to monitor hydrogeological changes in the spoils.

The resistivity surveys were made in the vicinity of three active lignite surface mines in western North Dakota. These sites are the Center, Indian Head, and Falkirk Mines (fig. 1). The Center and Indian Head Mines included areas of reclaimed spoils at the time of fieldwork. Reclaimed spoils were not available at the newest mine, the Falkirk Mine. This study is part of a more comprehensive investigation of undisturbed and reclaimed landscapes at these sites. The various integrated research activities at these sites have generated a large amount of subsurface control data. It was the availability of these data that justified evaluation of earth resistivity techniques at these sites. Available data at these sites include areal subsurface geologic and hydrogeologic information in undisturbed settings around the mines as well as extensive hydrogeologic information in the reclaimed spoils areas surveyed. Research in spoils settings at these sites has included studies to determine the effects of climatic and equipment variables on stability and settling characteristics of the spoils materials (Groenewold and Rehm, 1980), studies to determine the internal stratification and the engineering properties of the spoils (Groenewold and Bailey, 1979), and studies to determine the physical and chemical groundwater conditions and changes in the reclaimed spoils (Groenewold et al., 1980). Instrumentation installed at these sites includes concrete markers for monitoring changes in the surface configuration of the spoils and piezometers, soil water samplers, and neutron access tubes for monitoring subsurface water movement and chemical characteristics in the spoils. Lithologic and geophysical logs of test holes and piezometer holes are available. The major drawback in the type of information described above, with respect to resistivity surveys, is that it is essentially point data. Test holes indicate the stratigraphy at one point and piezometers indicate the hydraulic head and the groundwater chemical composition at one point. Earth resistivity is a method which provides information on the bulk or average conditions concerning a large volume of material; therefore, it provides a different type of information than test holes, groundwater monitoring equipment, and other types of point-specific instrumentation.

The general objective of the study was to apply earth resistivity techniques to undisturbed areas and reclaimed spoils in order to determine the potential usefulness of these techniques in evaluating hydrochemical and hydrogeologic conditions in these landscapes. The types of information desired included variations in stratigraphy and groundwater chemical composition.

## METHODS

### Earth Resistivity

Earth resistivity is a surface geophysical technique used to interpret subsurface geological conditions based on changes in the conduction of an electrical current passed through the ground. Current is induced into the

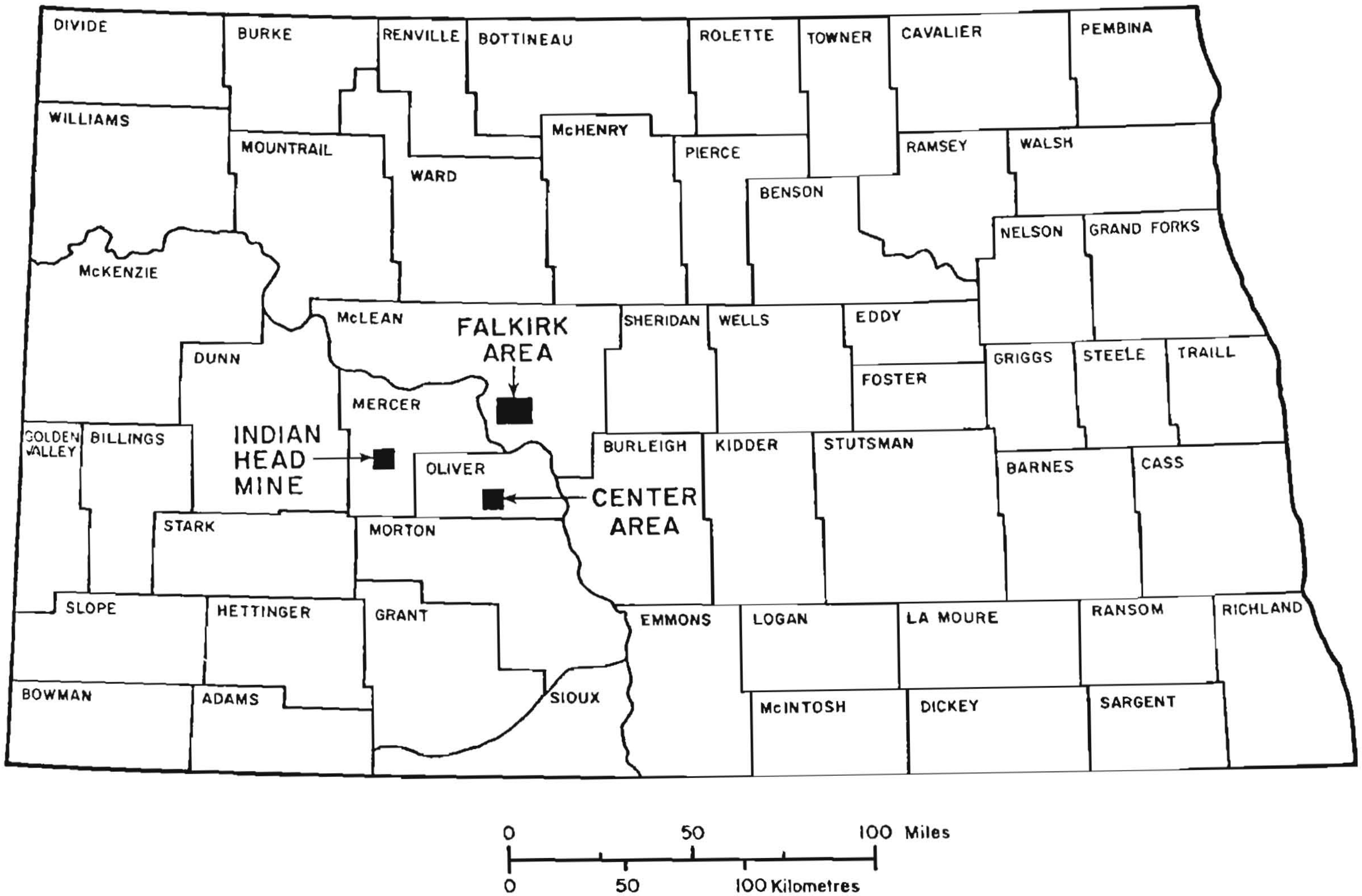


Figure 1. Location of the three areas of study.

ground using two electrodes spaced at some distance apart and connected to a power source. The potential drop is then measured between two additional electrodes inserted into the ground between the current electrodes. The resistivity, the resistance to current flow of a volume of material of given size and shape, can then be calculated for the material beneath the electrodes. If the material beneath the electrodes varies in its ability to conduct electrical current, as with almost all natural materials, the value calculated is called the apparent resistivity. It is the determination of this parameter that is the objective of resistivity investigations.

The derivation of the formulas used in earth resistivity is given in many geophysical textbooks (for example, Griffiths and King, 1981). The basic relationship involved in the flow of electrical current is Ohm's Law

$$\frac{V}{I} = R \tag{1}$$

where $V$ = potential difference between two surfaces of constant potential,
$I$ = current in a conducting body,
$R$ = constant called the resistance between the surfaces.

The definition of resistivity is:

$$\rho = \frac{RA}{L} \tag{2}$$

where R is the resistance measured between two equipotential surfaces of a conductor with cross-sectional area A separated by a distance L. The current density, j, within the conductor is given by

$$j = \frac{I}{A} = \frac{V}{\rho L} \tag{3}$$

Current density is an important consideration in media composed of layers of varying resistivity.

In earth resistivity theory, current is considered to flow from a source through a semi-infinite medium (the earth) to a sink. The potential at any point in the conducting medium resulting from the current, I, applied at the source is the sum of the positive potential due to the current source and the negative potential due to the current sink. With a four-electrode configuration and distances as shown in figure 1, the potentials at the two potential electrodes, $P_1$ and $P_2$, can be shown to be

$$V_1 = \frac{I\rho}{2\pi}\left(\frac{1}{r_1} - \frac{1}{r_2}\right)$$
$$V_2 = \frac{I\rho}{2\pi}\left(\frac{1}{R_1} - \frac{1}{R_2}\right) \tag{4}$$

The potential differences between $P_1$ and $P_2$ can be expressed as

$$V_1 - V_2 = \Delta V = \frac{I\rho}{2\pi}\left(\frac{1}{r_1} - \frac{1}{r_2} - \frac{1}{R_1} + \frac{1}{R_2}\right). \tag{5}$$

Equation (5) can then be solved for resistivity, $\rho$, to obtain

$$\rho = 2\pi\frac{\Delta V}{I}\left(\frac{1}{r_1} - \frac{1}{r_2} - \frac{1}{R_1} + \frac{1}{R_2}\right)^{-1}. \tag{6}$$

If the electrode separations are kept at a constant value, A, $r_1 = R_2 = A$, $r_2 = R_1 = 2A$, and equation (6) reduces to

$$\rho = 2\pi A \frac{\Delta V}{I}. \qquad (7)$$

Equation (7) is the basic expression for resistivity using the Wenner electrode configuration (fig. 2), the electrode configuration used in this study. For a heterogeneous medium, the quantity derived by equation (7) is called the apparent resistivity ( $\rho_a$ ).

The two general methods of resistivity surveying are horizontal profiling and vertical electrical sounding (VES). In the horizontal profiling method the electrode array is moved along a line with a constant electrode spacing (A). The vertical sounding method, which was used in this project, involves expansion of the electrode array about a central fixed point. At each station on the landscape, multiple values of apparent resistivity are obtained as the spacing increases from small to large values. As "A" increases, the depth penetration of the current increases and variations in resistivity of the material with depth can be determined. When layers of varying resistivity underlie a survey site, lines of current flowing in the ground become distorted with respect to the ideal homogeneous model. Current tends to flow vertically downward through poor conductors (high resistivity) and laterally through good conductors (low resistivity). Figure 3 shows a hypothetical 2-layer situation with a good conductor overlying a poor conductor. At short electrode spacings, the current flows through the upper layer as if the material were homogeneous with the resistivity of the upper layer. As the electrode array is expanded and depth penetration increases, the lines of current flow become distorted and crowded into the upper layer. Crowding of current lines increases the current density in the good conductor and therefore increases the voltage drop measured at the potential electrodes (eq. 3). In this example, as the electrode spacing is gradually increased, apparent resistivity gradually increases as the current flow is influenced by the layer of high resistivity at depth. Graphs of apparent resistivity versus electrode spacing (A) can then be plotted, which qualitatively indicate the sequence of resistivity layers beneath the site.

## Interpretation

While simple graphs of apparent resistivity versus electrode spacing give some qualitative information about subsurface geological conditions, quantitative interpretation is a much more difficult task. The objective of quantitative interpretation is to determine the thicknesses and resistivities of the layers beneath the survey site. Then, if control points are available, the resistivity survey results can be interpreted in terms of the stratigraphy and hydrogeology of the area.

Several methods exist for interpretation of Wenner sounding data. For this study the method chosen was automatic interpretation of the sounding curves using the computer program developed by Zohdy and Bisdorf (1975). This program inverts Wenner VES data to obtain layer thicknesses and resistivities for the site. One problem with the method is that it assumes horizontal, laterally homogeneous layers. However, interpretations can still be made if lateral heterogeneity is not excessive.

After the sounding curves have been automatically interpreted, they must be related to hydrogeologic conditions. This is a very difficult prob-

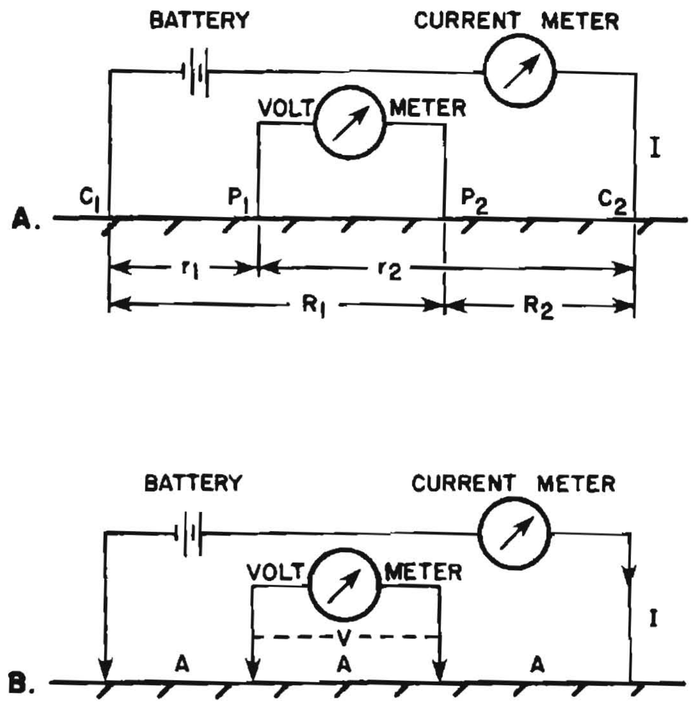


Figure 2. A. Configuration of the four-electrode array used in earth resistivity work. Current is passed through electrodes $C_1$ and $C_2$ and potential difference readings are made between electrodes $P_1$ and $P_2$. Distances below are used in derivation of formulas for apparent resistivity.

B. Equal spacing of electrodes (A) used in the Wenner electrode configuration.

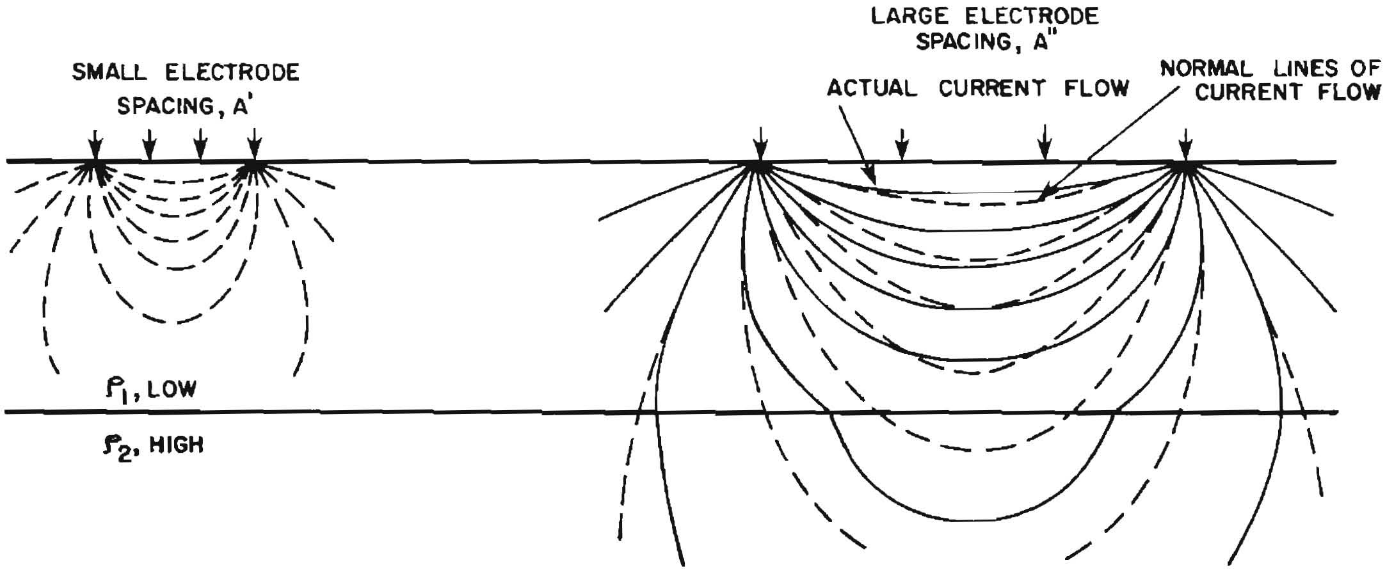


Figure 3. Influence of a layer of high resistivity at depth on the lines of current flow as the vertical electrode sounding (VES) is expanded from small electrode spacings (left) to large electrode spacings (right). Current flow tends to become concentrated in the more conductive layer and therefore higher apparent resistivity readings are obtained. (From Soiltest, 1968.)

lem in most places because resistivity boundaries do not necessarily correspond to stratigraphic contacts and, in addition, resistivity values can vary from place to place in similar materials. For these reasons, accurate resistivity interpretations require independent subsurface control information. In this study, relatively abundant subsurface data were available for comparison with resistivity results.

### General Approach to the Problem

Electrical currents are transmitted through the subsurface in two ways. In rock materials and non-clayey unconsolidated sediments, current is transmitted by groundwater moving in pores, joints, fissures, and fractures of the material. The matrix of these materials is mostly non-conducting; therefore, the resistivity is mainly controlled by factors such as the porosity, degree of saturation, amount of fracturing, and groundwater quality. Resistivity is affected by the dissolved-solids content of groundwater and by changes in water quality. An increase in dissolved ionic solute results in better conduction of electricity and lower resistivity. This relationship is often used in groundwater contamination studies in which earth resistivity is used for detection of contaminated groundwater.

In clayey materials, electrical conduction is promoted by weakly-bonded ions on clay particle surfaces. The high clay content in coal-bearing bedrock (sediments) and associated Quaternary materials in the Northern Great Plains suggests that this mode of conduction is very important in this region. Sedimentary materials at the study sites used in this project were determined to have extremely low resistivity values.

### Specific Methodology

Resistivity surveys were made in undisturbed (unmined) areas at all three study sites and in reclaimed spoils at the Center and Indian Head Mines. The number of sites surveyed is shown in table 1. Undisturbed sites were chosen to compare mined and unmined areas in similar geological settings. Undisturbed sites were chosen near test-hole locations for subsurface control. As previously discussed, extensive subsurface information was available for the reclaimed spoils areas.

TABLE I--Numbers of sites surveyed:

| Location | Number of sites |
|---|---|
| Falkirk area (undisturbed) | 6 |
| Indian Head Mine (spoils) | 12 |
| Indian Head area (undisturbed) | 4 |
| Center Mine (spoils) | 26 |
| Center area (undisturbed) | 5 |

Readings were made with a Soiltest R-50 Stratameter[1] and a Soiltest R-65 voltmeter. The R-65 voltmeter was chosen for greater accuracy in

[1] Reference to specific brands, equipment, or trade names in this report is made to facilitate understanding and does not imply endorsement by the Bureau of Mines.

determining the very low potential differences that were common at large electrode spacings because of the low resistivity of the materials investigated. The Wenner electrode configuration (fig. 2B) was used for all surveys. The most common spacings for each vertical electrical sounding were 5, 8, 12, 20, 30, 40, 60, 80, and 100 feet. Some sites were surveyed along two perpendicular lines to evaluate resistivity variations with direction. Seven sites were resurveyed during 1981 for comparison with data obtained during 1980.

Field data was then entered into the Zohdy and Bisdorf (1975) computer program for automatic interpretation. Appendix I gives the locations of the sites surveyed in unmined areas. Appendix II shows the information obtained at the survey sites. Each diagram includes the field curve plotted as apparent resistivity (eq. 7) versus electrode spacing, the depths and resistivities obtained by automatic interpretation, and other available information such as stratigraphy, piezometer depths, water levels, and groundwater chemistry.

In many resistivity investigations reported in the literature, the layers have contrasts in resistivity that differ by orders of magnitude. Interpretation of actual depths and resistivities is most successful in such cases. The various types of sediments in these study areas show much less contrasts than in many other regions. They are, however, typical of the coal-bearing sediments of the Northern Great Plains. Most of the bedrock sediments, even the sand and silt beds, are rich in clay minerals. Beds of high resistivity are quite rare in the study areas. The spoils derived from these sediments maintain their general resistivity characteristics. At the larger electrode spacings, very small changes in potential difference result in significant differences in apparent resistivity. For example, at an electrode spacing of 100 feet, a change in potential difference of only one millivolt is equivalent to a change in apparent resistivity of 6.28 ohm-ft. Differences on the order of several millivolts are probably not within the limits of accuracy of the equipment or the field methods used; the layering sequence produced from the input data by the computer, however, is very sensitive to small changes in the slope of the apparent resistivity curve. In materials with the degree of electrical uniformity found in most of the sediments in the study areas used in this project, the detailed computer-interpreted sequence of layers must be regarded with low confidence. However, the overall resistivities determined, and the layering interpreted in the occasional cases of high resistivity contrast, are accurate.

## RESULTS

### Falkirk Area

The Falkirk area is characterized by relatively thick glacial sediments overlying bedrock units of the Sentinel Butte and Bullion Creek Formations (Groenewold et al., 1979). The glacial deposits include till and interbedded sand and gravel. The Underwood Sand, an important aquifer near Underwood, North Dakota, occurs as the uppermost bedrock unit in much of the Falkirk area. The abundance of sandy materials both in the glacial and Tertiary sediments results in layers of greater resistivity contrast than either of the other study sites. Of the six sites surveyed in the Falkirk area (app. I), three (sites 531, 553, and 545) (app. figs. A1-3) produced an excellent correlation between apparent resistivity and lithology. Sites 531 and 553 were probably the most successful sites in the study. The computer interpretation of the depths and resistivities shows a very accurate correspondence with the lithologic log. The highest resistivities measured in the study were obtained at site 545, where the Underwood Sand occurs at the surface. The combination of sandy lithology and presumably low moisture content combine to produce very high resistivities. Sites 531 and 553 indicate that the Underwood Sand does not produce resistivity values as high when it is overlain by a low resistivity layer. Site 545 also indicates the unusually high resistivity measured for lignite and clay when they are overlain by the high resistivity sand. These three sites support the common observation that surficial materials influence the resistivities of the materials below. There is no absolute correspondence between lithology and apparent resistivity. Materials can exhibit a wide range of resistivities depending on stratigraphy and moisture conditions. The ideal situation for resistivity interpretation is a sequence of layers with alternating high and low resistivities. This will permit accurate interpretation based on the relative resistivities of the layers.

The surveys at Falkirk sites 581, 526, and 565 (app. figs. A4-6) were less successful in interpreting subsurface conditions. While the interpreted resistivities are generally appropriate for the materials they represent, the interpreted contacts do not agree with those indicated on the lithologic logs. Lateral discontinuity is a possible explanation for the lack of correlation between the lithologic logs and the interpreted layer sequence.

## Indian Head Mine

The geologic setting of the Indian Head Mine consists predominantly of alternating beds of silt, clay, and lignite (Groenewold et al., 1979). There are only a few thin, sandy beds in the section. The deposits are interpreted as fine-grained alluvial sediments rich in sodium montmorillonitic clay. Such sediments contain slow-moving groundwater flow systems characterized by high dissolved-solids contents. Total-dissolved-solids (TDS) values ranging from 937 mg/L to 4390 mg/L have been measured in water from the Beulah-Zap Bed (lignite) in the vicinity of the Indian Head Mine (Groenewold et al., 1979). Spoils derived from clayey overburden materials can be expected to generate groundwater high in dissolved-solids content, particularly if the sediments contain even small amounts of pyrite. The geochemical considerations involved in the evolution of spoils groundwater have been discussed by Groenewold et al. (1979) and Groenewold et al. (1980). TDS values ranging from 1,560 mg/L to 15,880 mg/L have been measured in spoils from the Indian Head Mine. Hydraulic conductivity values in reclaimed spoils at the Indian Head Mine show a relationship to precontouring spoils topography. Higher hydraulic conductivity in precontouring spoils valleys can be attributed to poor compaction obtained by contouring the spoils with dozers in winter (Groenewold and Rehm, 1980).

Resistivity surveys were conducted at four unmined sites adjacent to test-hole locations (app. I) around the Indian Head Mine and at 12 sites within the USBM reclaimed spoils study plot within the mine (fig. 4). Prior to contouring and reclamation the USBM study site consisted of several adjacent ridges and valleys. The site was mapped in detail prior to contouring. Instrumentation at the site consisting of concrete markers, piezo-

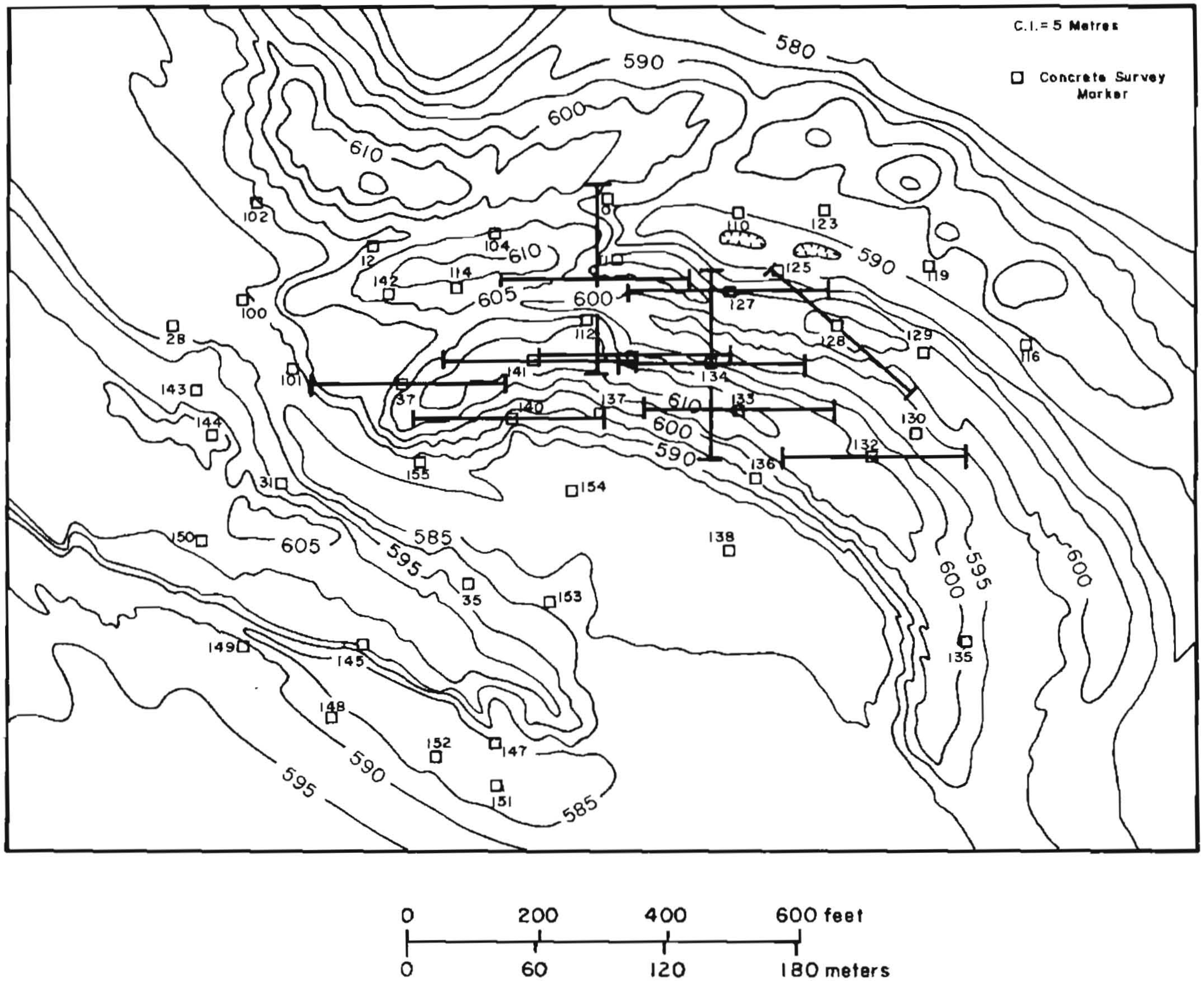


Figure 4. USBM spoils study area at the Indian Head Mine. Contours indicate topography of spoils prior to reclamation. Resistivity surveys are shown by heavy lines and identified by concrete markers located along survey traverse (see app. IIB).

meters, soil water samplers, and neutron access tubes has allowed for detailed landscape stability and subsurface water characterization of the reclaimed site. Diagrams summarizing the information gathered at the Indian Head Mine are included in appendix IIB.

The four unmined sites surveyed at the Indian Head Mine (app. figs. B1-4) are typical of the area in that they consist of alternating beds of silt, clay, and lignite with only thin beds of sand in the sections. Indian Head site 165 (app. fig. B1) differs from the others because it contains relatively thick surficial Quaternary sediments. Apparent resistivities at the four unmined sites are characterized by thin shallow layers of high resistivity at the surface underlain by materials of uniform low resistivity with depth. This correlates well with the test-hole logs at the site. The thin high resistivity surface layers probably result from low moisture content soil conditions in the zone caused by evapotranspiration. In addition, soil forming processes transport clay downward in soil profiles to zones of accumulation in the B horizons. The variations in lithology indicated in the test-hole logs have very little effect on the apparent resistivity curves below the surface layers. The field curve for Indian Head site 165 shows an increase in resistivity at the 40-foot spacing which seems to correlate with beds of till and sand between 30 and 55 feet in depth.

The general pattern of the field curves from spoils sites in the USBM plot resembles quite closely the field curves from the undisturbed sites. The average values of apparent resistivity with depth are similar for both cases, indicating that the overall resistivity characteristics of a landscape composed of relatively uniform materials are unchanged following surface mining and reclamation. There are, however, three specific types of differences recognized between the unmined and spoils sites.

(1) The thin high-resistivity surficial layer at the unmined sites is not present at the spoils sites. A surface layer is present at several of the spoils sites that has a somewhat higher apparent resistivity than the materials at greater depth. However, the highest value interpreted by the computer program for near-surface materials at a spoils site is 72 ohm-ft. compared to a range of 87 to 252 ohm-ft. for the undisturbed sites. The lower surface resistivity in spoils could be explained by higher clay content in that portion of the spoils than in naturally developed soils or less evapotranspiration in spoils because of poorly developed vegetation.

(2) A number of resistivity curves from the spoils surveys have a more regular, broken shape with frequent slope reversals as compared to the undisturbed sites. This suggests greater localized, non-stratigraphic heterogeneity in the spoils than in the undisturbed materials. Good examples of this type of curve include Indian Head sites 132, 137, 111-112, and 133 (app. figs. B9-13). Mining and reclamation tends to destroy the original stratigraphic heterogeneity of the spoils; that is, materials from different stratigraphic units are mixed together during mining and reclamation, creating less stratified material. Reclamation results in a different type of stratification (Groenewold and Winczewski, 1977). The heterogeneity recorded in the resistivity profiles could be the result of lithologic segregation of materials during reclamation, differences in moisture content, or variations in water chemistry. These factors may be interrelated to some extent; for example, clayey sediment concentrated in a particular part of the spoils would probably generate poor quality water if infiltration from the surface moves through the material.

The sharp changes in resistivity in some of the spoils profiles shown in appendix IIB cannot be correlated with other sites; therefore, the materials or conditions causing the heterogeneity are localized in the spoils and discontinuous. In fact, discontinuous heterogeneity in spoils resulting from mining activities would be expected. Data pertaining to this problem are provided by six cored spoils borings made at the Indian Head Mine. Moisture content analyses made at regular intervals in the cores suggest that the variation in moisture content in the spoils is not large. Most of the samples were described as being somewhat to slightly below saturation. The moisture content commonly varied about five percent in a particular boring. This amount of variation does not seem to be sufficient to cause significant changes in resistivity. The reason for the lateral discontinuity in resistivity curves, therefore, is unknown. It could be the result of localized concentrations of clayey sediment, but there is no evidence which supports either lithologic or moisture content variations.

It is possible, however, that a small change in moisture content from unsaturated to saturated conditions could be significant if it occurred at a fairly continuous level or in a significant concentrated volume of spoils material. A mechanism of this type would produce a low resistivity layer in the vicinity of the water table. Six surveys in the Indian Head spoils were made adjacent to piezometers (fig. 4). Of the six piezometers, three are dry and three have measurable water levels. The interpretation for the three sites with measurable water levels, sites 134, 127, and 140 (N-S) (app. figs. B14-16), does show a rather thick layer of low resistivity which extends both above and below the water level in the piezometer. TDS levels in two of the wells are approximately 4,500 mg/L. It is possible that the low resistivity layer represents the combined effect of the water table and the mineralized groundwater present in the base of the spoils and the upper bedrock zone. Surveys adjacent to two of the three wells which do not intersect the water table, sites 111-112 (N-S) and sites 111-112 (E-W) (app. figs. B11 and 12), have low resistivity layers at and below the position of the dry wells. These low resistivity layers are apparently a reflection of the water table which is below the base of the piezometer. The other site having a piezometer above the water table, site 133 (app. fig. B13), has a resistivity curve which is relatively uniform in its lower part. If the low resistivity layers in the mid to lower sections of the profiles do represent the approximate position of the water table, then it is also possible that the discontinuities in the upper parts of the curves are indicating localized perched saturated zones in the spoils. Such zones were noted during drilling of test holes in the spoils.

## Center Area

The third area used in this study was the Center Mine and adjacent areas. Five surveys were made in undisturbed ground in the vicinity of the mine and 26 surveys were made in the 5 areas of reclaimed spoils.

The physiographic and geological setting of the Center Mine is generally similar to that of the Indian Head Mine. The mine is located in an upland surface water divide area underlain by beds of sand, silt, clay, and lignite (Groenewold et al., 1979). Till is somewhat more abundant at the top of the section than at Indian Head. The Center area also has more sand above and between the lignite beds than Indian Head; therefore, the spoils at Center are sandier than the Indian Head spoils.

At the unmined sites, the resistivity field curves and interpreted layers and resistivities show a generally good correlation with the lithologic logs. A particularly good example is the difference between the curves for Center sites 363 and 361 (app. figs. C1 and 2) for which the stratigraphy consists of till overlying relatively thick sand beds, and Center site 372 (app. fig. C3) which consists of till overlying lignite and clay beds. At Center sites 361 and 363, the resistivity data clearly show sand underlying the surficial till as indicated by increasing resistivity with depth. The interpreted resistivity for the sand at Center site 361 is among the highest values determined in this study. This suggests especially dry conditions in that area. In addition, the fine-grained clay and lignite beneath the sand are indicated by decreasing apparent resistivity. In contrast, the results for Center site 372 indicate low resistivity for the till and the underlying thick lignites. The results at Center site 360 (app. fig. C4) show a general correlation with the materials, but the results at Center site 364 (app. fig. C5) do not correlate well with the lithologic log.

The spoils at Center were surveyed in more detail than Indian Head because of the variability of reclamation procedures used at specific study plots. The Center spoils include seven study plots which are instrumented to test the effects of various combinations of contouring equipment and climatic variables on spoils stability. Five of these plots were used for resistivity surveys. All resistivity surveys in Center spoils are identified according to the identification numbers of piezometers along the survey traverse. The piezometers are commonly nested with the screened intervals of the piezometers in a nest at different stratigraphic positions. Figures 5 through 9 show the precontouring topography, the piezometer locations, and the resistivity survey locations on these five test plots.

Spoils area 2 (fig. 5) was contoured by dozers in winter. This combination frequently results in excessive settlement and surface disruption of the reclaimed spoils (Groenewold and Rehm, 1980). Spoils are thick in area 2, ranging from 55 to 85 feet. Resistivity surveys were centered at the locations of six piezometers which are screened at or slightly below the spoils--bedrock contact. These are piezometers 59, 62, 63, 65, 66, and 68 (fig. 5). Three of these piezometers are above the water table. The water tables recorded at the remaining three piezometers screened in the base of the spoils are very near or slightly above the spoils--bedrock contact.

The resistivity curves and interpretations from area 2 (app. fig. C6-11) indicate relatively uniform subsurface conditions. Three of the locations with water tables in the piezometers (sites 64-65, 59-60, 66-67) show an interpreted resistivity contact at the approximate level of the water table. Because the variation in resistivity is not large in this area, these contacts may or may not be significant. Center site 61-62 (app. fig. C6), a site that was surveyed in 1980 and 1981, illustrates the effect of a slight change in the potential difference measured in the field on the resulting computer interpretation. The apparent resistivity curves are generally similar for the two years, but differ by 6 to 8 ohm-ft. at the 100-foot spacing. As mentioned earlier, this variation could be caused by a difference in measured potential difference of only one millivolt. The effect on the interpreted resistivity section is great, however; the layers show the opposite trend for the two years. The 1980 curve suggests a high resistivity layer at depth, while the 1981 curve indicates a low resistivity layer at the base of the section. Thus, the problem of distinguishing layers of relatively uniform lithology by resistivity again becomes apparent.

Spoils area 3 (fig. 6) was contoured by dozers in summer. Of the six piezometers screened in the base of the spoils and used as centerpoints of

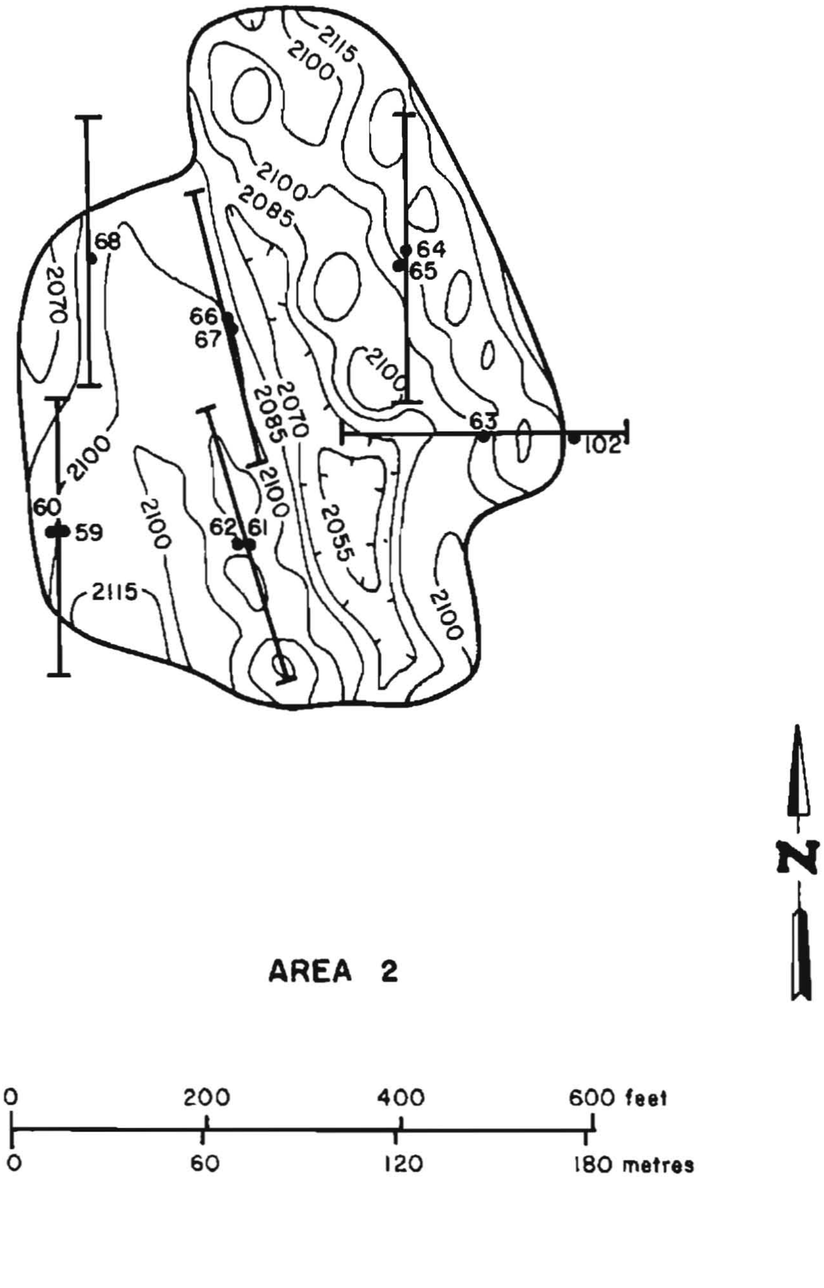


Figure 5. Precontouring topography (elevations in feet) of area 2 at the Center Mine. Piezometer locations shown by dots and resistivity surveys shown by heavy lines.

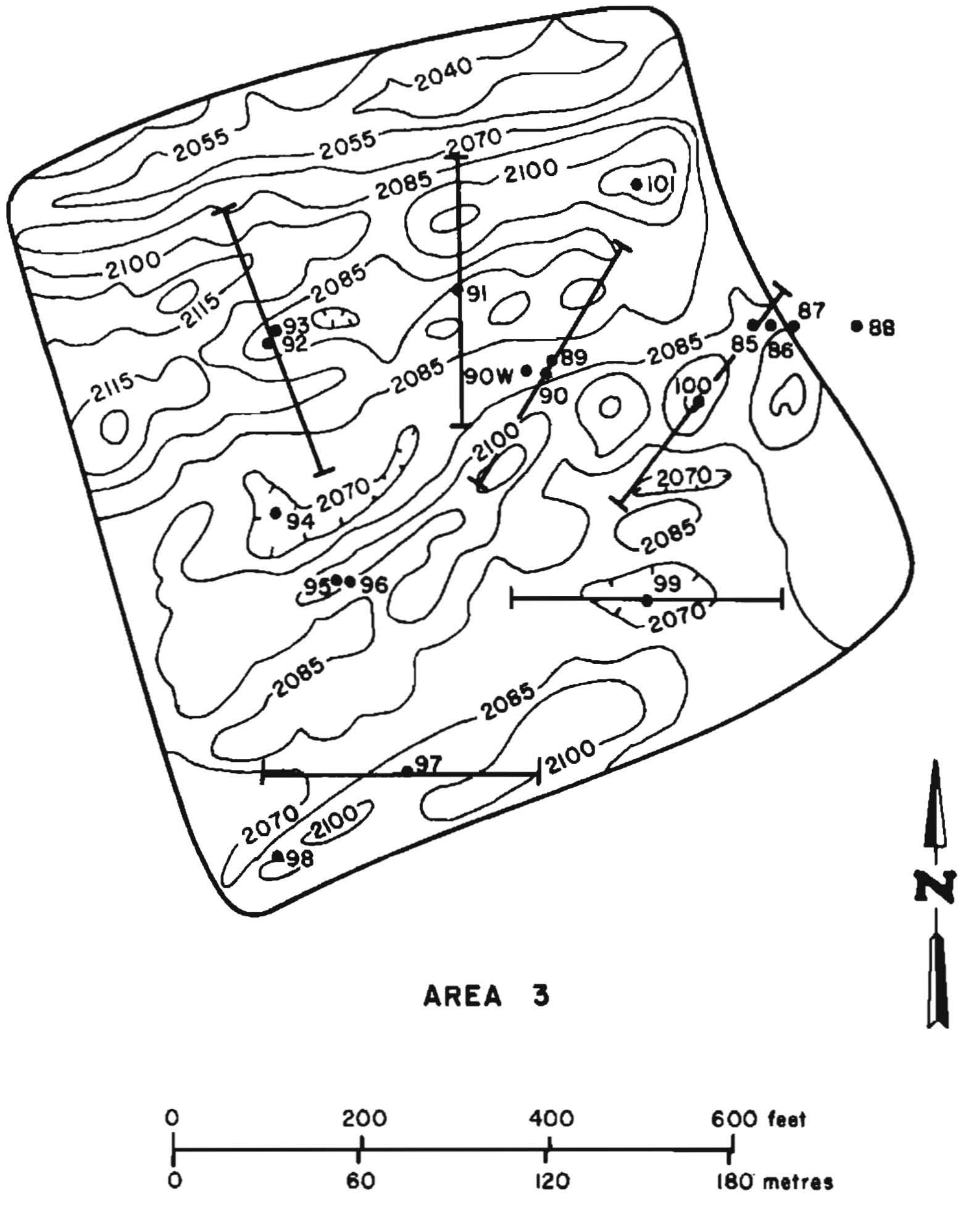


Figure 6. Precontouring topography (elevation in feet) of area 3 at the Center Mine. Piezometer locations shown by dots and resistivity surveys shown as heavy lines.

resistivity surveys at this site, one (92) is dry and the other five (90, 91, 97, 99, 100) have water levels just above the base of the spoils. Five of the field curves and interpretations (sites 91, 97, 100, 92-93, 99) indicate a sequence of relatively high resistivity in the upper part of the spoils (app. figs. C13-17), lower resistivity in the base of the spoils, and higher resistivity downward from the approximate spoils--bedrock contact. Site 90 (app. fig. C12) shows the opposite pattern, with a decrease in resistivity, occurring below the spoils--bedrock contact. Assuming the layering is real, the low resistivity in the base of the spoils could be explained by moist conditions and/or chemical reactions between spoils minerals and oxygen and water leading to water with high-dissolved-solids content. Total-dissolved-solids content in four piezometers in area 3 ranges from 2,989 to 6,564 mg/L.

One of the sites in area 3, site 99 (app. fig. C16) is notable for several reasons. The resistivity results indicate very low resistivity in the lower half of the spoils, and very high resistivity in the bedrock below. The TDS in piezometer 99 is 6,564 mg/L, the highest in area 3. The precontouring topographic map (fig. 6) shows that piezometer 99 is located near the center of a closed depression with the lowest precontouring elevation in area 3. This depression would have been a collection point for surface runoff from the surrounding spoils ridges, and therefore probably concentrated infiltration. The combination of unusually low resistivity in the base of the spoils, as in site 99, and unusually high TDS in the well at the base of the spoils at this site supports the interpretation of high moisture content at this site. In addition, the excellent correspondence of the curves from 1980 and 1981 leads to increased confidence in the results. The extremely high resistivity of the lowest layer is probably not real, but instead represents the slope of the curve as the base of the low resistivity layer is encountered. Readings at greater spacings would probably alter the interpretation of the lowest layer. This site suggests that resistivity can detect subsurface changes in spoils conditions, but only when such changes are major.

Five surveys were made in spoils area 4 (fig. 7). This plot was contoured by scrapers in winter. The results of four of the surveys (app. figs. C18, 19, 20, and 21) indicate relatively high resistivity in the lower part of the spoils. Three of the profiles (C18, 19, and 21) suggest a resistivity contact in the vicinity of the base of the spoils and the water table with higher resistivity above the contact and slightly lower resistivity below. This is similar to the majority of the sites in area 2, but the lack of contrast present in the area 4 soundings makes conclusions questionable. The patterns obtained could be reversed by slight changes in potential difference at wide spacings.

Area 6 (fig. 8), contoured by dozers in summer, yielded ambiguous results. All six surveys in this area (app. figs. C23-28) indicated a change from higher to lower resistivity, but at varying positions in the section. The contact ranges from about 10 feet above the spoils--bedrock contact and water table to as much as 35 feet below the spoils--bedrock contact. Moisture content variation in the spoils may be more than usual in this area. Four of the sites in this area (sites 136-137, 140 N-S, 140 E-W, and 141-142) were surveyed in both 1980 and in 1981 (app. figs. C25-28). The results of two of these surveys (app. figs. C25 and C28) are in good general agreement. One interesting change becomes apparent by comparing the 1980 and 1981 curves. The 1980 curves, except for site 141-142 (app.

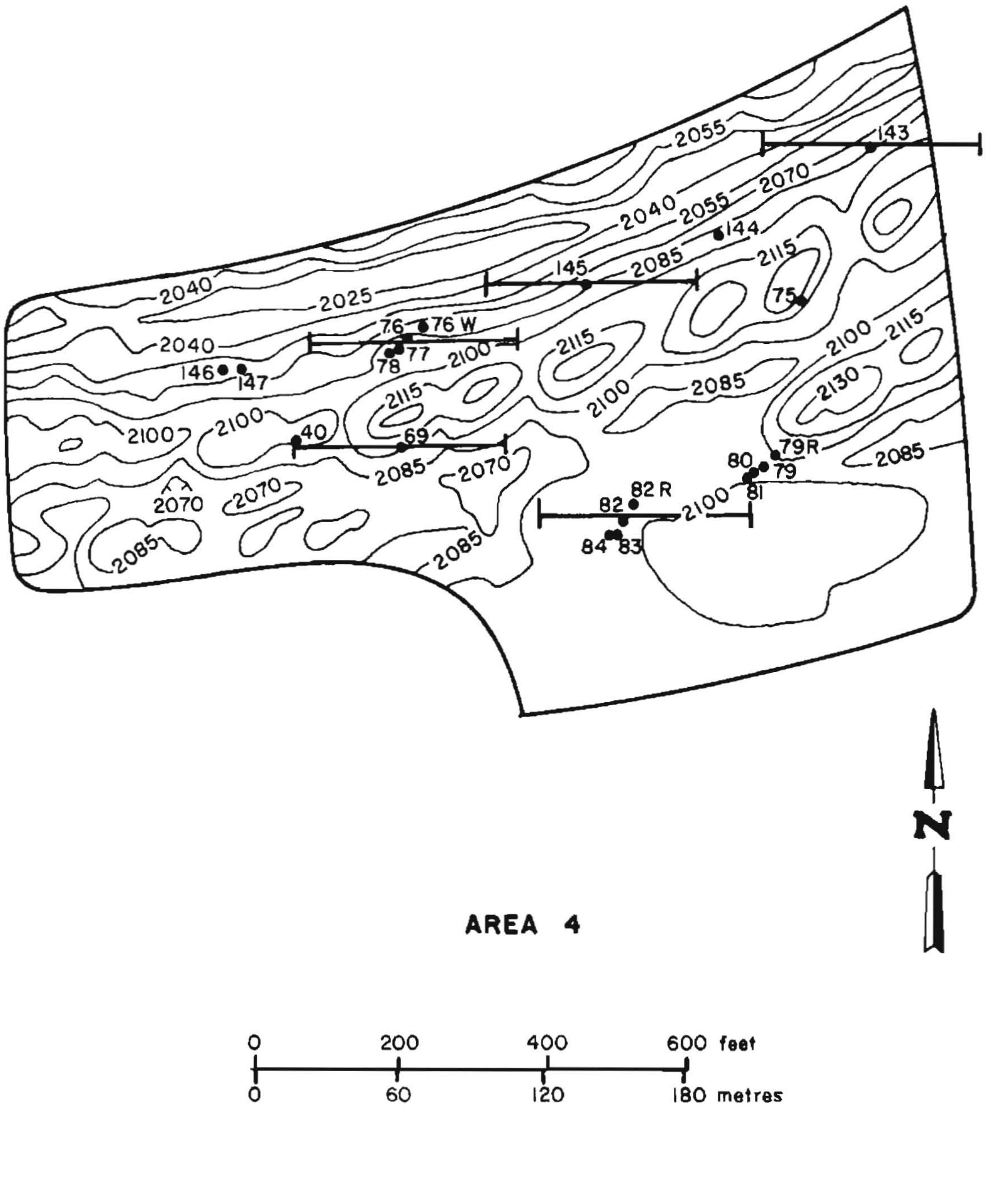


Figure 7. Precontouring topography (elevations in feet) of area 4 at the Center Mine. Piezometer locations shown as dots and resistivity surveys shown as heavy lines.

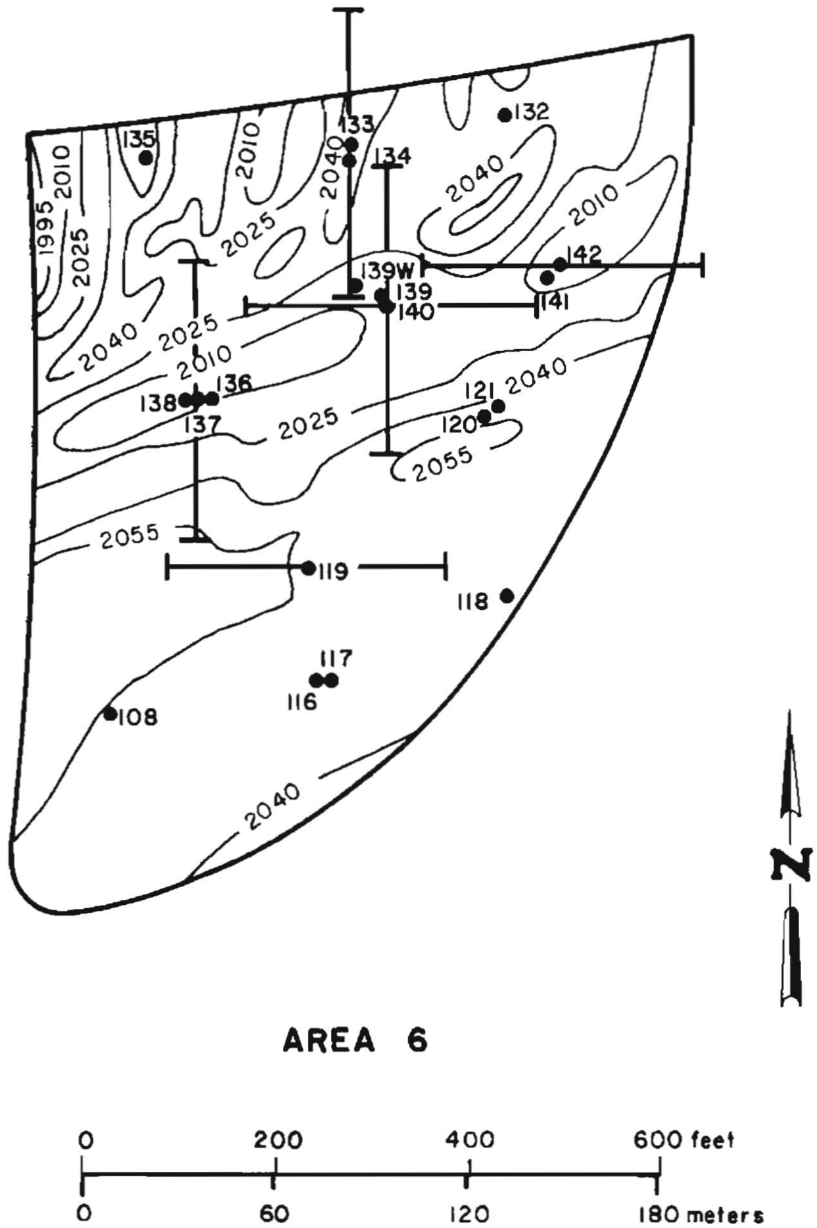


Figure 8. Precontouring topography (elevations in feet) of area 6 at the Center Mine. Piezometer locations shown as dots and resistivity surveys shown as heavy lines.

fig. C28), all show extremely high readings at the 5-foot spacing. The 1981 values are much lower at this spacing. These differences can be directly correlated with climate, as 1980 was a very dry year in comparison to 1981, which had typical rainfall. Apparently, climatically controlled moisture conditions have a very significant effect on resistivity results at small spacings. These moisture changes do not generally affect the soil below a depth of about 10 feet.

Center spoils area 7 (fig. 9), a plot contoured by scrapers in summer, was surveyed at three locations. Two of these sites (sites 129-130, 124) (app. figs. C29 and 30), indicate a change from higher resistivity in the lower part of the spoils to lower resistivity in the vicinity of the spoils--bedrock contact and water table. The remaining site (site 128) (app. fig. C31), shows very little change across the spoils--bedrock contact; however, a water table is not present at that inverval.

## DISCUSSION

This study was intended to be a reconnaissance evaluation of earth resistivity as a tool for investigation and interpretation of subsurface conditions in reclaimed spoils at surface lignite mines. The general geologic setting of the mines studied was determined to present serious limitations to the application of the method. The basic difficulty encountered was the lack of resistivity contrast within subsurface materials at the mines. The clayey, unconsolidated bedrock (sediment) of the region provides limited examples of layered beds of highly contrasting resistivity. Reclaimed spoils, because they are composed of the original overburden materials, present similar problems in interpretation. The greatest success in interpretation was achieved in glacial materials, which are generally thin and not widely distributed at the two mined areas studied. These limitations preclude the degree of usefulness of earth resistivity envisioned at the beginning of the project. The conclusions that can be drawn from the study are further developed in this section and summarized in the following section.

### Differences Between Mined and Unmined Areas

Interpretations of unmined areas were most successful in the Falkirk and Center areas where somewhat contrasting stratigraphic sections are present. Agreement with lithologic test-hole logs varied from excellent to poor. Contacts between glacial or bedrock sands and fine-grained deposits could usually be detected with the resistivity method. At the Indian Head Mine, an area of relatively uniform lithologies, stratigraphic layering could not be defined with earth resistivity.

The major effect of mining and reclamation on resistivity profiles seems to be a reduction in resistivity layer contrast which makes interpretation less successful than in unmined areas. At the Indian Head Mine, unmined and spoils resistivity curves are quite similar; at the Center Mine, however, the surveys made in spoils yield curves that are much more uniform. The variations that do occur appear to be non-stratigraphic and discontinuous.

### Resistivity Variations in the Spoils

It is likely that the major variations in resistivity in spoils are the result of moisture content and geochemical (mineralogical) factors rather than

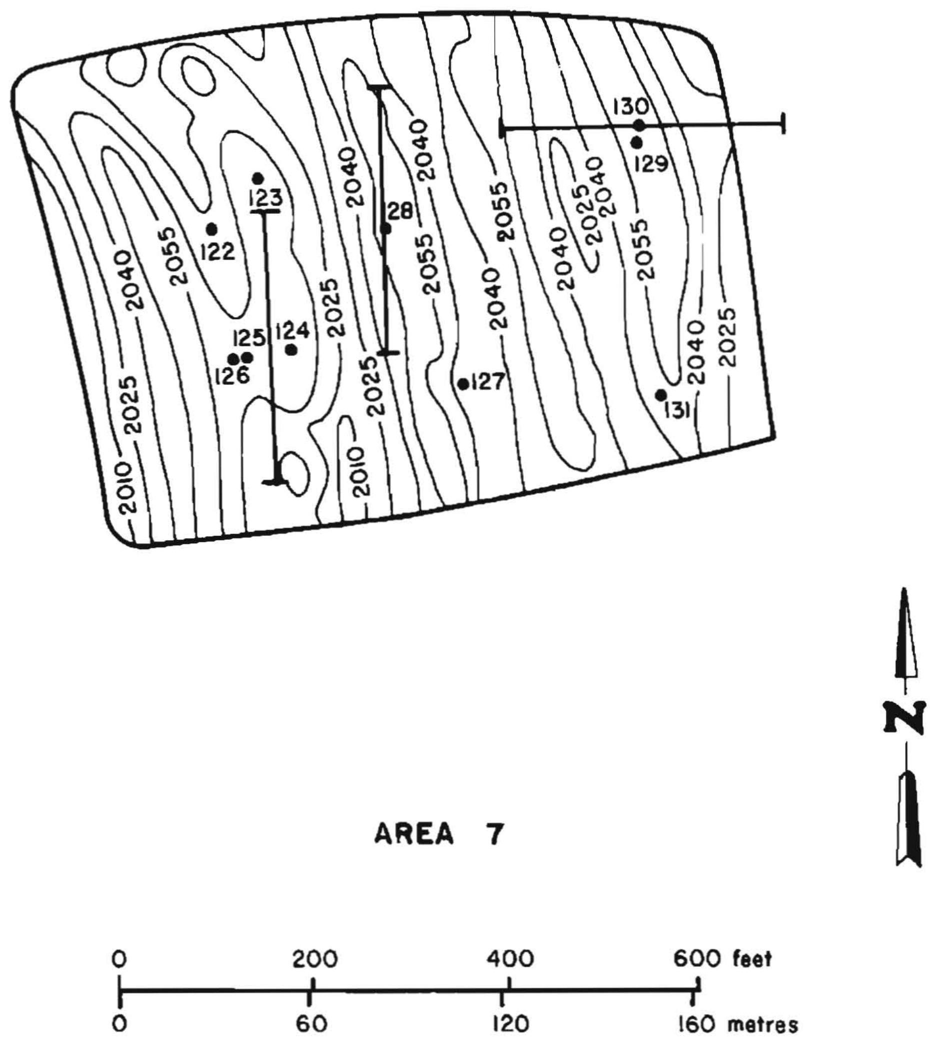


Figure 9. Precontouring topography (elevations in feet) of area 7 at the Center Mine. Piezometer locations shown as dots and resistivity surveys shown as heavy lines.

stratigraphy. These variations are much more subtle and much more difficult to interpret with confidence. At Indian Head, where overburden materials are very clayey, surveys at three piezometers with water tables indicate a relatively low resistivity layer which extends both above and below the water table. A conclusive explanation for this layer is not possible, but it may represent the production of degraded groundwater in a zone which includes the base of the spoils. Highly mineralized groundwater in the vicinity of the water table is common in the Indian Head spoils.

A different spoils resistivity pattern exists at the Center Mine where five distinct study areas were investigated. At four of the study areas, the typical pattern includes a moderately high resistivity surface layer, occasional discontinuous low resistivity layers in the upper part of the spoils, a relatively high resistivity zone at the base of the spoils, and a change in the vicinity of the water table to lower resistivity below. One possible explanation for this pattern is that, because the Center overburden is sandier than the Indian Head overburden, degraded groundwater is not being generated to the extent that it is at Indian Head. The main change in resistivity, therefore, is a change from unsaturated to saturated conditions at the water table. The exception to this trend is area 3, in which all but one of the resistivity soundings indicate exactly the opposite layering in the lower part of the soundings. The major portion of the spoils in area 3 is interpreted to have relatively low resistivity with a change to higher resistivity in the vicinity of the water table. It is not known whether or not there is a local concentration of clayey materials in the spoils in area 3, but there is some indication of unusually high TDS levels from the wells in the area. One site in particular, site 99, has extremely low resistivity layers in the spoils and also the highest TDS values at the mine. As mentioned earlier, this site is located in a precontouring depression which would have probably collected surface runoff resulting in greater infiltration into the spoils.

The above discussion provides the best interpretation of the data obtained, but it must again be emphasized that the lack of resistivity contrast in the spoils material makes the level of confidence low in the field data interpretations.

One result of this study that can be reported with confidence is the overall difference in resistivity between the spoils at the Center and Indian Head Mines. Spoils at the Center Mine have consistently higher resistivity than the Indian Head Mine. This can best be illustrated by comparison of the average apparent resistivities for each electrode spacing for all surveys at the two mines (table II). Higher resistivity at the Center Mine can be explained by sandier (less clayey) overburden materials. The consistency of the differences between the mean resistivities indicates that the method was very successful at distinguishing the overall lithologic variations between the mine spoils.

## Relationship Between Resistivity and Groundwater Quality in Spoils

The lithology of the spoils is the most important factor in the chemical evolution of groundwater in the postmining landscape. Spoils at the Indian Head Mine site generate groundwater high in dissolved solids because of the high clay and associated reactive mineral content. Center Mine spoils produce better quality groundwater because reactive minerals are less abundant. This relationship suggests the possibility that there is a cor-

Table II.--Mean apparent resistivities (ohm-ft. ) at the Center and Indian Head Mines

| Mine | Electrode Spacing (ft.) 5 | | | 12 | | | 20 | | | 30 | | | 40 | | | 60 | | | 80 | | | 100 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $\bar{x}$ | N | $\bar{s}$ | $\bar{x}$ | N | $\bar{s}$ | $\bar{x}$ | N | $\bar{s}$ | $\bar{x}$ | N | $\bar{s}$ | $\bar{x}$ | N | $\bar{s}$ | $\bar{x}$ | N | $\bar{s}$ | $\bar{x}$ | N | $\bar{s}$ | $\bar{x}$ | N | $\bar{s}$ |
| Center | 51.8 | 34 | 18.6 | 47.8 | 34 | 6.4 | 50.2 | 34 | 6.9 | 52.0 | 34 | 10.4 | 52.6 | 34 | 10.4 | 49.2 | 34 | 7.7 | 45.6 | 34 | 6.5 | 45.5 | 33 | 6.4 |
| Indian Head | 40.1 | 14 | 8.7 | 33.8 | 14 | 8.9 | 30.4 | 14 | 7.4 | 28.6 | 14 | 8.5 | 27.8 | 12 | 8.5 | 29.1 | 13 | 4.7 | 29.3 | 13 | 5.4 | 32.7 | 11 | 4.0 |

$\bar{x}$ = Mean apparent resistivity at indicated spacing

N = Number of readings

$\bar{s}$ = Standard deviation

relation between chemical quality of groundwater generated in the spoils and resistivity. Several approaches were used to test this hypothesis. Figure 10 shows a plot of TDS, a measure of the overall groundwater quality, for each well at which a resistivity survey was made, against the interpreted layer resistivity which corresponds to the elevation of the piezometer screen. Regression analysis of this plot gives a correlation coefficient of -.44. The weak correlation indicated by this correlation coefficient can be explained by several factors. An extremely significant consideration is that we are trying to correlate point data with bulk material data. The TDS content of a piezometer indicates the water quality at one specific point in the spoils. There is a large variation in TDS in the piezometers in both mines. A detailed determination of the distribution of this variation is not possible. The resistivity measurement, on the other hand, reflects a weighted average of the materials beneath the current electrodes, a distance of 240 feet at the 80-foot spacing. It is reasonable to assume that TDS at the groundwater table is quite variable over that distance. The second factor in the poor correlation is that the interpreted resistivity layers are probably not extremely accurate for the reasons discussed earlier. In addition, the interpreted layers are average, best-fit solutions to actual conditions which may be quite discontinuous in the spoils.

An alternative plot of the data, figure 11, shows TDS versus the apparent resistivity at the 80-foot spacing for the resistivity survey centered at that well. The value plotted for resistivity in this case has the advantage of being a field measured value, independent of interpretation. Regression analysis of this plot gives a correlation coefficient of -.613, a significant improvement over figure 10. A regression equation fitted to the points in figure 11 has the form:

$$\text{TDS (mg/L)} = 8{,}537 - 128\,\rho_{80}\ \text{(ohm-ft.)},$$

where $\rho_{80}$ is the apparent resistivity at the 80-foot spacing. This spacing was chosen because it should be a good approximation of the entire thickness of spoils above bedrock. Similar results would be obtained using several other spacings. This equation could be used as a rough estimate of groundwater quality as a function of measured apparent resistivity in an area of reclaimed spoils. Use of the equation, however, could still yield misleading results if applied to any random point in the spoils because the local variation in groundwater quality in the spoils has still not been taken into account.

An approach which could be taken for predictive purposes for the groundwater quality for an entire mine is shown in figure 12. In this figure, the mean apparent resistivity at the 80-foot spacing for all resistivity soundings at the Center and Indian Head Mines in reclaimed spoils is plotted against the mean TDS for wells at the respective mines. Fourteen values for TDS of groundwater in Indian Head Mine spoils and twenty-one values for TDS in Center Mine spoils used in this plot are given by Groenewold et al. (1981). By using mean values of TDS, the effects of local variations on the chemical development of groundwater are minimized. The two points plotted show the predicted relationship between resistivity and groundwater quality; that is, apparent resistivity and TDS are inversely proportional. The data cannot be subjected to regression analysis, however, because only two data points are available. If spoils resistivity data and groundwater quality data were available for more mines, this relationship could be properly assessed. In general, however, it is clear

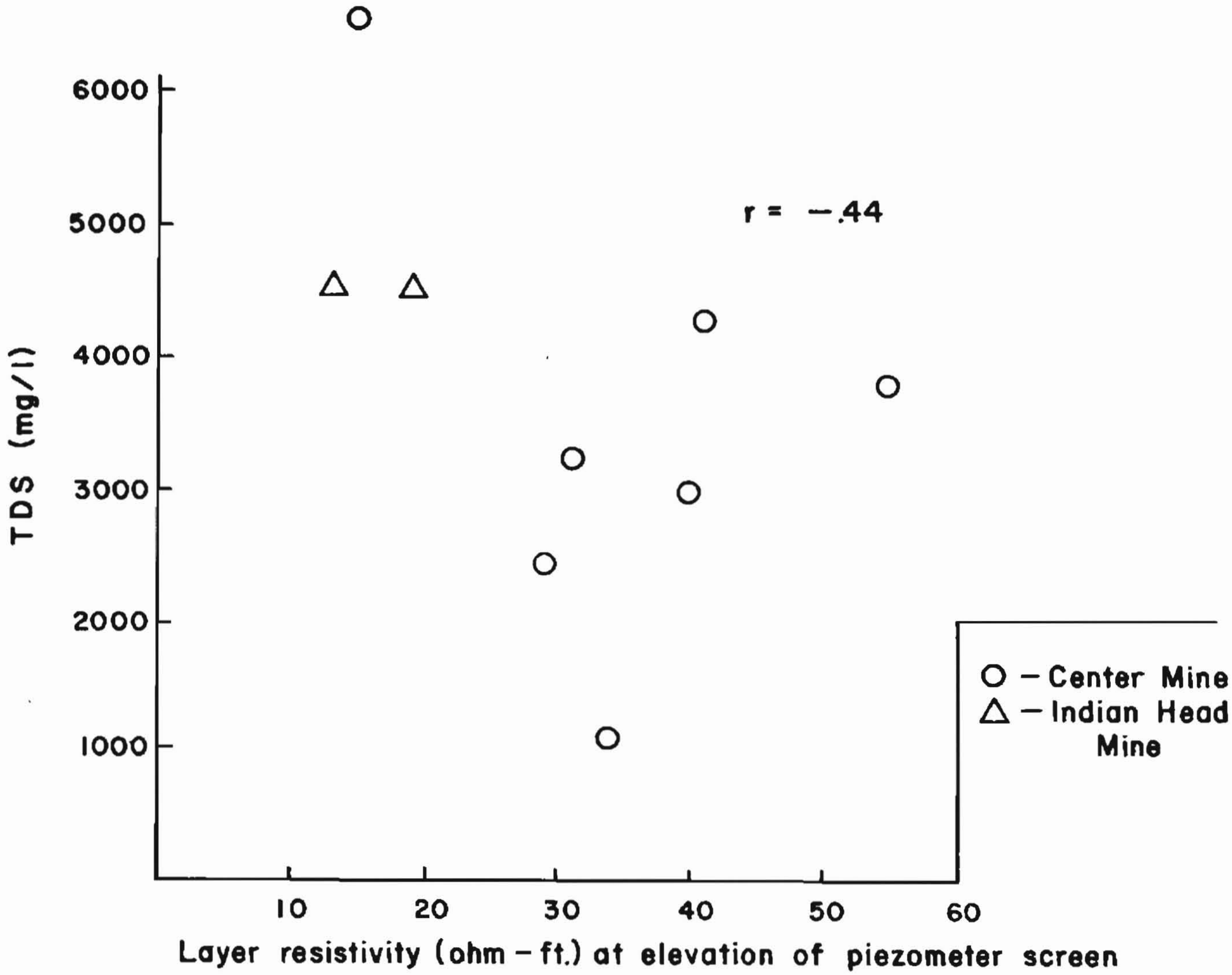


Figure 10. Plot of TDS for individual piezometers in spoils against interpreted layer resistivity at the elevation of the piezometer screen.

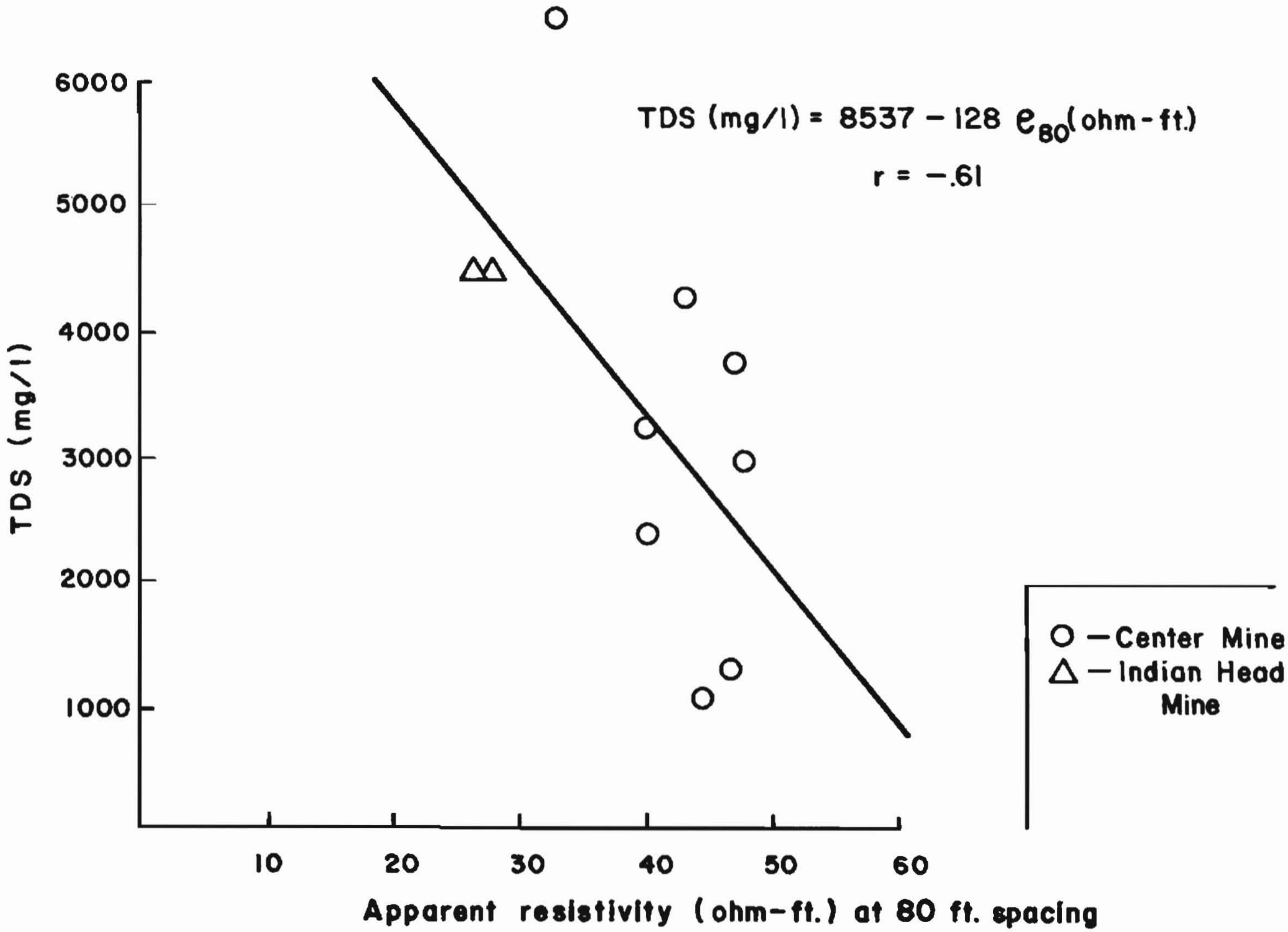


Figure 11. Plot of TDS values from piezometers in spoils against the apparent resistivity at 80-foot electrode spacing of the piezometer location.

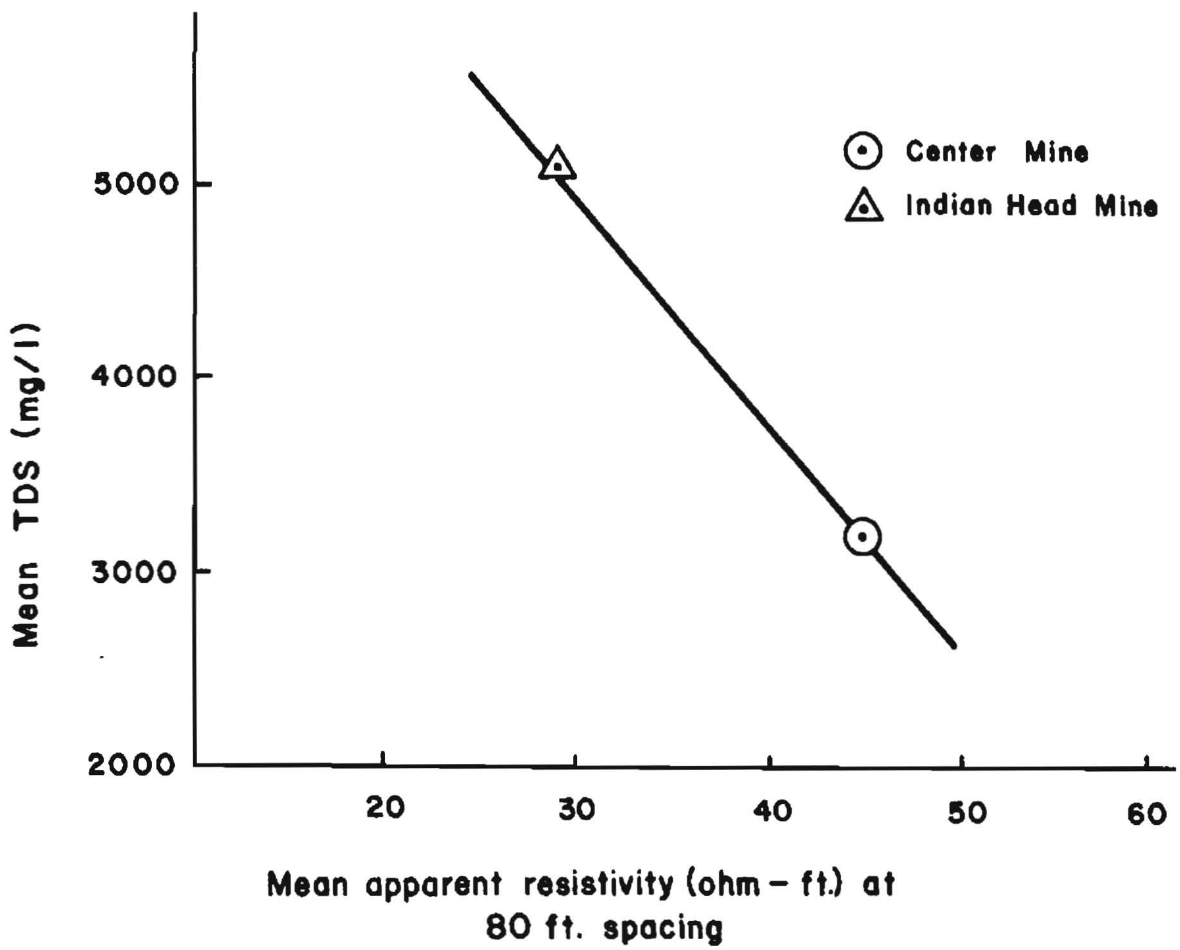


Figure 12. Relationship between mean TDS for all wells at each mine and mean apparent resistivity at the 80-foot spacing for all surveys made at each mine.

that an inverse relationship exists between spoils resistivity and groundwater quality in spoils. This relationship appears to be very useful in predicting groundwater quality in reclaimed spoils in other surface lignite mines in the Northern Great Plains.

## CONCLUSIONS

In this study, earth resistivity surveys were made in three unmined locations and compared to similar surveys in two areas of reclaimed spoils at surface lignite mines in North Dakota. Resistivity surveys were made at piezometer and test-hole locations in order to correlate resistivity data with direct subsurface information. The conclusions of the study are briefly summarized below.

1. In unmined areas, the resistivity techniques and interpretive methods used were most successful in defining stratigraphy where maximum contrast between the resistivity of subsurface layers occurred. This requires layers of sandy material alternating with layers of silty and clayey sediment. Sands of glacial origin provided the best contrast with most of the bedrock (sediment) of the Fort Union Group. Where glacial sediments were lacking and bedrock was composed of predominantly clayey materials, such as at the Indian Head Mine, resistivity was unsuccessful in determining subsurface stratigraphy. At a few sites, resistivity could not define the stratigraphy where test-hole logs indicated that contrasting materials were present. This may be due to lateral discontinuity of the stratigraphic units along the line of survey.

2. The resistivity curves in spoils indicated more homogeneous conditions in comparison to the unmined areas. Lithologic units are apparently mixed sufficiently during reclamation to the extent that resistivity curves are much more uniform. The layering sequence in spoils generated by the automatic interpretive method (Zohdy and Bisdorf, 1975) must therefore be used with caution. The interpreted layering can be substantially changed with very small changes in the field resistivity measurements at large electrode spacings.

The curves do suggest resistivity variations in the spoils. These variations are discontinuous and usually cannot be correlated between profiles. The explanation for these variations could be local lithologic changes or changes in moisture content. Despite low confidence in the exact thicknesses and resistivities derived from the automatic interpretation, general patterns of spoils resistivity are thought to be real. For example, if most profiles at a mine indicate low or high resistivity conditions over a large part of the spoils section relative to material above or below, this information is probably significant even though the exact values of depths and layer resistivities are not accurate.

3. Resistivity curves in spoils at the Indian Head Mine, a mine with extremely clayey overburden, are similar to curves in unmined areas around the mine. A minor exception to the previous statement is that the thin high resistivity layer found at the surface in unmined areas is not present in the spoils. Most of the spoils surveys indicate a relatively low resistivity layer corresponding to the lower part of the spoils and upper part of the bedrock section where a water table is present near the base of the spoils. This is thought to be the result of high moisture contents in that zone in combination with chemical reactions in the spoils which are

generating groundwater with a high dissolved-solids content. The resistivity of material decreases with increasing ionic dissolved-solids content in the groundwater.

4. At the Center Mine, resistivity curves are more uniform in spoils than in unmined areas around the mine. This is a response to mixing of lithologic units during reclamation. In four of the five areas surveyed the general resistivity pattern indicates a layer of relatively high resistivity near the base of the spoils underlain by a layer of lower resistivity with the contact between the two occurring in the vicinity of the water table. This pattern can be explained by lower resistivity in the saturated zone below the water table. The sandier Center spoils are producing less mineralized groundwater than the Indian Head spoils and therefore have higher resistivity in the lower part of the spoils. The only exception at Center to this pattern is area 3, which is interpreted as having lower resistivity conditions in the lower part of the spoils and a change to higher resistivity conditions below the water table. Area 3 has the most highly mineralized groundwater in the Center Mine spoils sites and the lower spoils resistivity in this area apparently is a reflection of the high dissolved-solids content in the groundwater. One resistivity survey location in area 3, site 99, recorded unusually low resistivity in the base of the spoils. Analysis of groundwater from a piezometer at this location indicated the highest TDS recorded at the Center Mine.

5. The spoils at the Center and Indian Head Mines have a significant and consistent difference in resistivity. This confirms the inverse relationship between clay content and resistivity recognized in resistivity studies from many other areas. Overburden materials at the Indian Head area are significantly higher in clay content than materials at Center and consequently lower in resistivity.

6. There is an inverse correlation between spoils resistivity and TDS values from wells in spoils. The best correlation was obtained by plotting field values of apparent resistivity against TDS at the piezometers located at the centers of the resistivity survey lines. Some of the variation preventing an even better correlation can be explained by the fact that piezometer data are point data while resistivity data reflect average conditions of materials along the survey line. A potentially useful approach involves plotting mean 80-foot apparent resistivity in spoils for an entire mine against mean TDS for all wells in the mine spoils. More than two mines are needed to test the relationship, but the data generated by this study suggest that this could prove to be a very useful predictive tool. The value of this relationship is that it could be used to predict mean groundwater quality parameters in surface-mine spoils using inexpensive earth resistivity surveys. The amount of direct monitoring with piezometers and chemical analyses would be minimized.

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# APPENDIX I

## LOCATION OF RESISTIVITY SURVEYS AT UNMINED SITES

## APPENDIX I
## LOCATION OF RESISTIVITY SURVEYS AT UNMINED SITES[1]

### Falkirk Area

| Site | Location |
|---|---|
| 531 | 146-82-28 CCC |
| 553 | 146-82-20 CDD |
| 545 | 145-82-27 BCC |
| 581 | 146-82-13 BBB |
| 526 | 143-83-25 CCC |
| 565 | 146-83-14 CDC |

### Indian Head Area

| Site | Location |
|---|---|
| 165 | 144-89-26 DCB |
| X-2 | 144-89-36 ABB |
| 149 | 144-89-25 BDD |
| 127 | 144-89-26 DCC |

### Center Area

| Site | Location |
|---|---|
| 364 | 141-84-3 BBB |
| 363 | 141-84-3 DDA |
| 361 | 142-84-35 BBB |
| 372 | 142-84-16 DDD |
| 360 | 142-84-23 CCC |

[1]Locations are based on public land classification system used by the U.S. Bureau of Land Management.

# APPENDIX II

## SUBSURFACE AND RESISTIVITY DATA FROM UNMINED AND MINED SITES

## APPENDIX IIA

SUBSURFACE GEOLOGIC, GROUNDWATER, AND RESISTIVITY DATA FROM UNDISTURBED SITES IN THE FALKIRK AREA.

## APPENDIX IIB

SUBSURFACE GEOLOGIC, GROUNDWATER, AND RESISTIVITY DATA FROM UNDISTURBED AND MINED AREAS AT THE INDIAN HEAD MINE.

## APPENDIX IIC

SUBSURFACE GEOLOGIC, GROUNDWATER, AND RESISTIVITY DATA FROM UNDISTURBED AND MINED AREAS AT THE CENTER MINE.

# APPENDIX II

## SUBSURFACE AND RESISTIVITY DATA FROM UNMINED AND MINED SITES

Each page shows the information collected and used for one particular site. Columns 1 and 2 show a generalized version of the test-hole lithologic logs. Column 3 shows the position of the piezometer screen, if present, and the approximate position of the water table by a dashed line. All surveys are identified by the adjacent piezometer or concrete marker identification numbers. TDS values are given when available. Column 4 shows the sequence of layers and resistivities generated by the automatic interpretive method of Zohdy and Bisdorf (1975). Very thin layers were not included. The graph on the right side of each figure is the plot of apparent resistivity versus electrode spacing obtained from the resistivity surveys. The scales may vary as indicated from diagram to diagram.

# APPENDIX IIA

## SUBSURFACE GEOLOGIC, GROUNDWATER, AND RESISTIVITY DATA FROM UNDISTURBED SITES IN THE FALKIRK AREA.

See appendix I for locations of resistivity surveys.

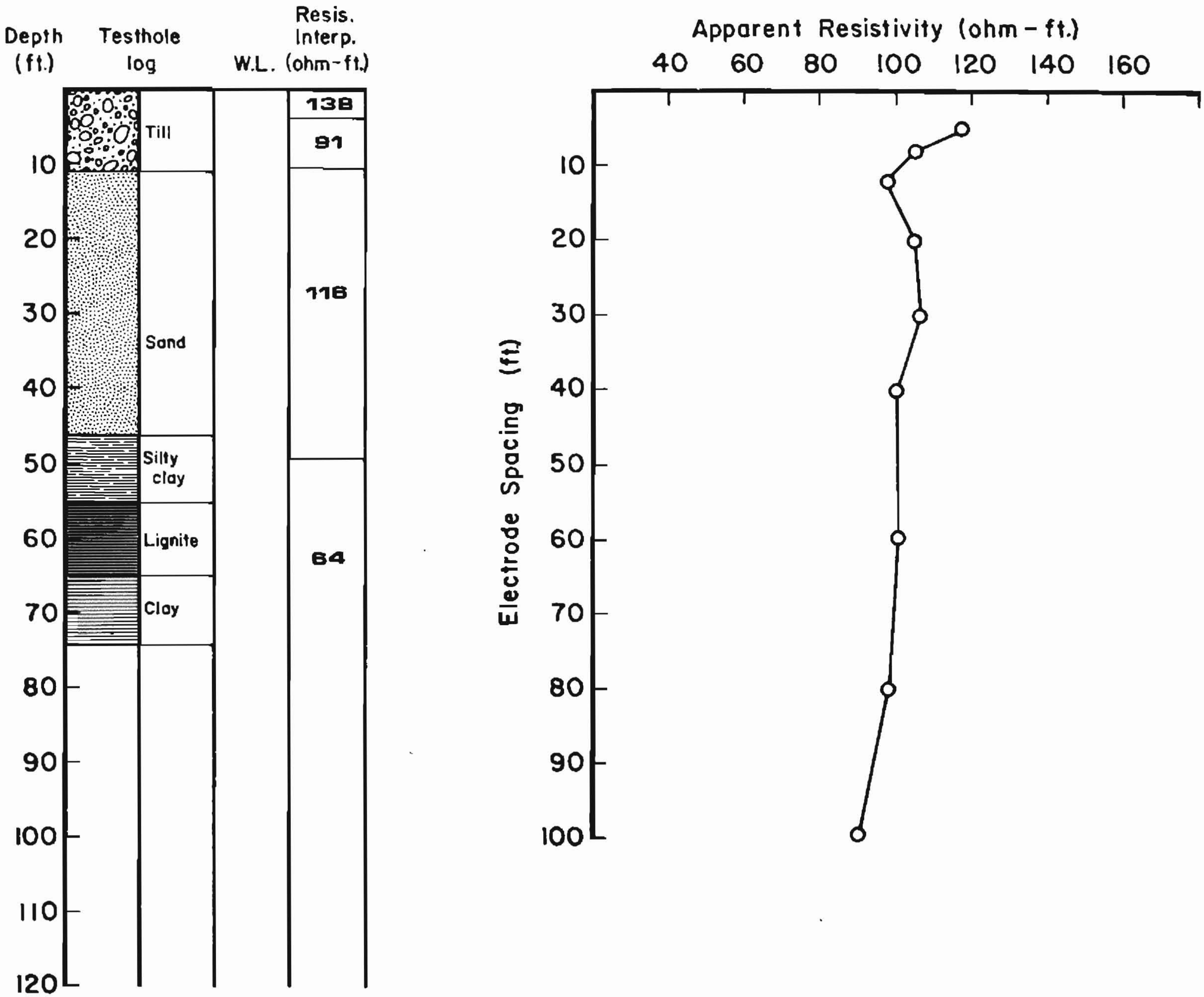



Figure A1. **Falkirk Undisturbed 531**

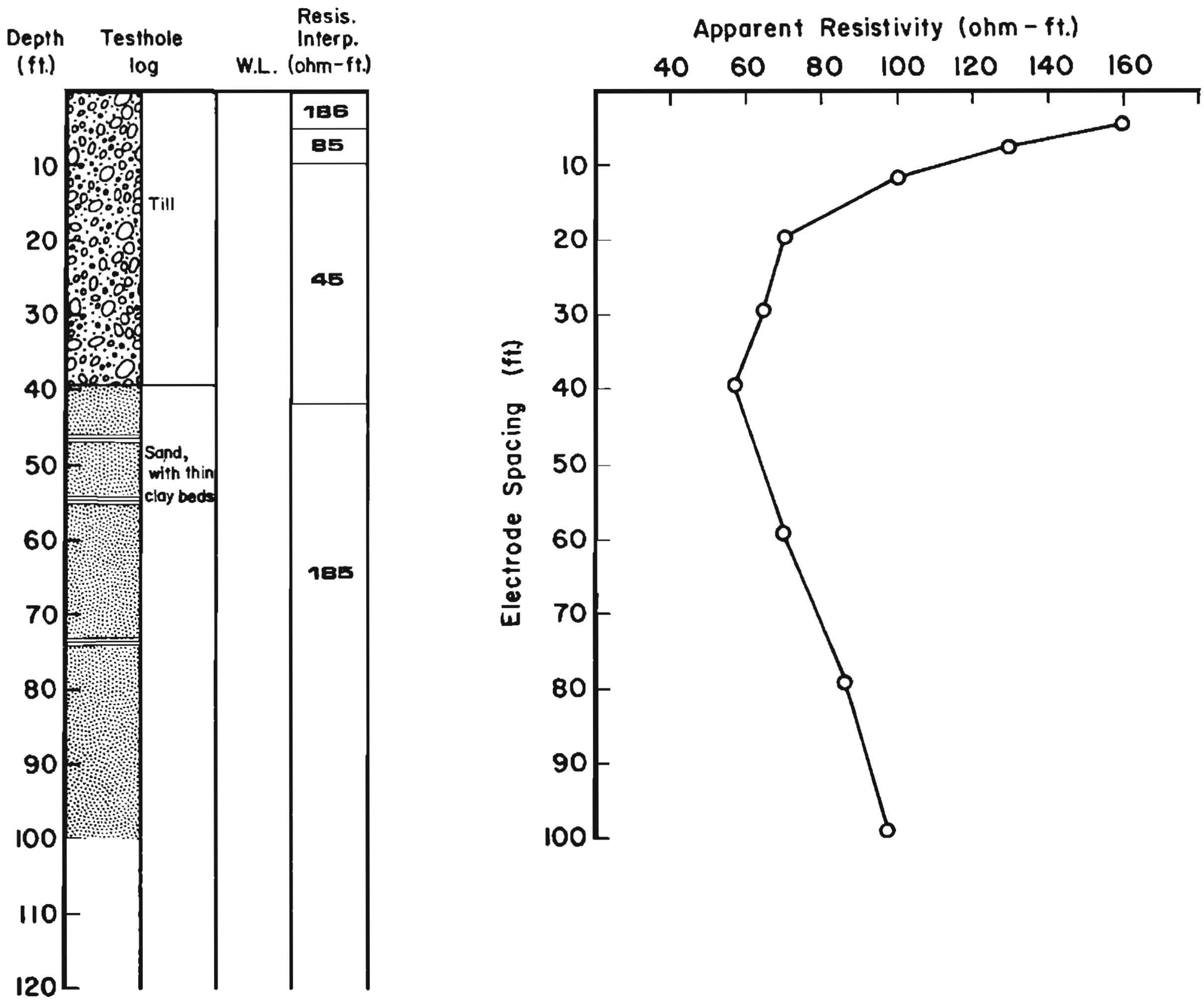



Figure A2. **Falkirk Undisturbed 553**

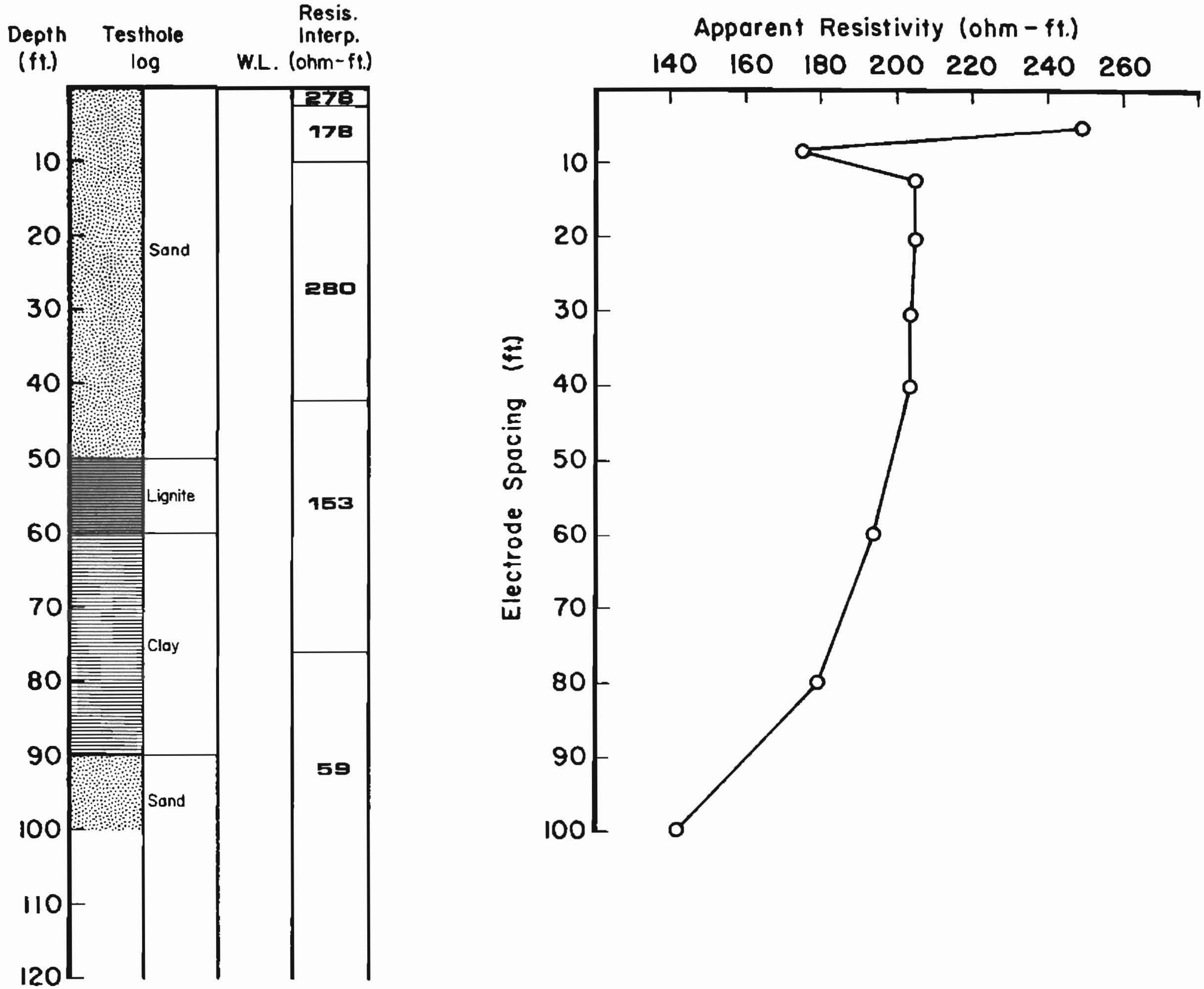



Figure A3. **Falkirk Undisturbed 545**

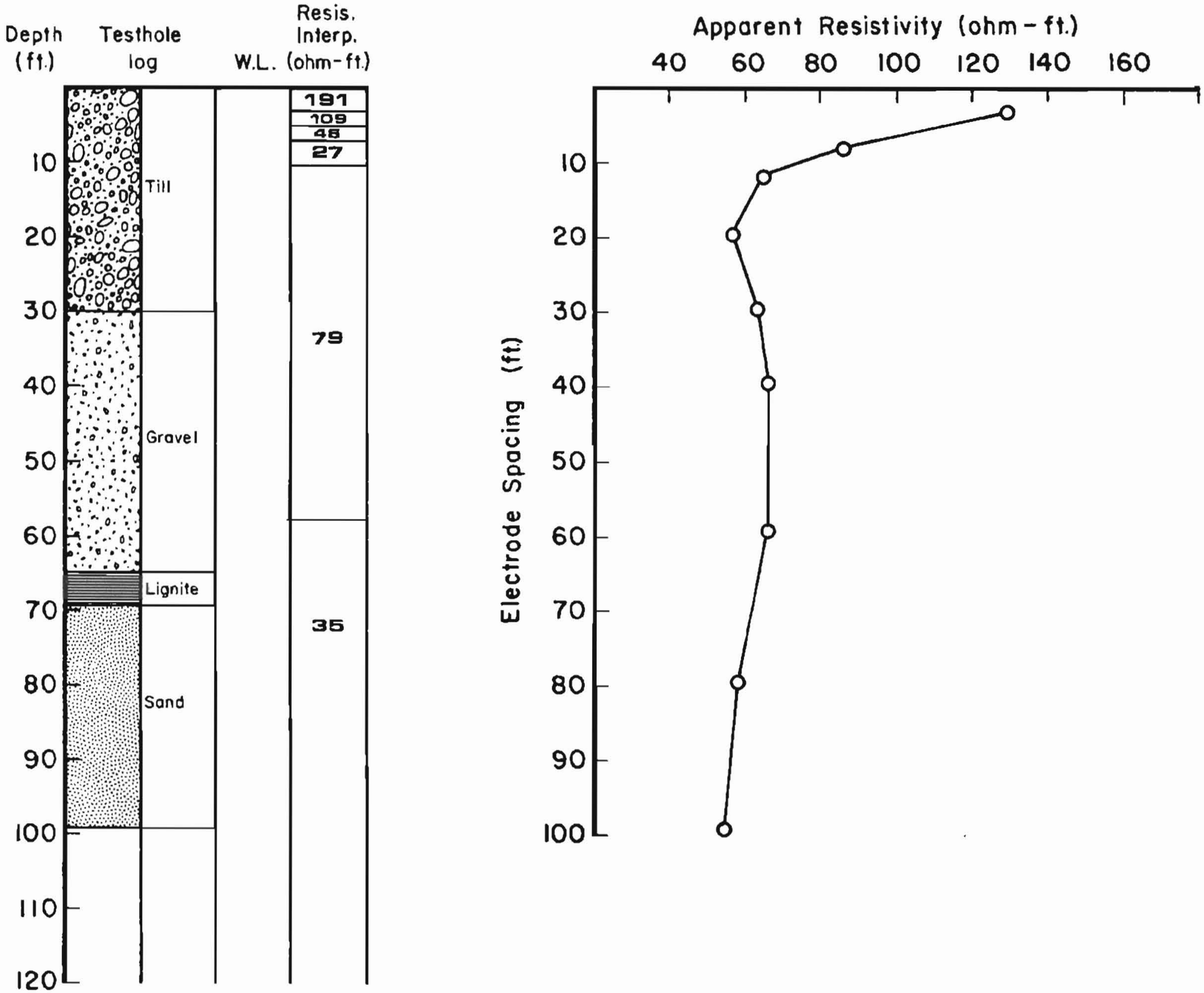



Figure A4. **Folkirk Undisturbed 581**

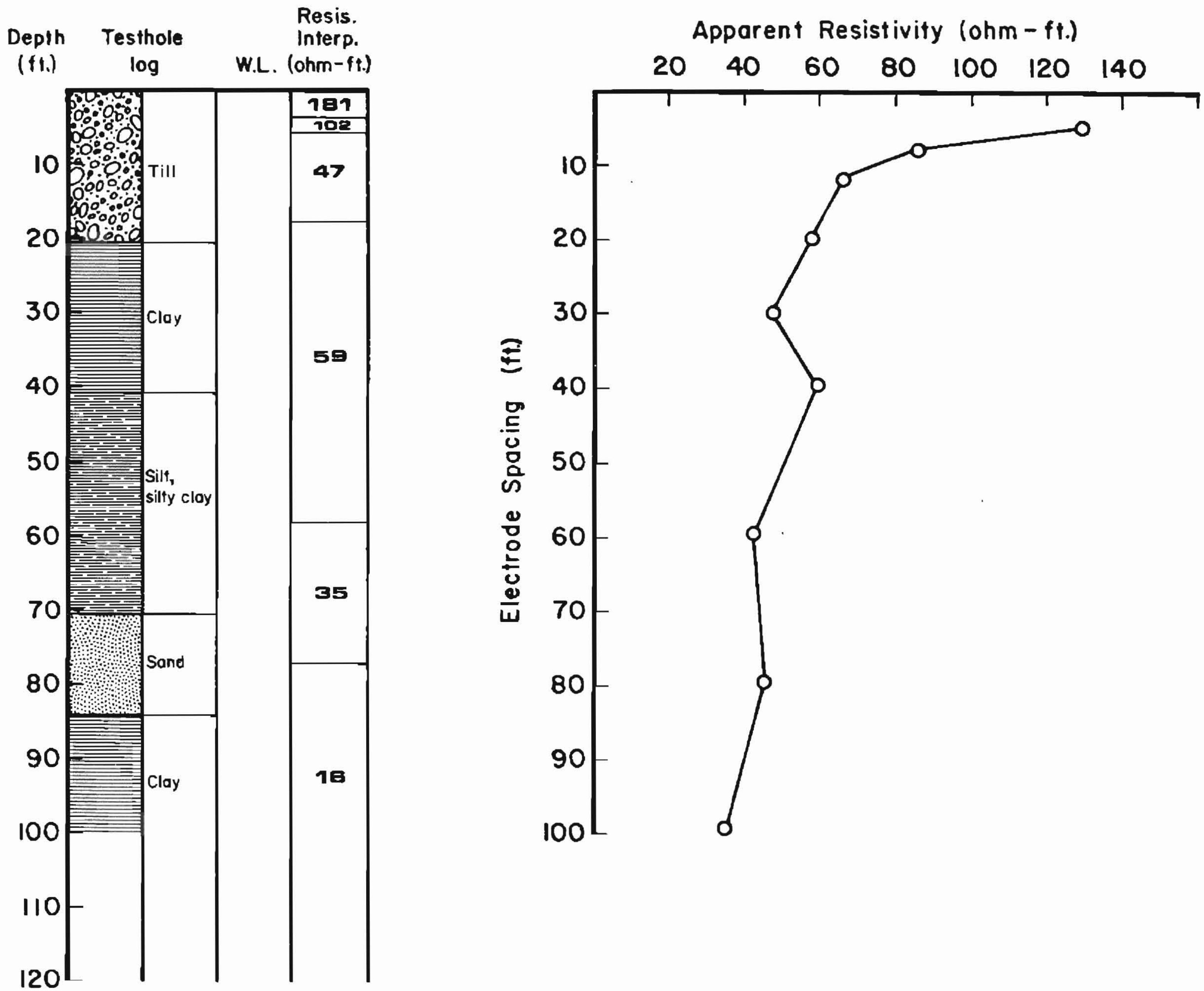



Figure A5. **Falkirk Undisturbed 526(N-S)**

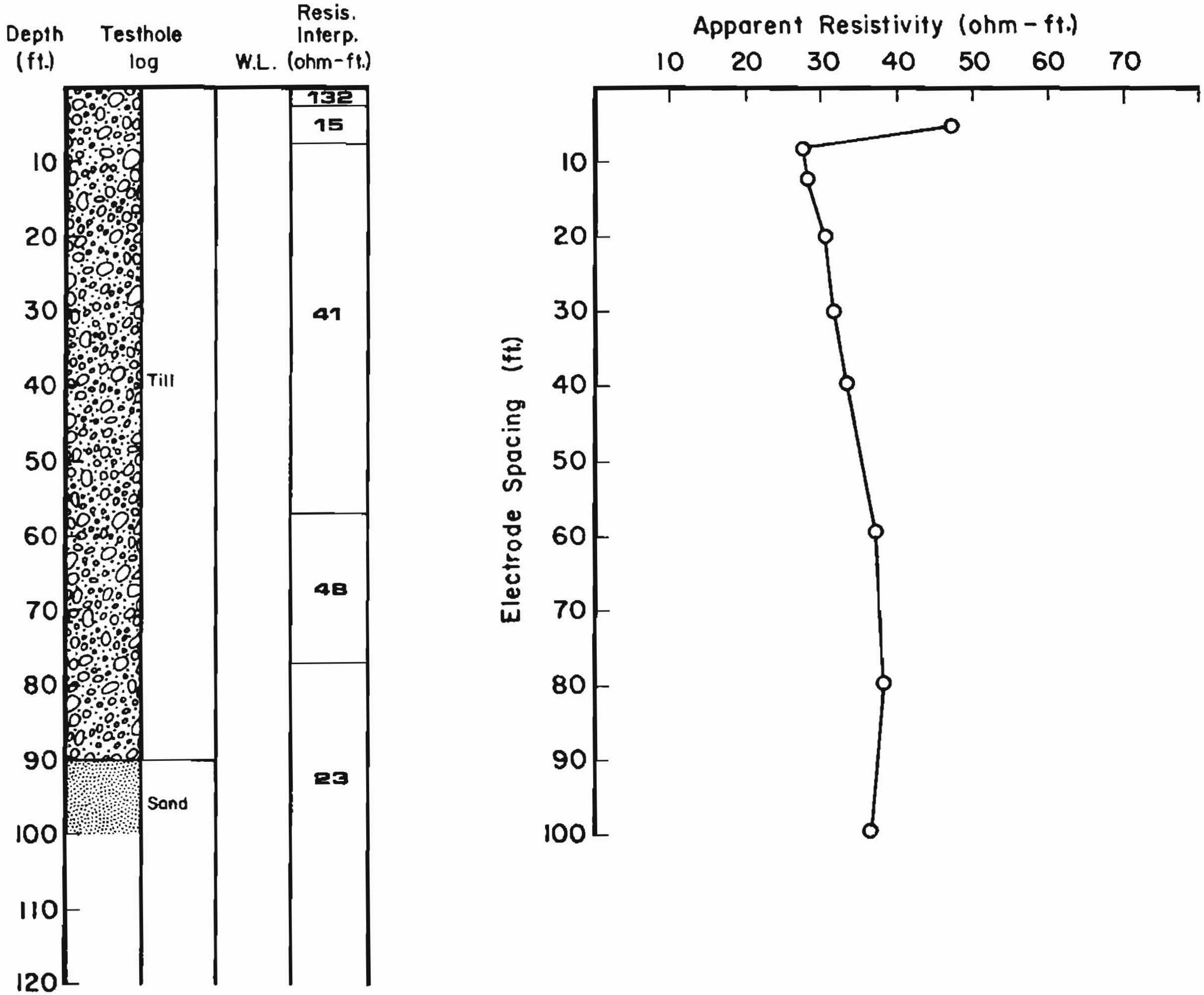



Figure A6. **Falkirk Undisturbed 565**

# APPENDIX IIB

## SUBSURFACE GEOLOGIC, GROUNDWATER, AND RESISTIVITY DATA FROM UNDISTURBED AND MINED AREAS AT THE INDIAN HEAD MINE.

See appendix I for locations of resistivity surveys in undisturbed areas. See figure 4 for location of resistivity surveys in mined area.

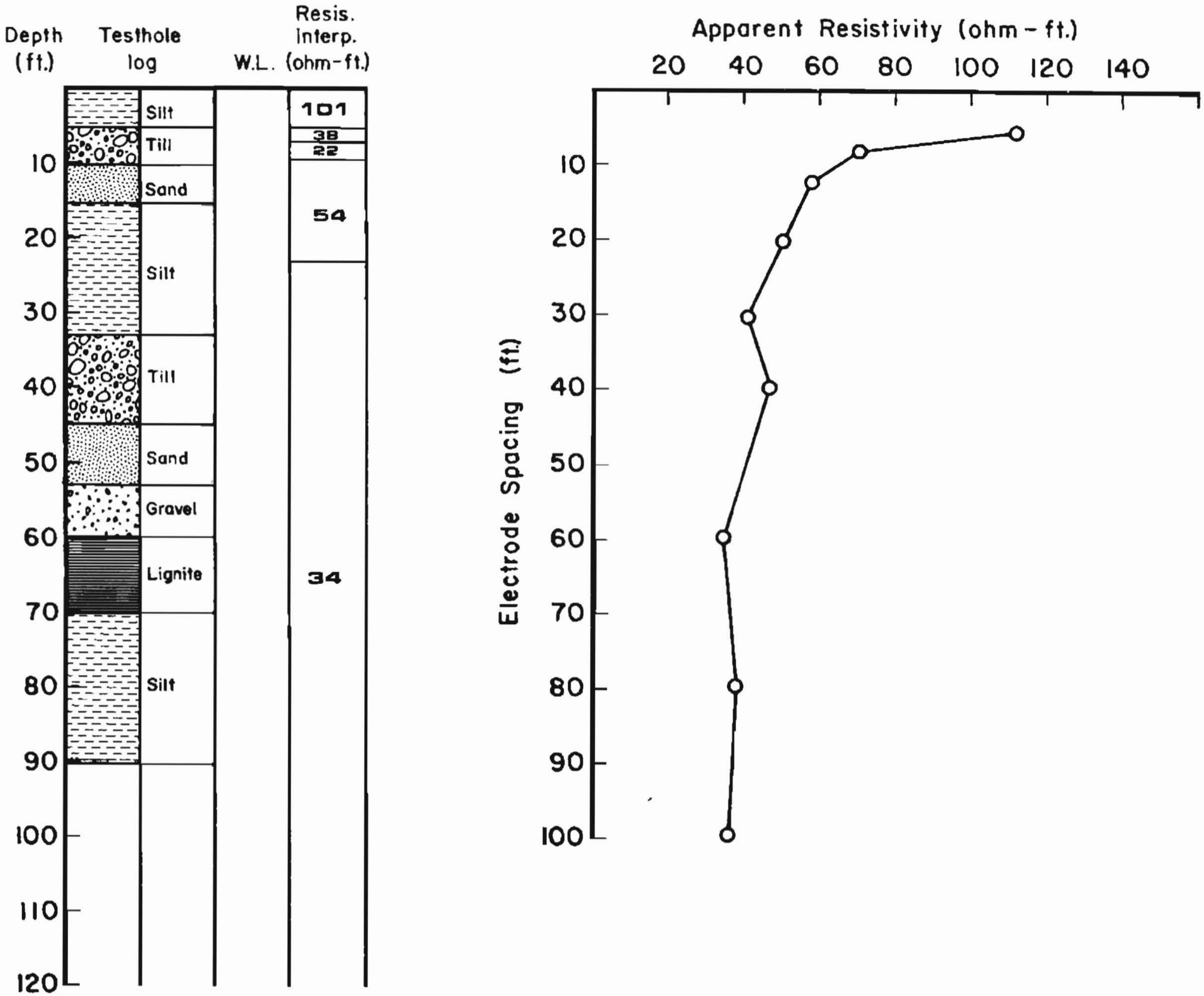



Figure B1. **Indian Head Undisturbed 165**

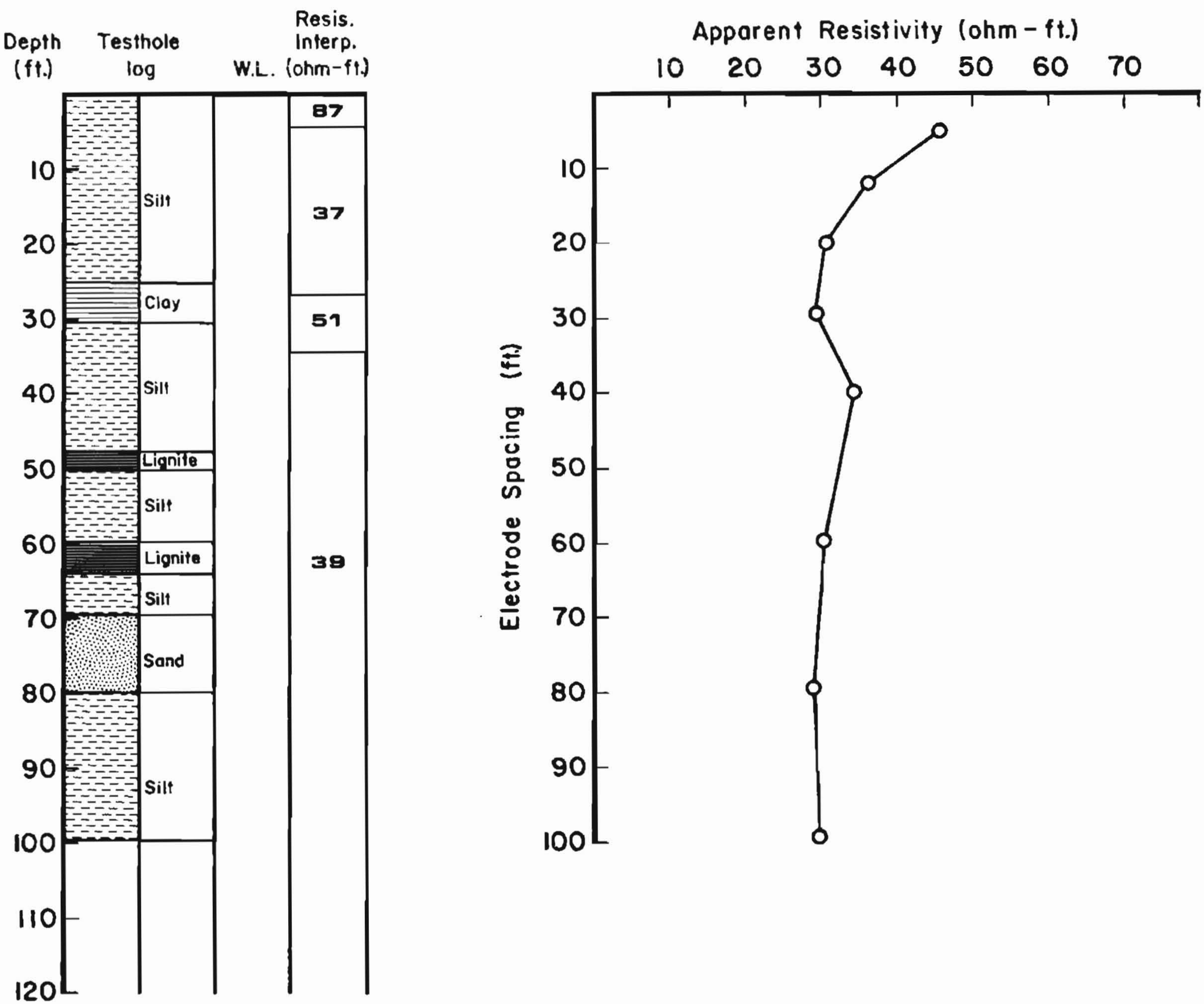



Figure B2. **Indian Head Undisturbed X-2**

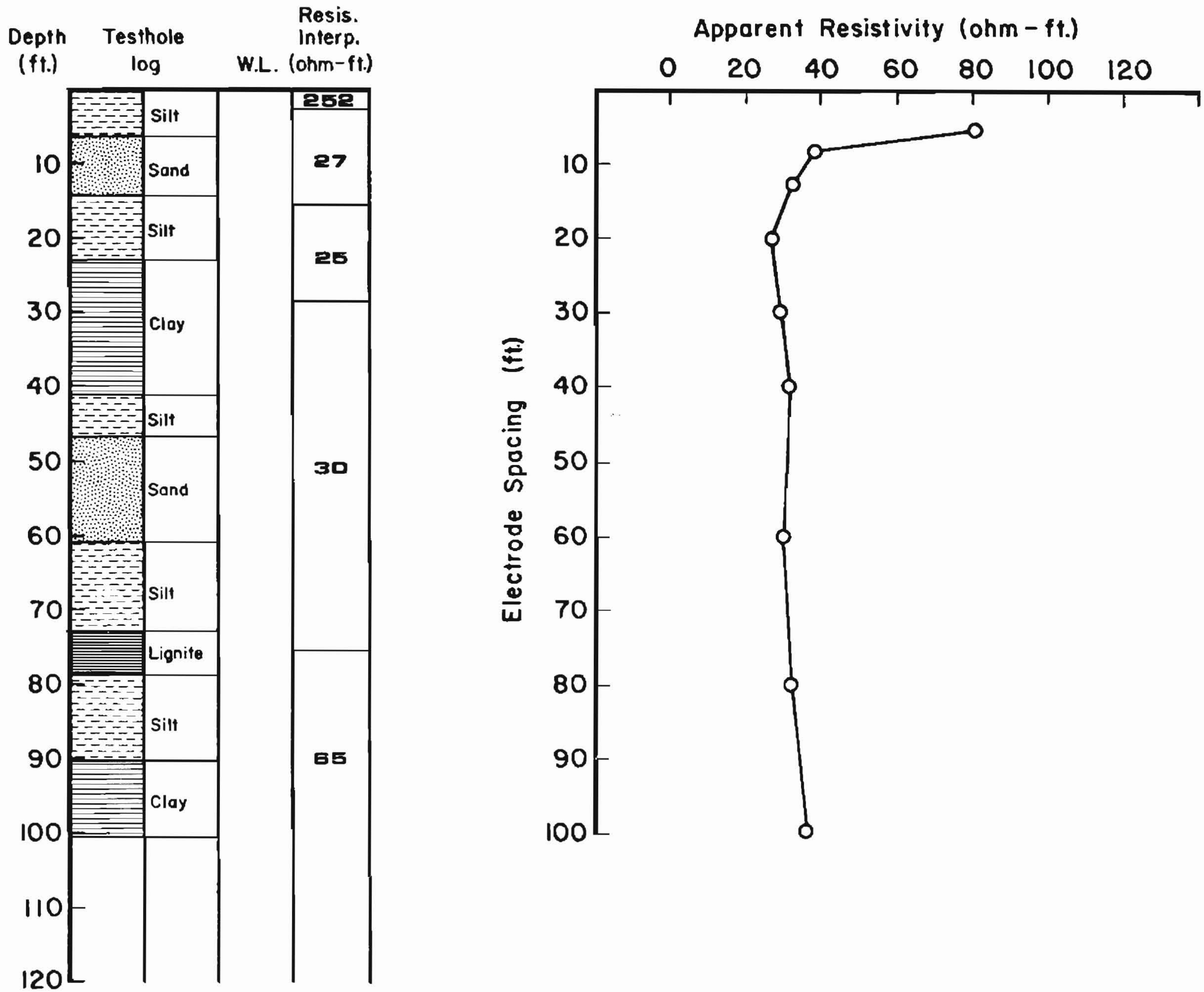



Figure B3. Indian Head Undisturbed 149

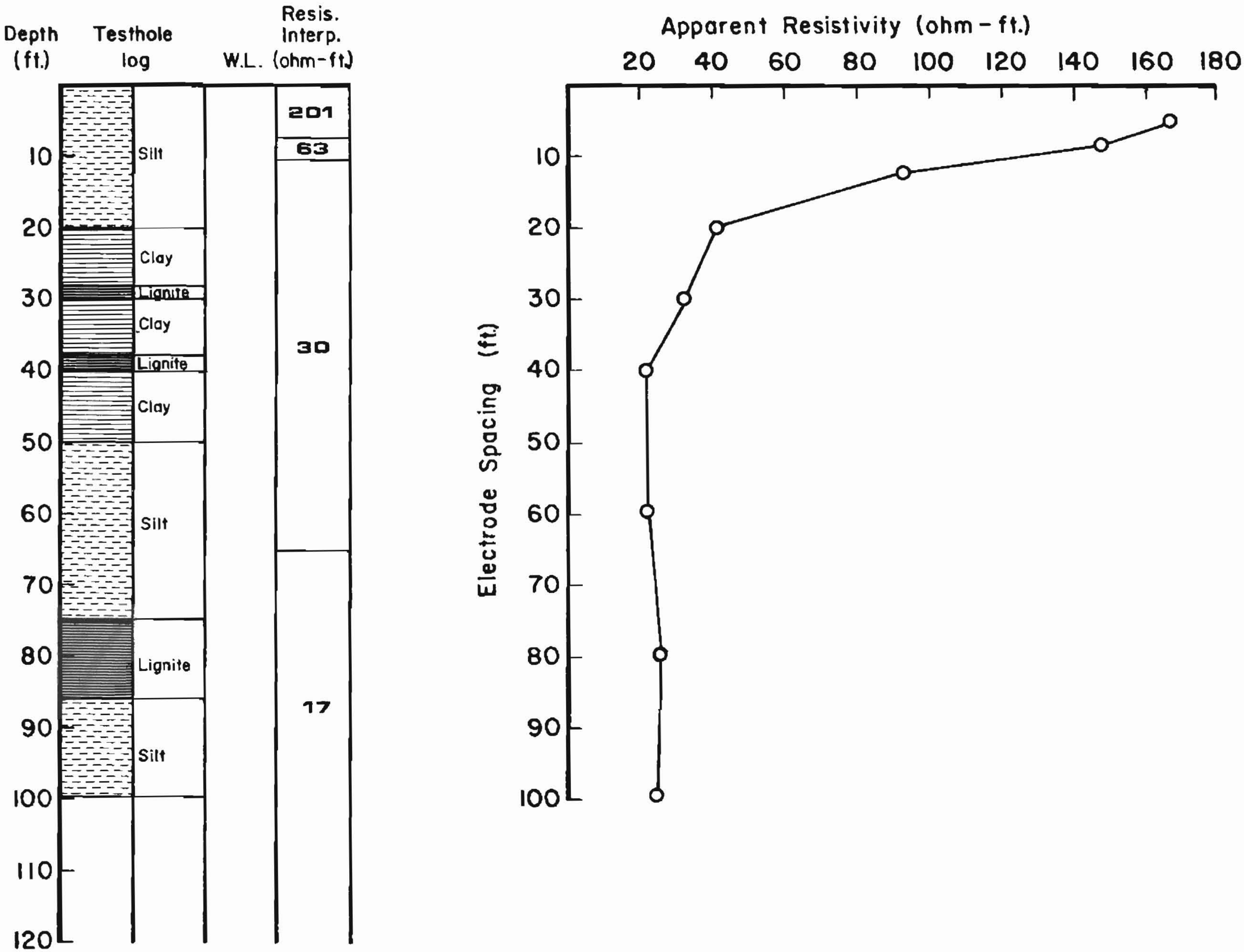



Figure B4. Indian Head Undisturbed 127

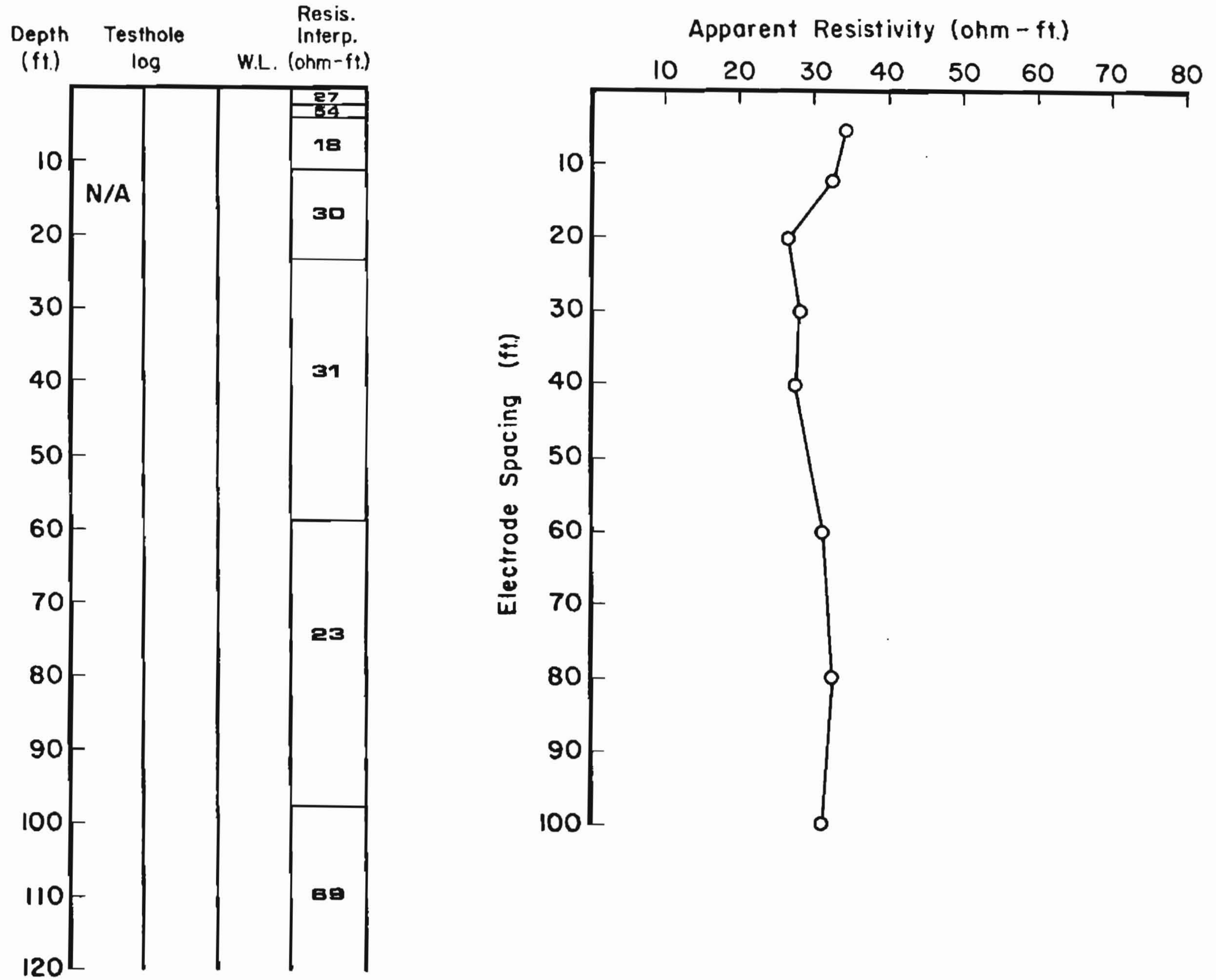



Figure B5. Indian Head Spoils 115 (E-W)

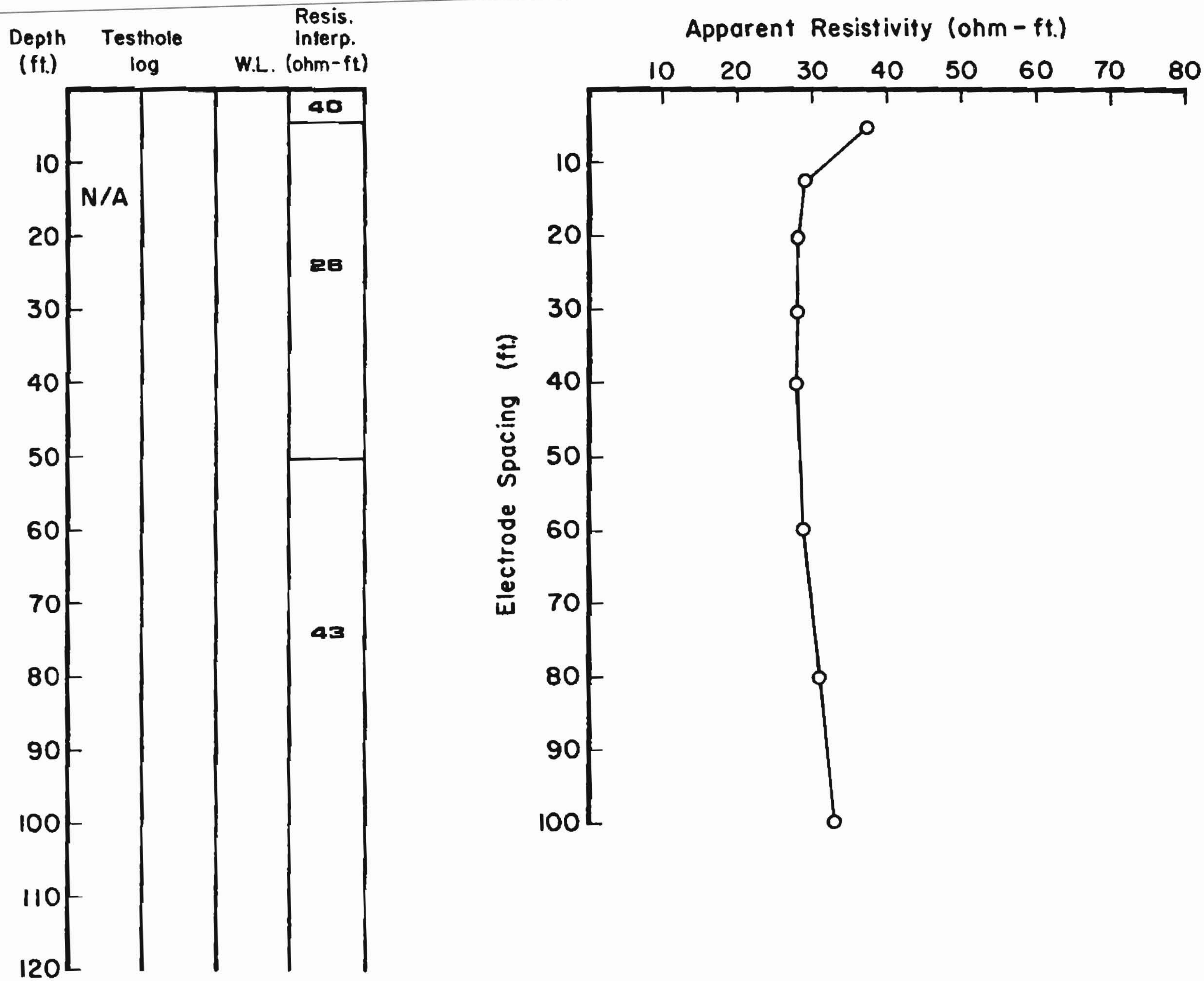



Figure B6. **Indian Head Spoils 141 (E-W)**

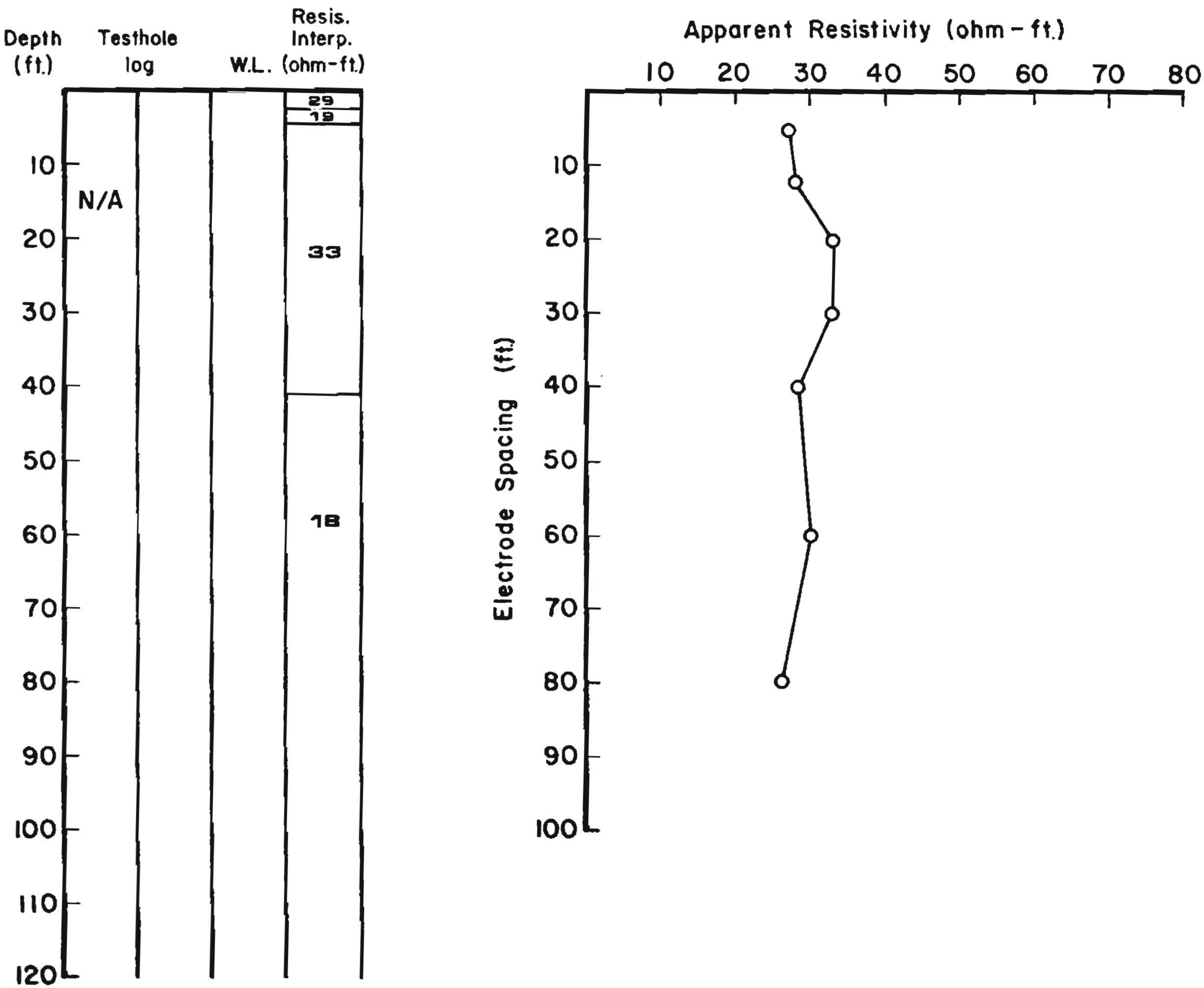



Figure B7. **Indian Head Spoils 128(NW - SE)**

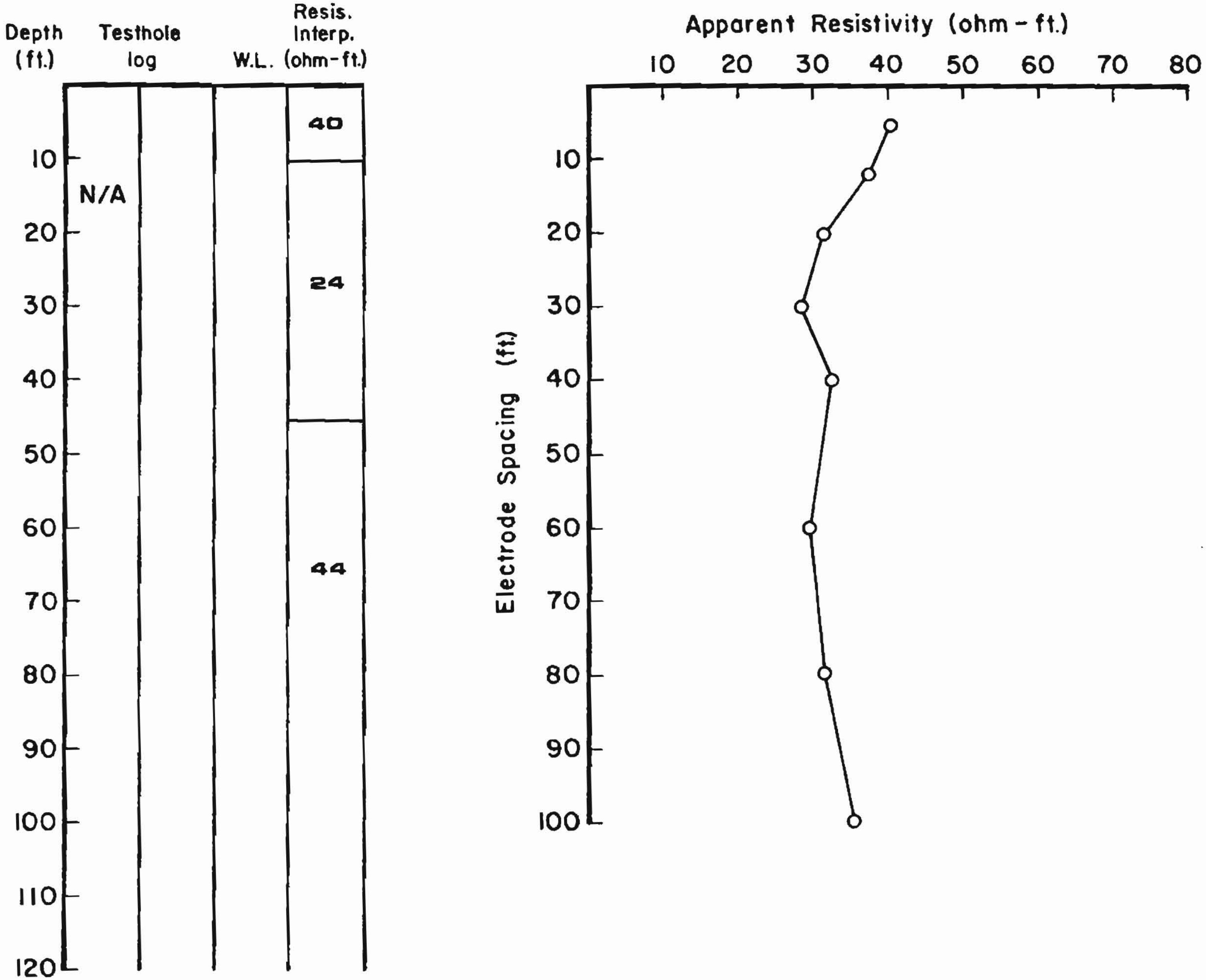



Figure B8. **Indian Head Spoils 134(E-W)**

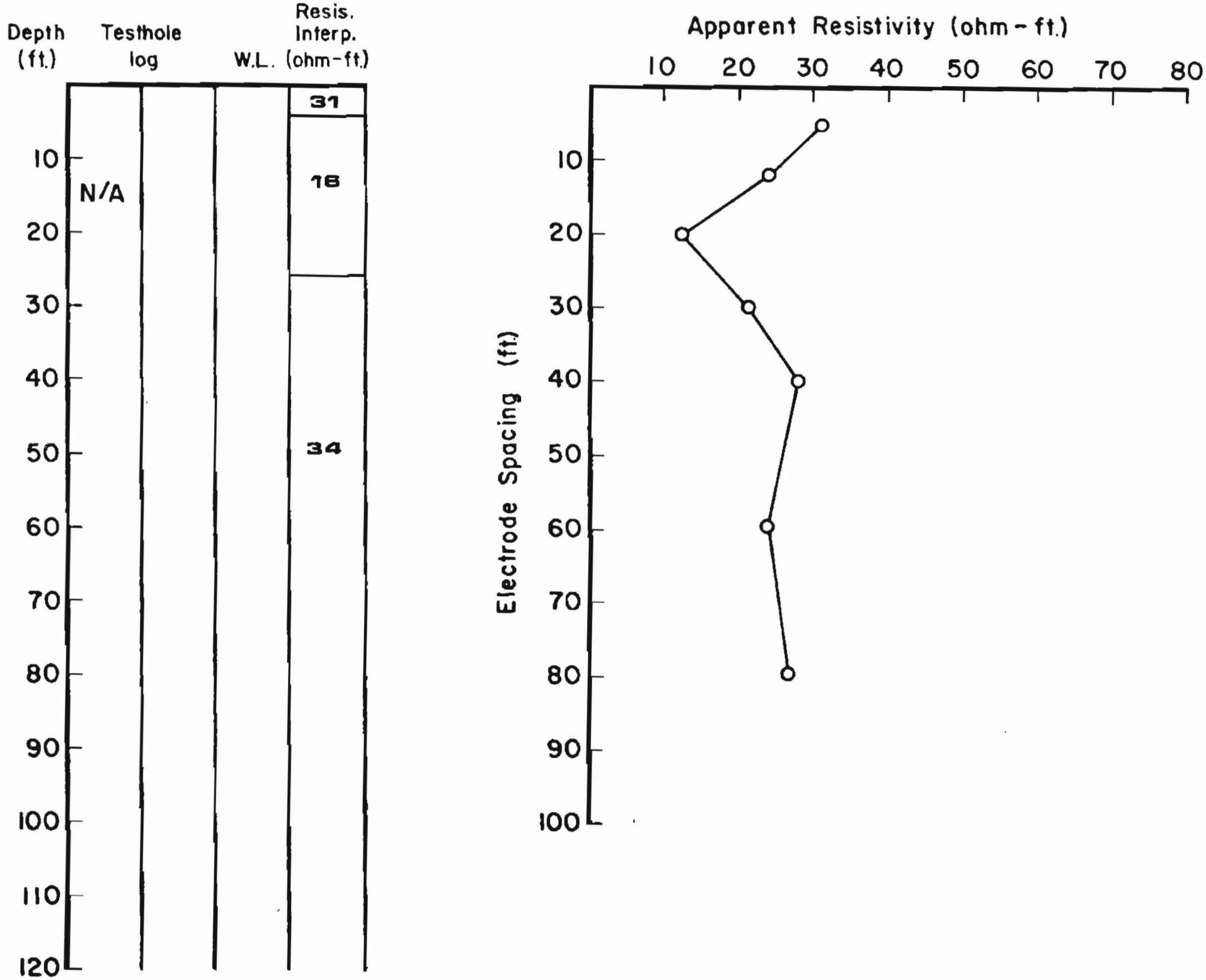



Figure B9. **Indian Head Spoils 132(E-W)**

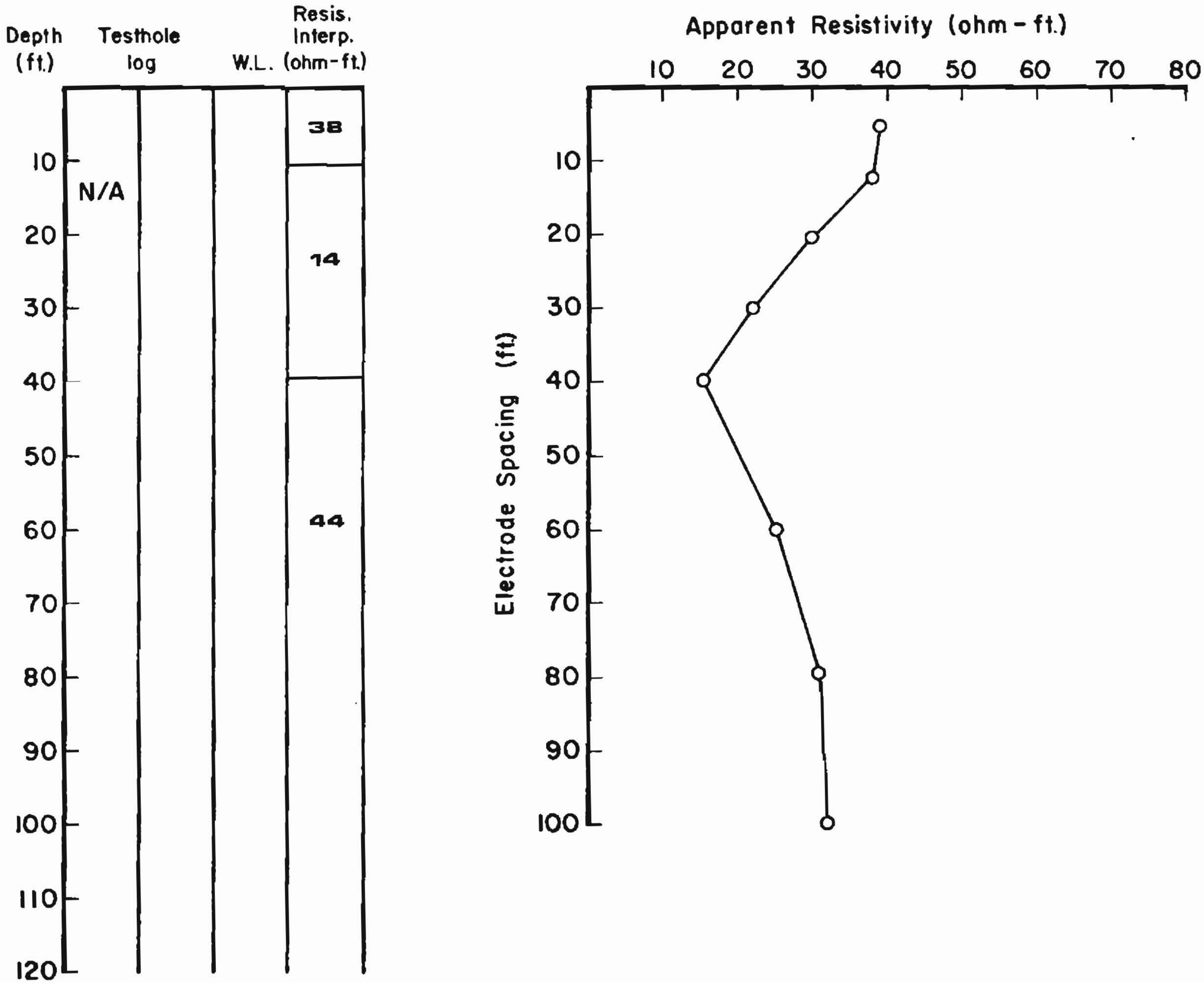



Figure B10. **Indian Head Spoils 137 (E-W)**

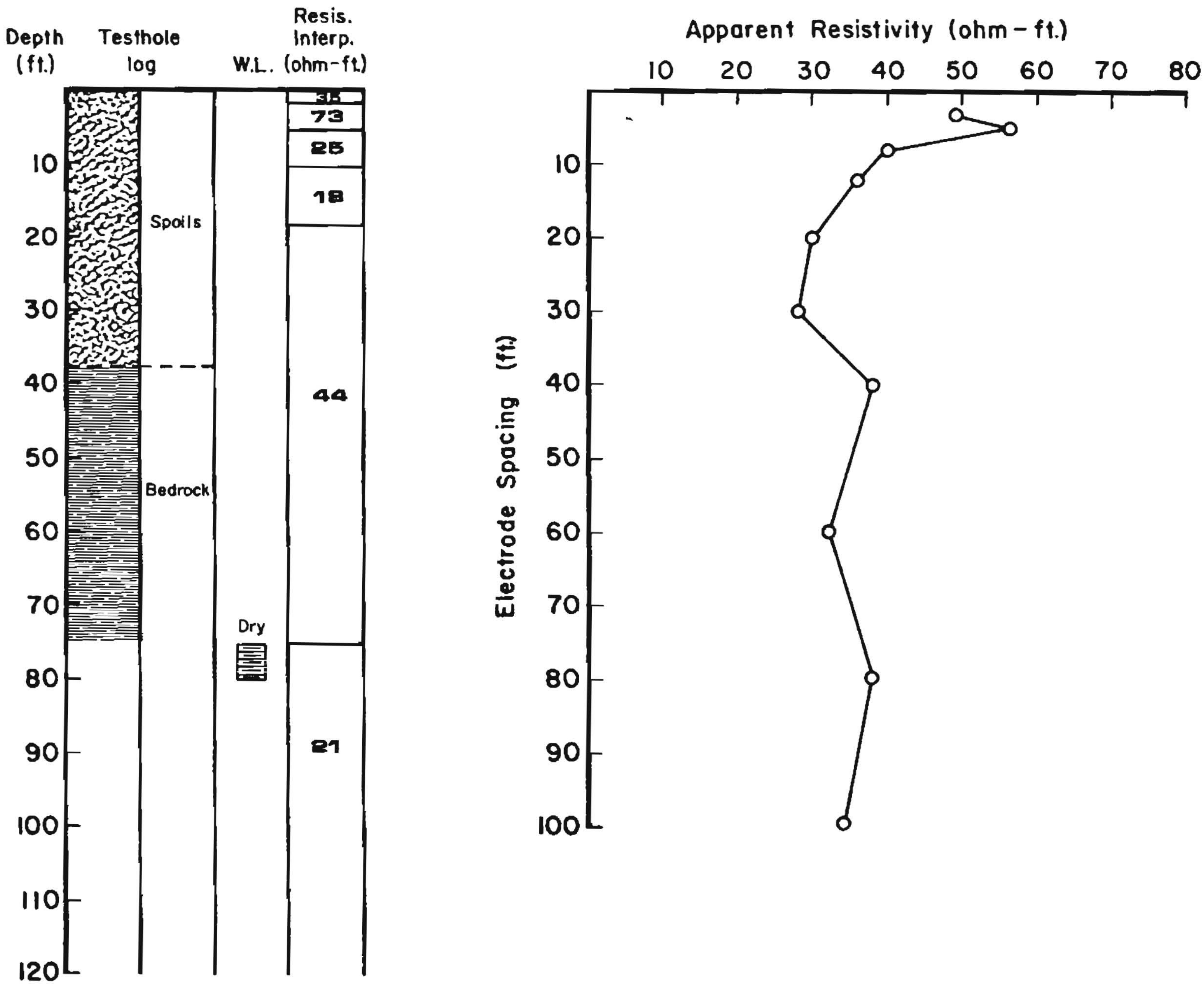



Figure B11. **Indian Head Spoils Valley between 111 and 112 (N-S)**

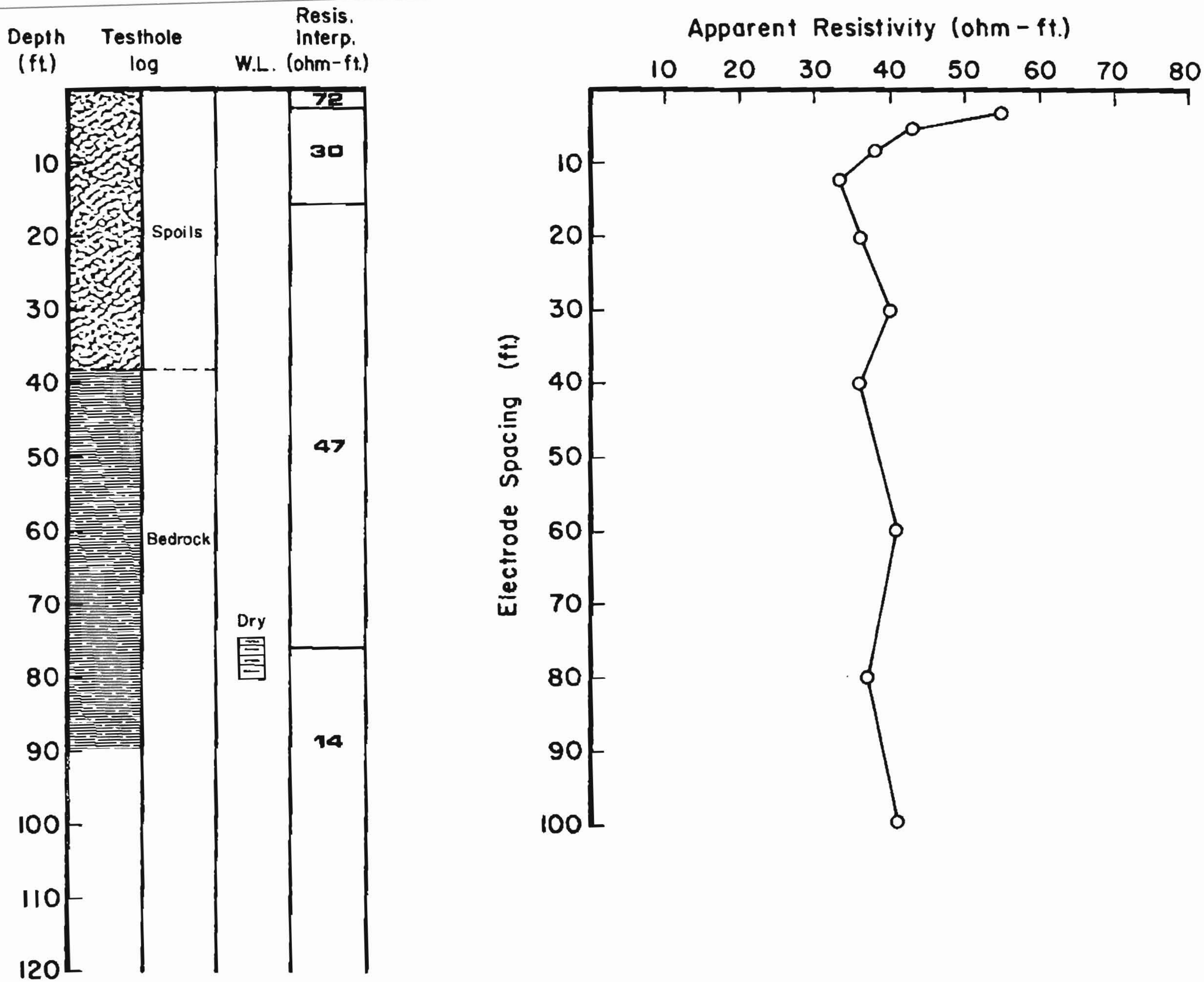



Figure B12. **Indian Head Spoils - Valley between 111 and 112 (E-W)**

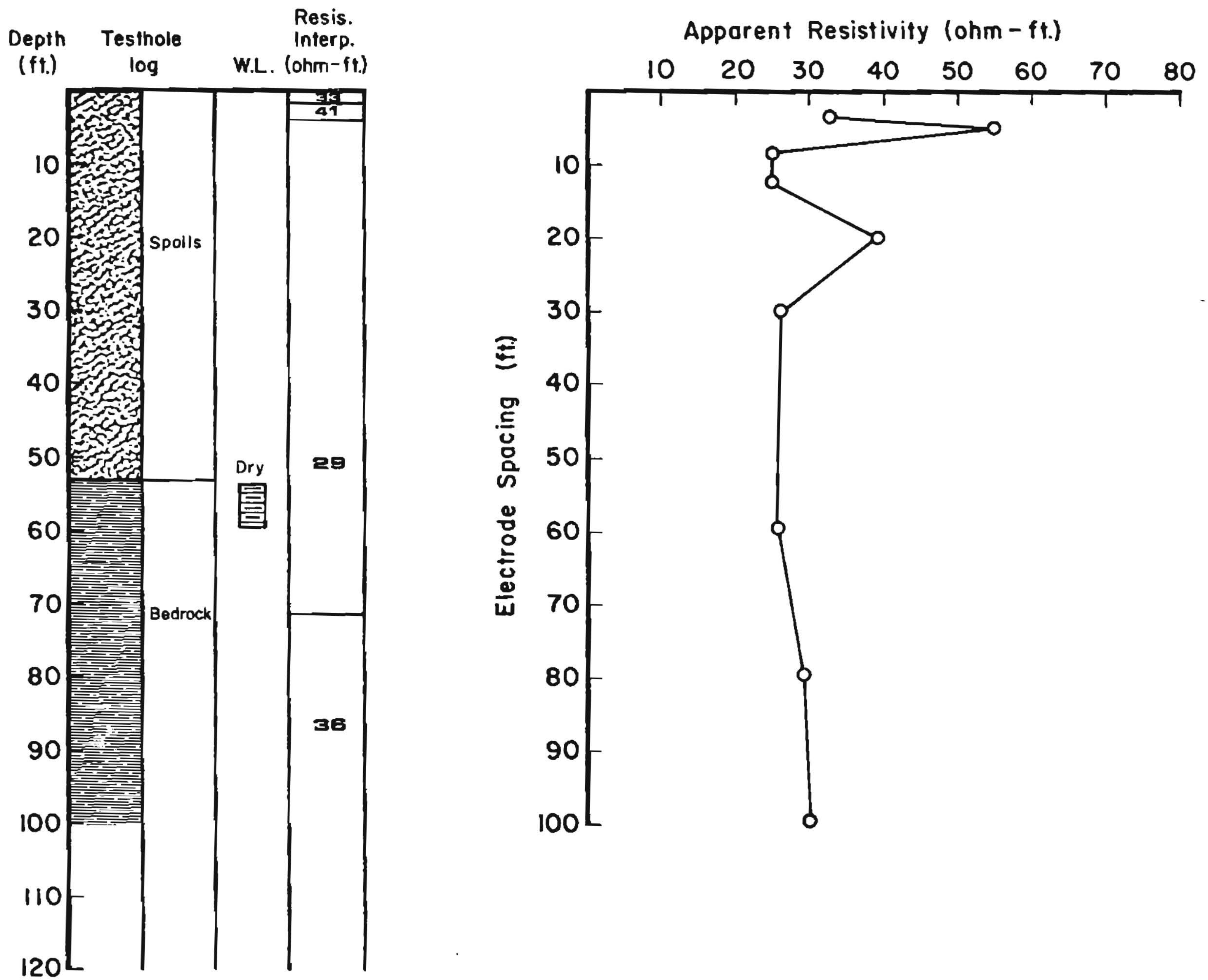



Figure B13. **Indian Head Spoils 133(E-W)**

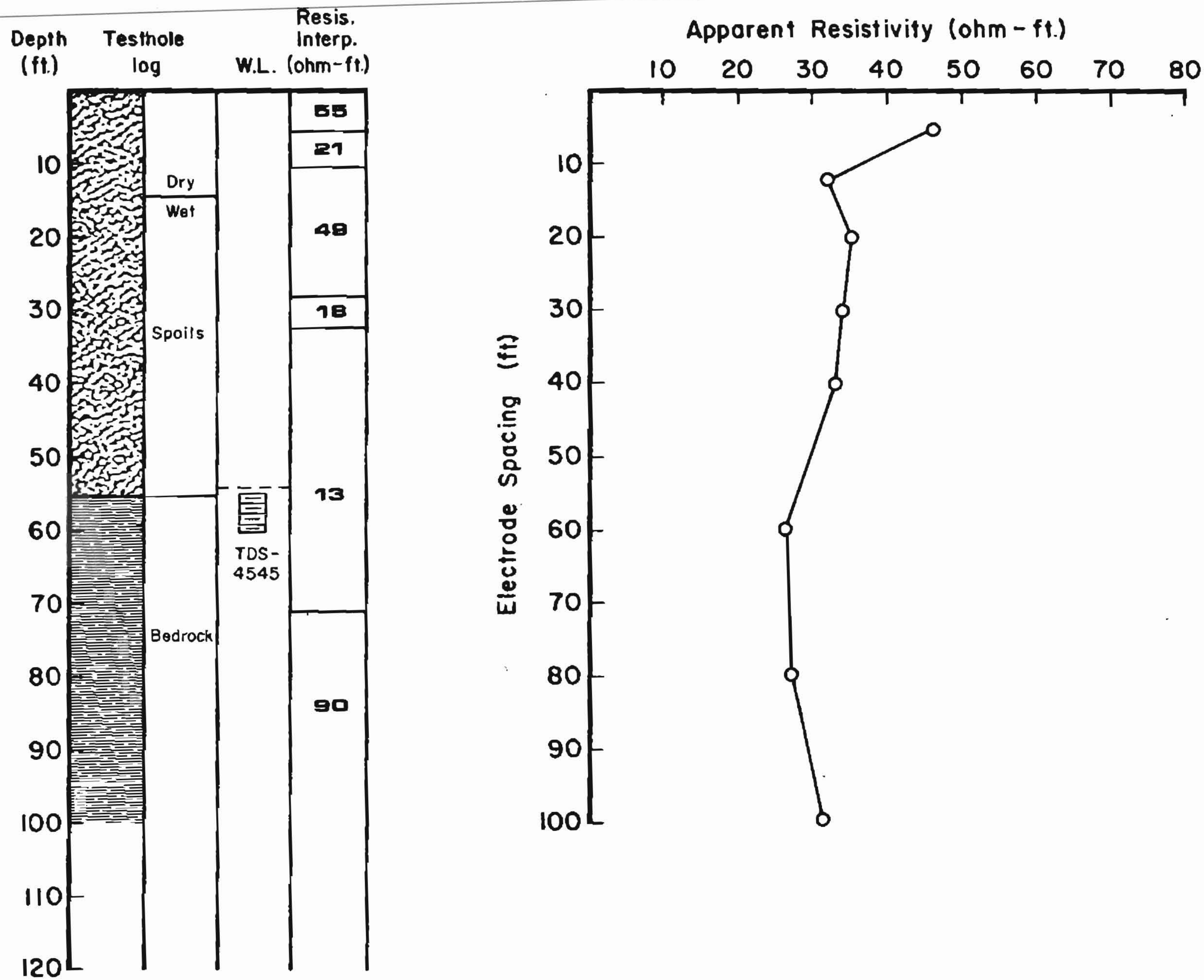



Figure B14. **Indian Head Spoils 134 (N-S)**

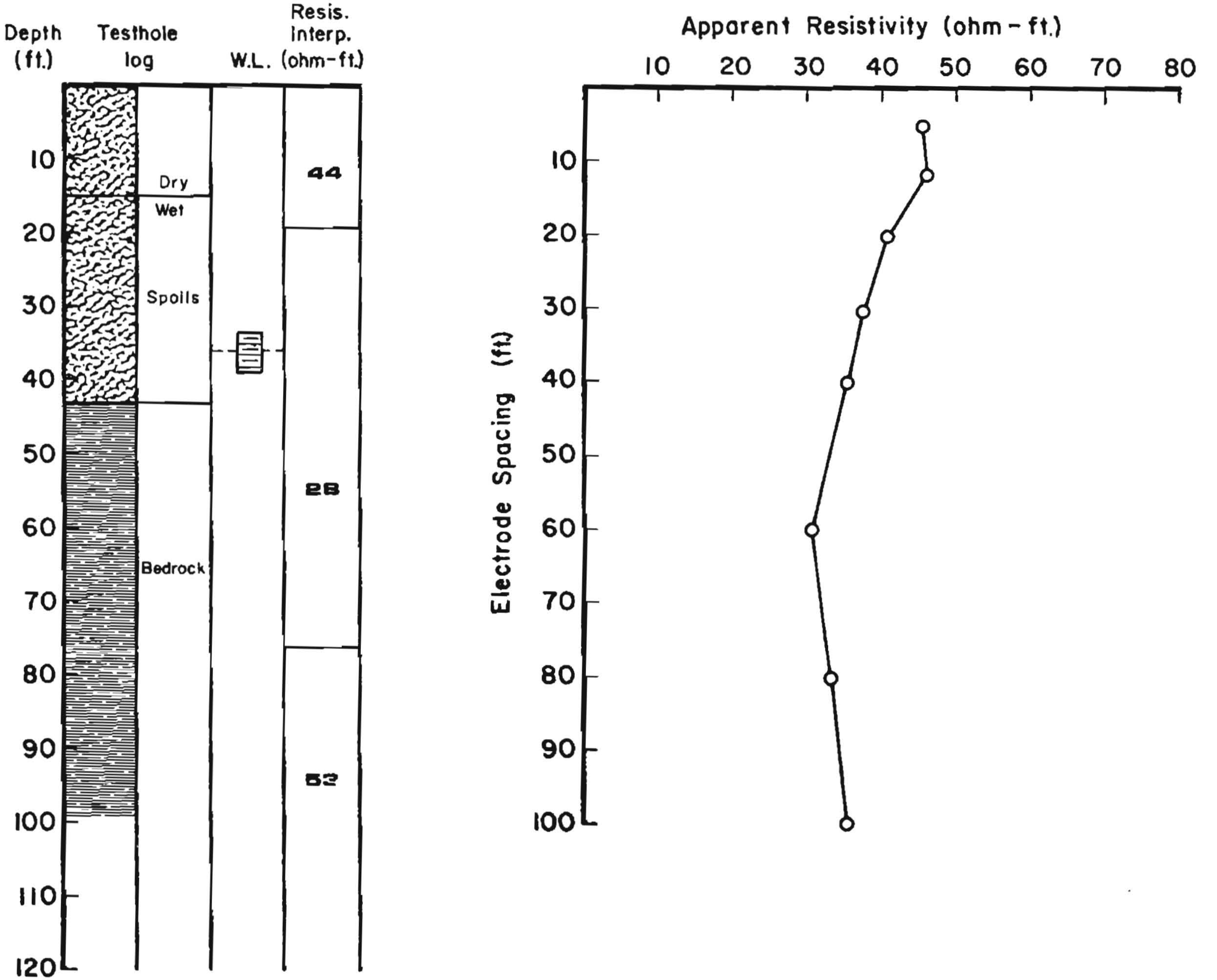



Figure B15. **Indian Head Spoils 127 (E-W)**

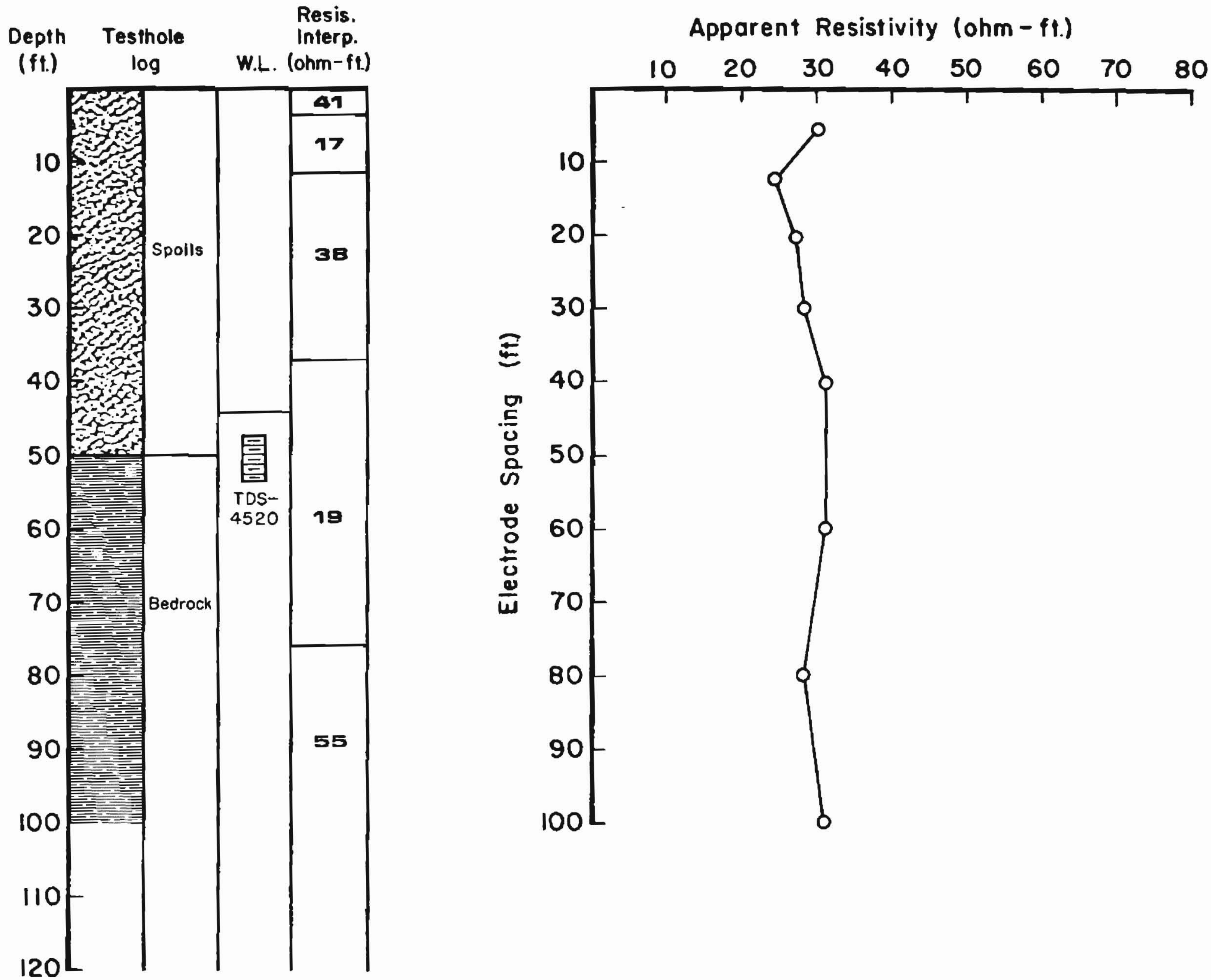



Figure B16. Indian Head Spoils 140 (E-W)

## APPENDIX IIC

## SUBSURFACE GEOLOGIC, GROUNDWATER, AND RESISTIVITY DATA FROM UNDISTURBED AND MINED AREAS AT THE CENTER MINE.

See appendix I for locations of resistivity surveys in undisturbed areas. See figures 5-9 for locations of resistivity surveys in mined area.

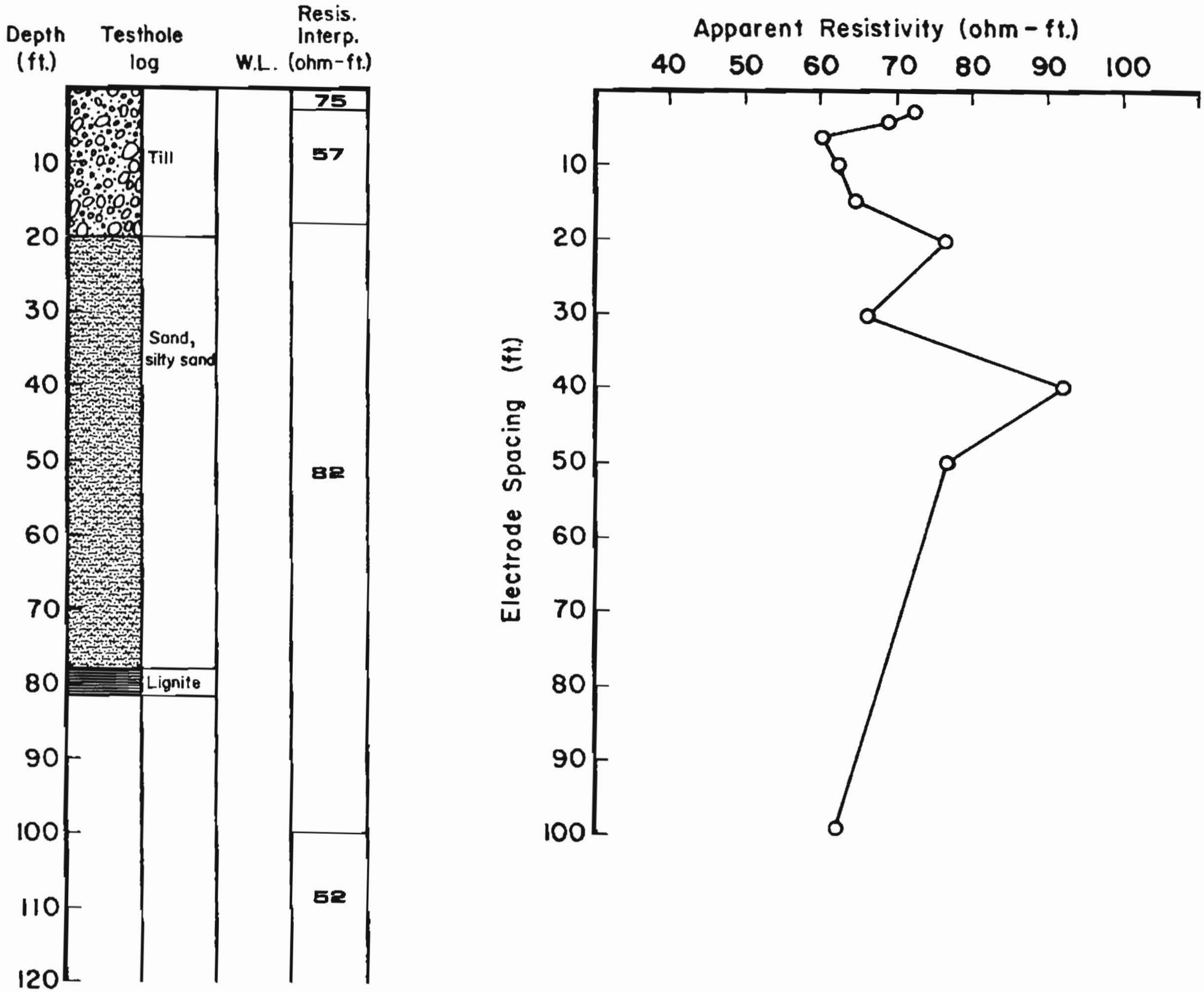



Figure C1. **Center Undisturbed 363**

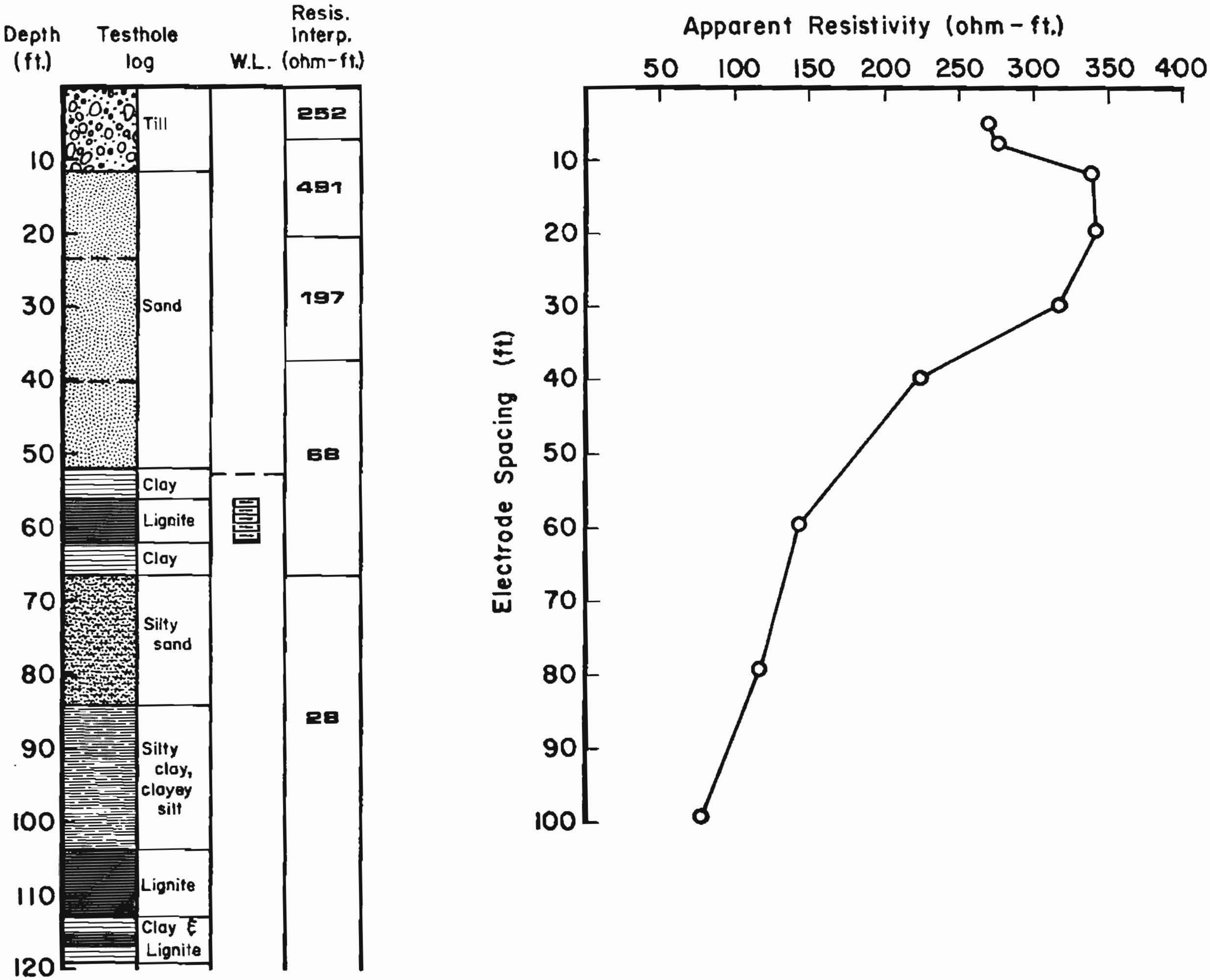



Figure C2. **Center Undisturbed 361**

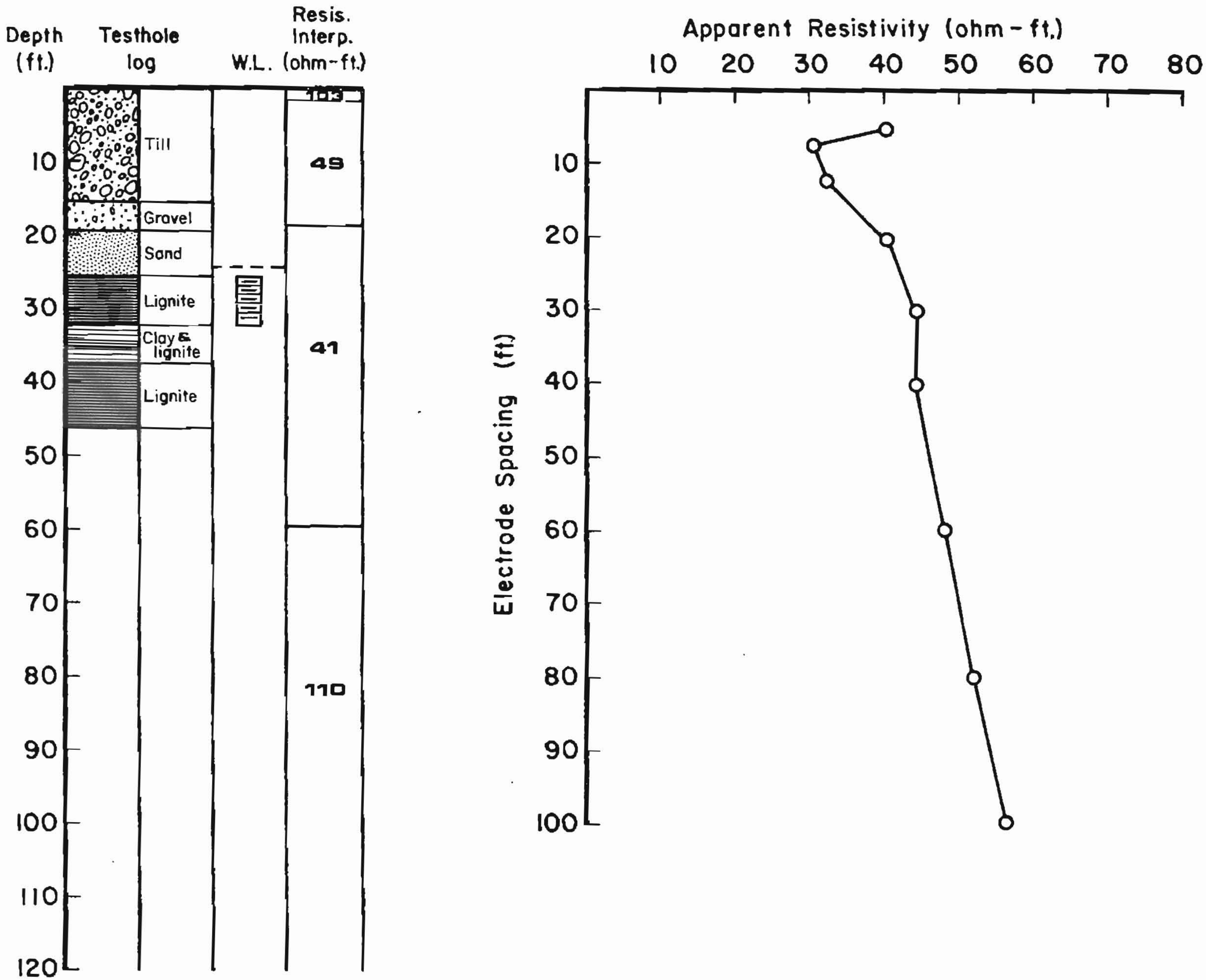



Figure C3. **Center Undisturbed 372**

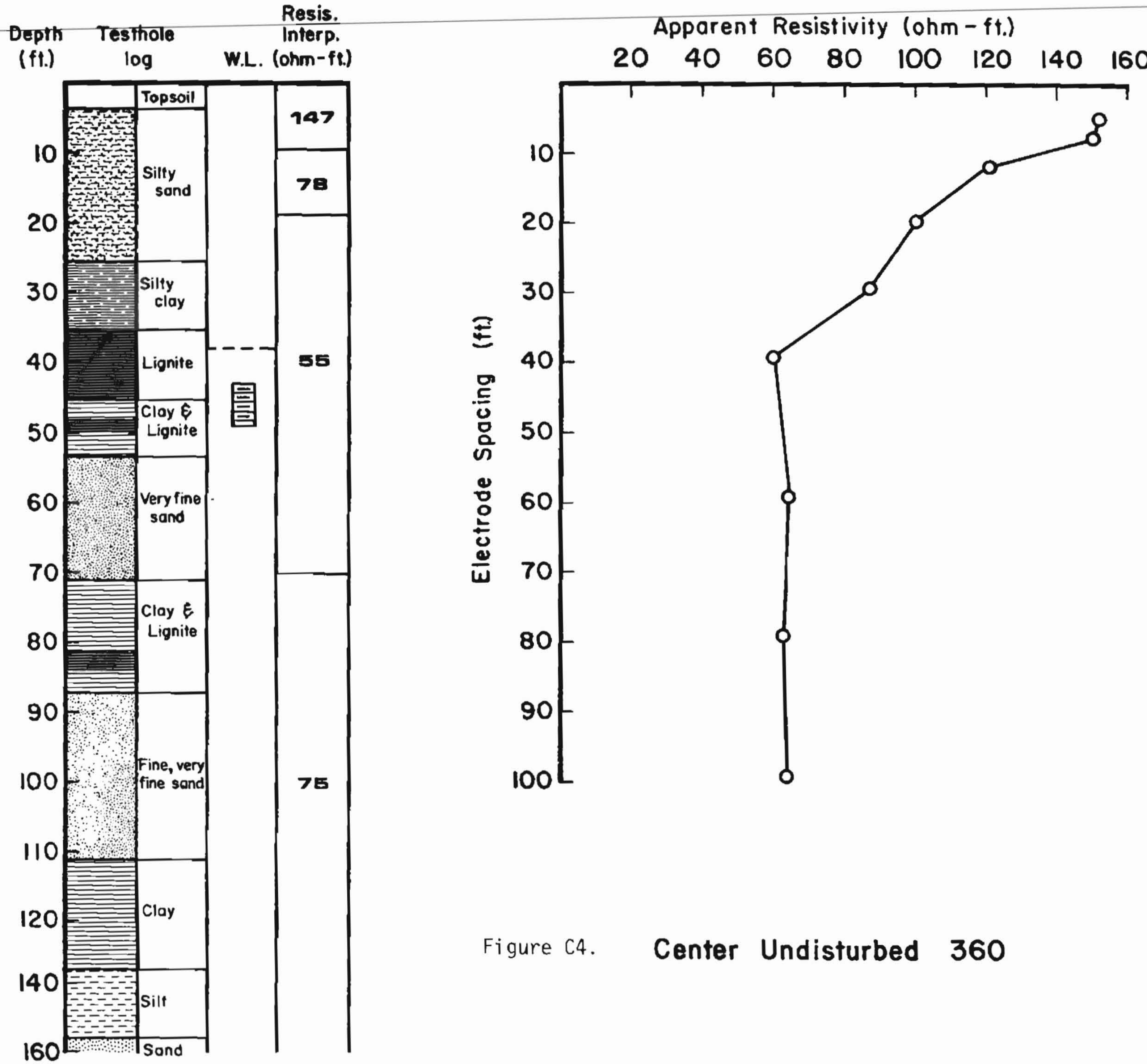



Figure C4. **Center Undisturbed 360**

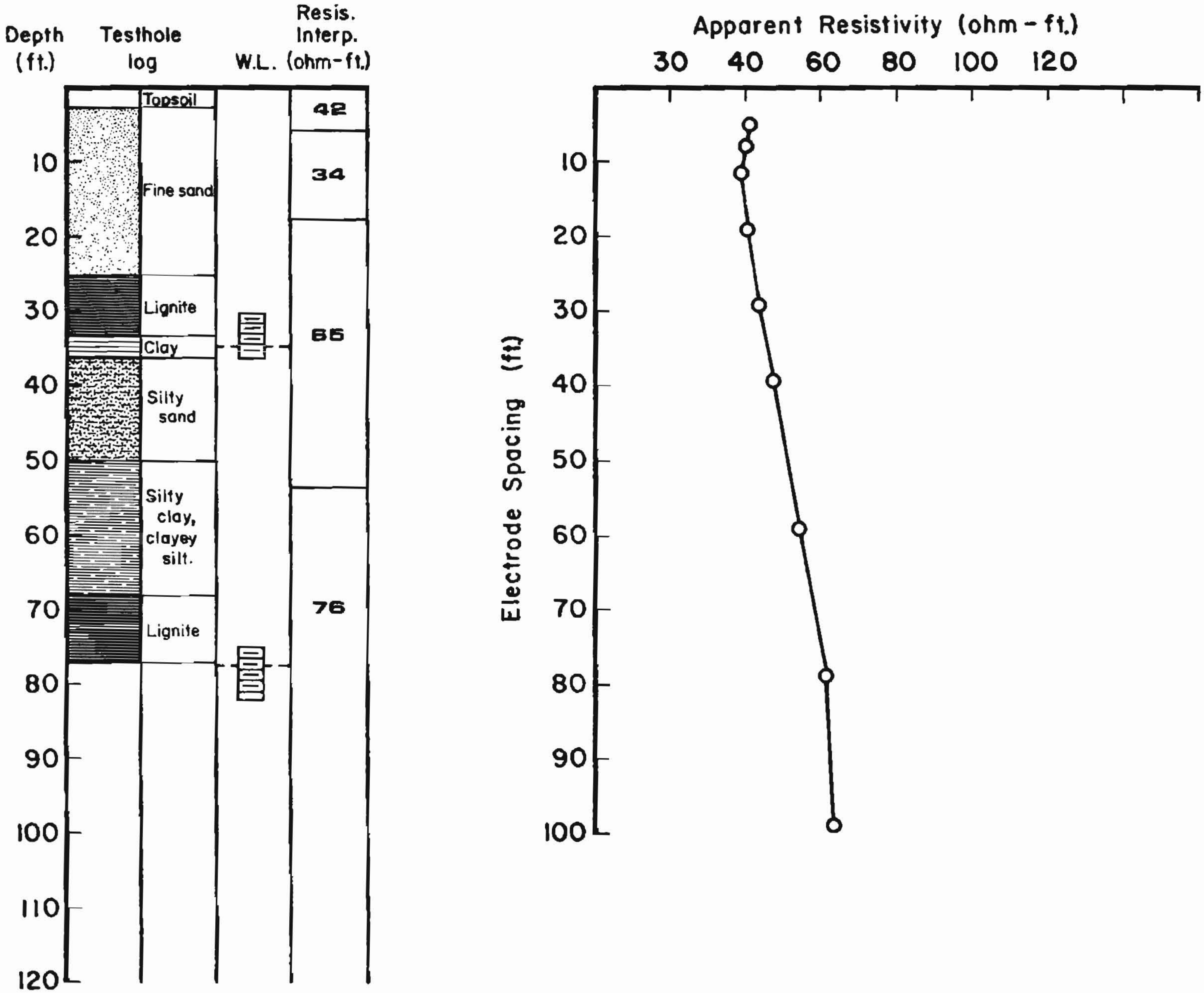
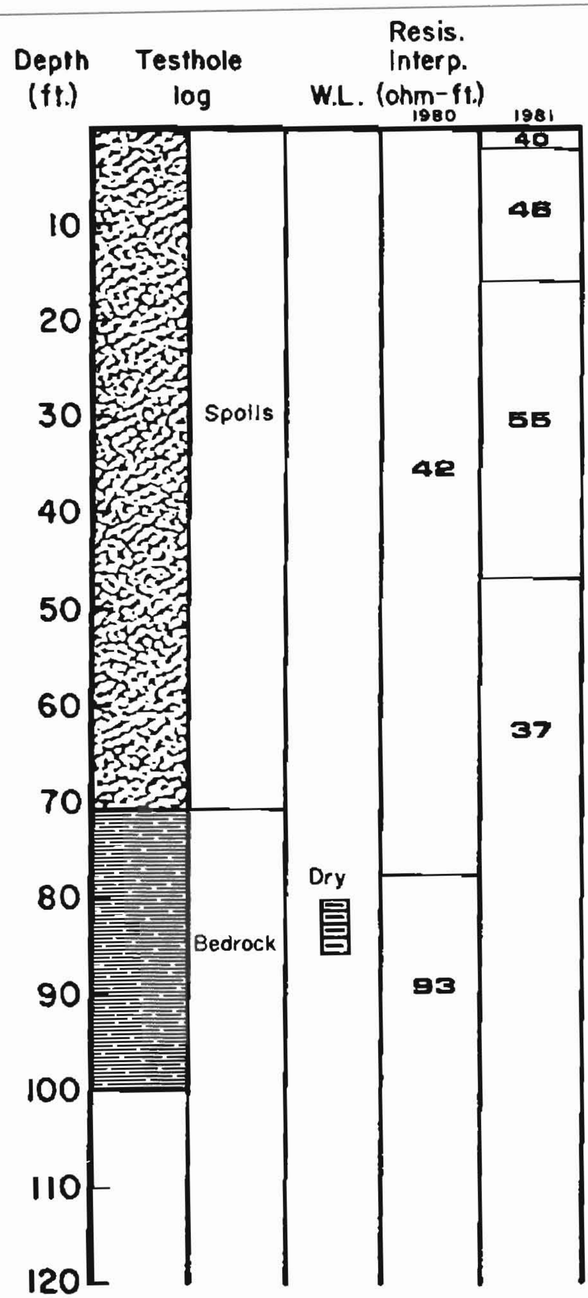



Figure C5. **Center Undisturbed 364**



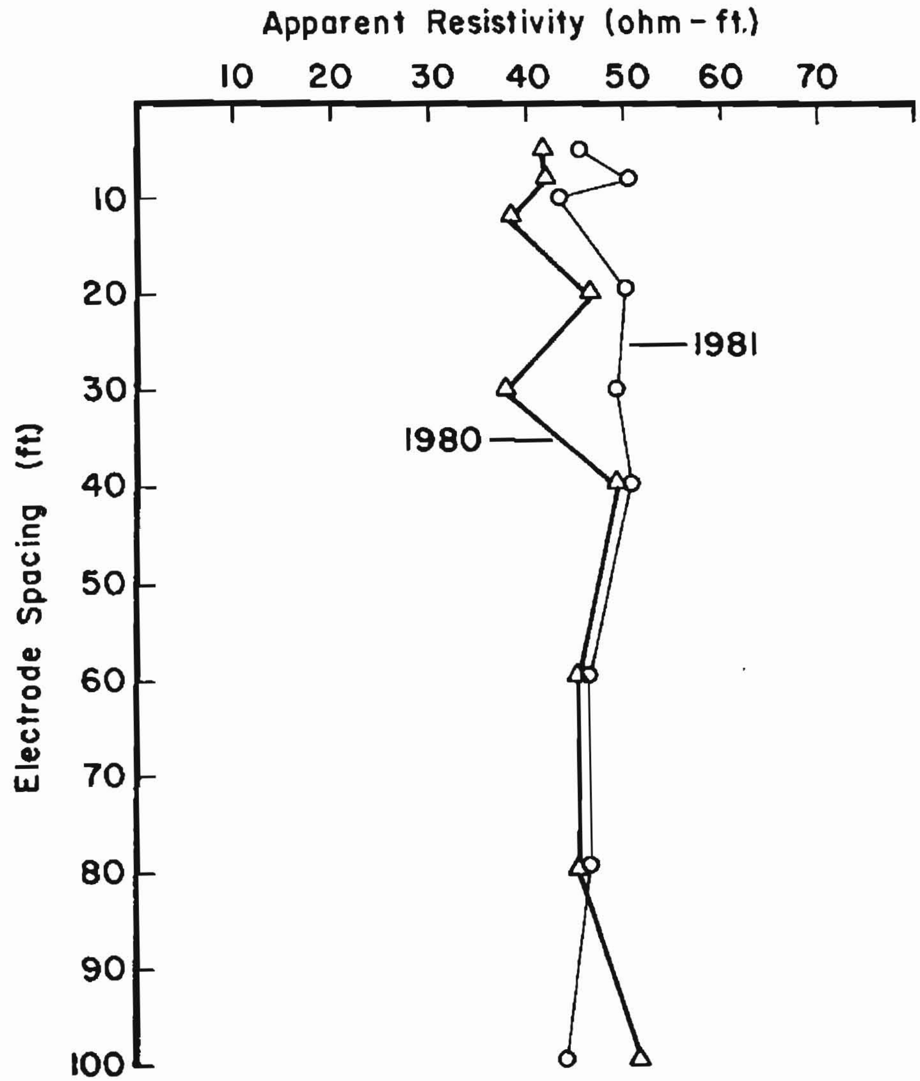



Figure C6. Center Spoils 61-62 (N-S)

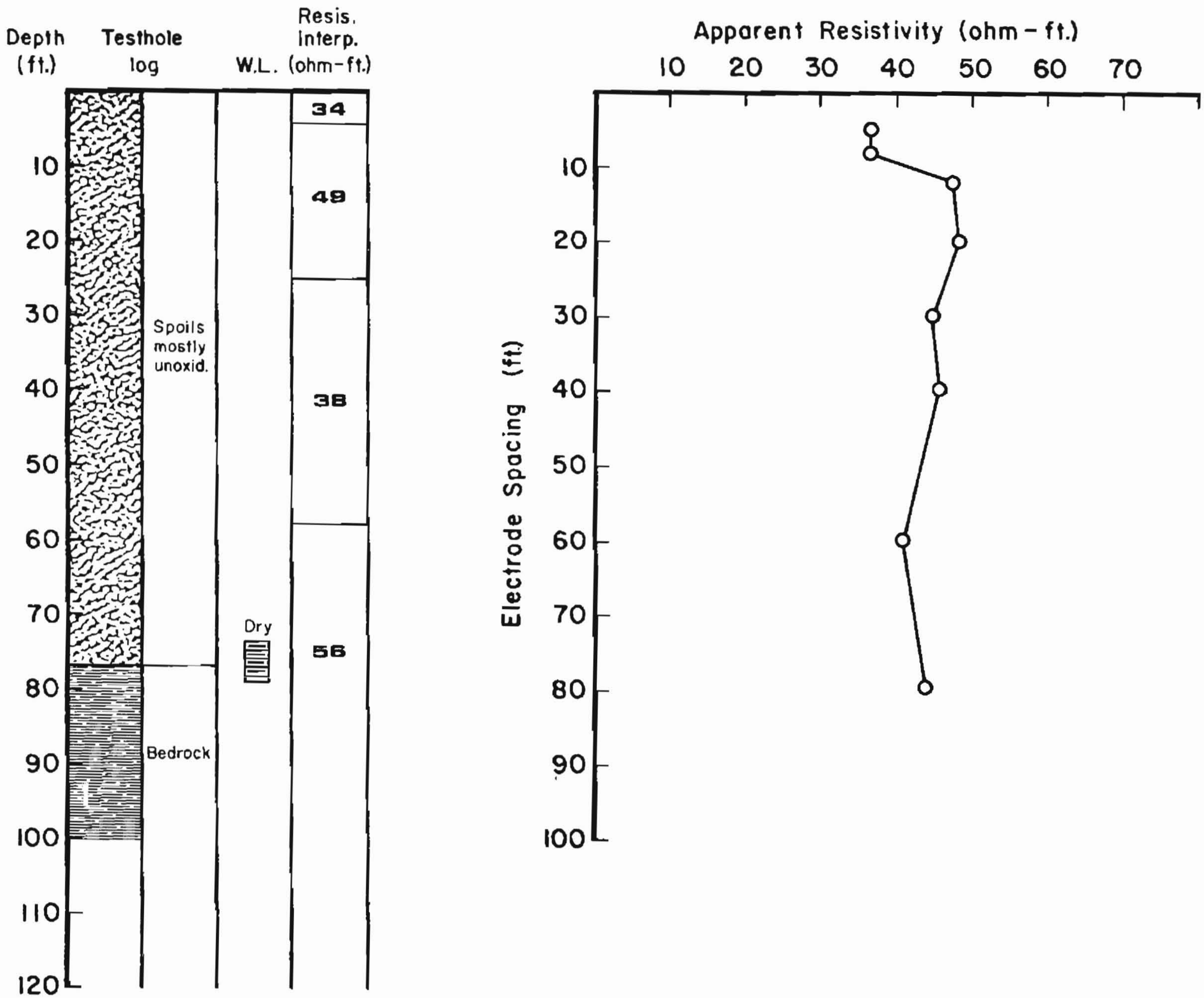



Figure C7. Center Spoils 63 (E-W)

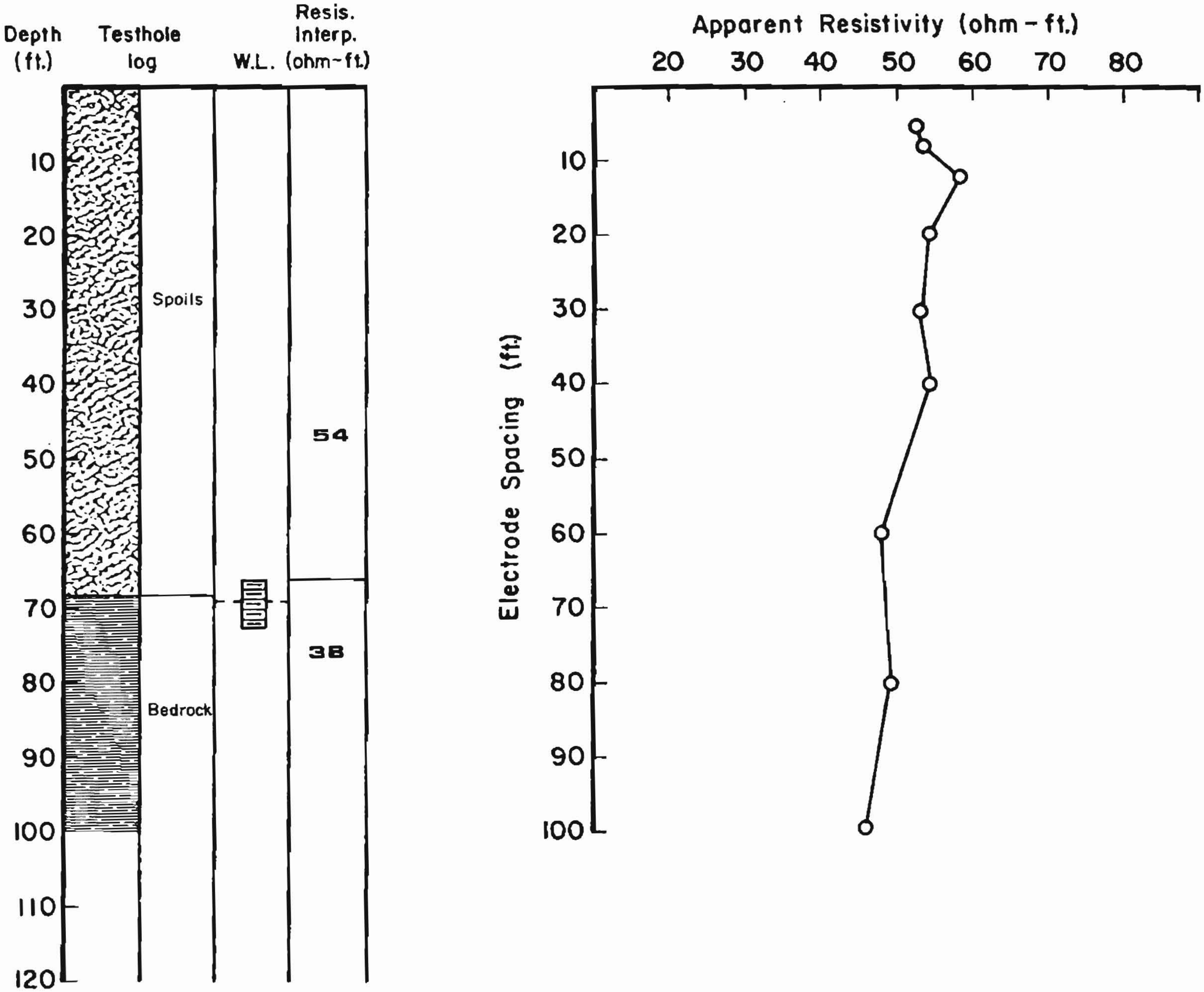



Figure C8. Center Spoils 59 and 60(N-S)

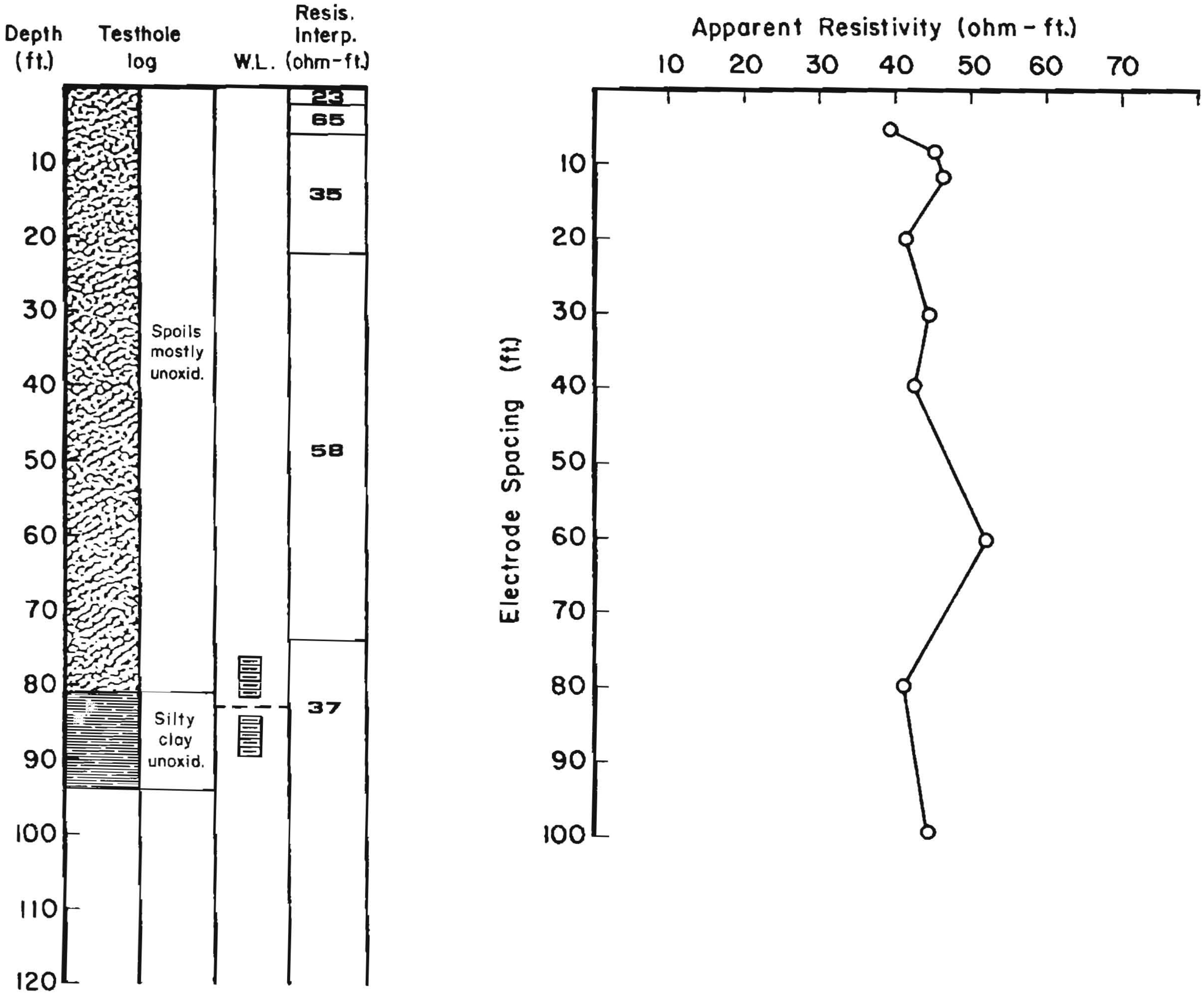



Figure C9. **Center Spoils 64 and 65 (N20 W)**

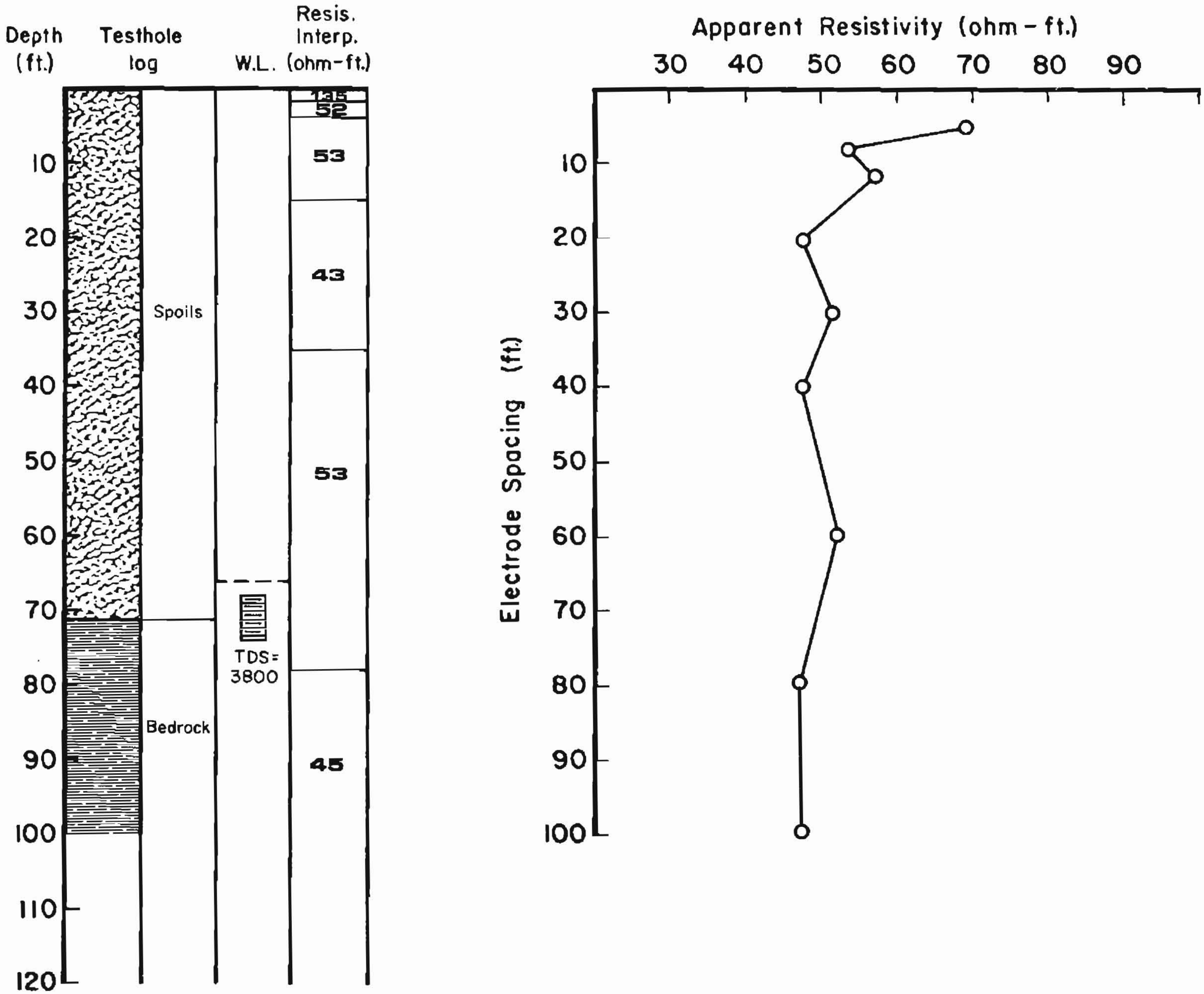



Figure C10. **Center Spoils 66-67 (N-S)**

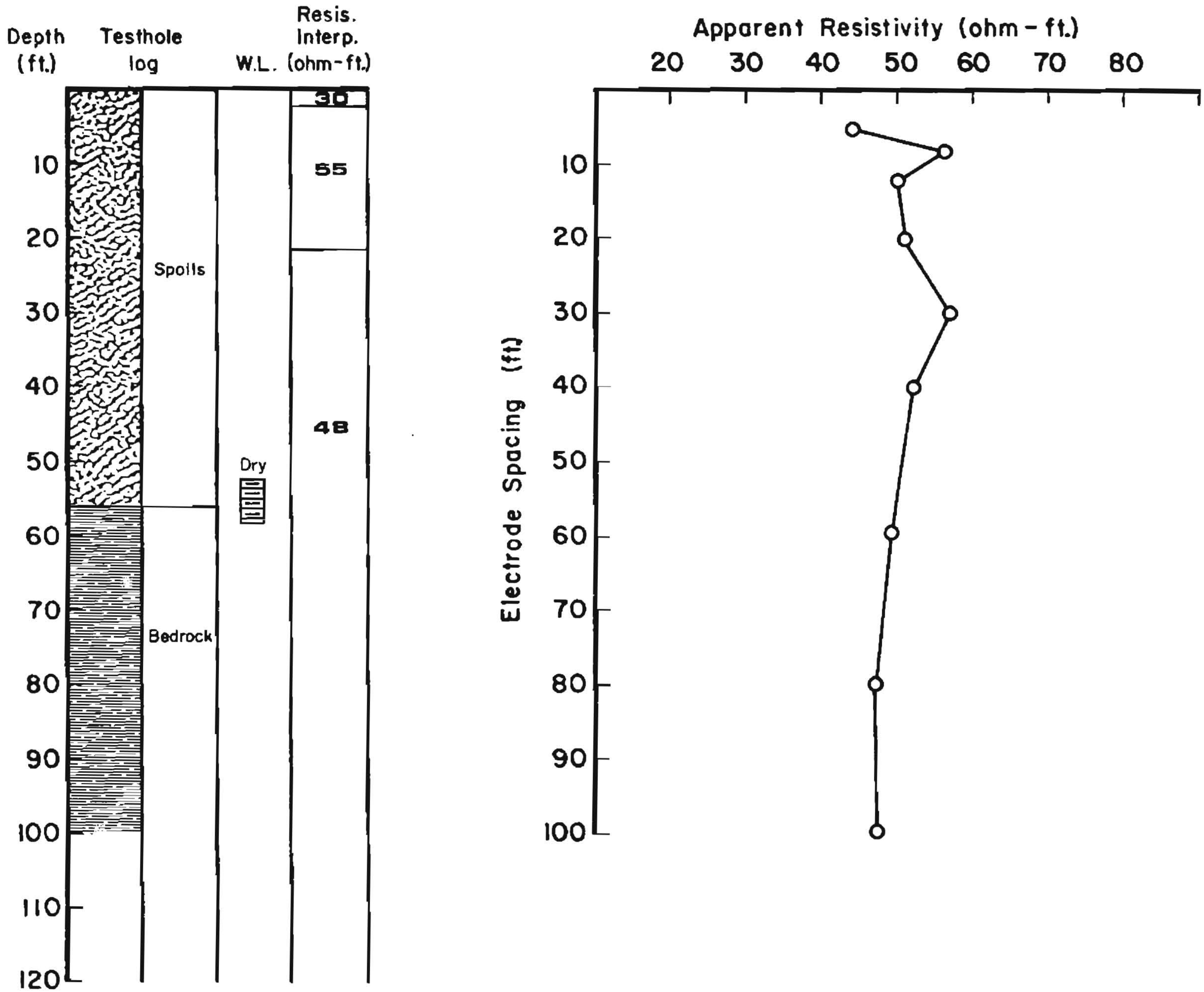



Figure C11. **Center Spoils 68 (N-S)**

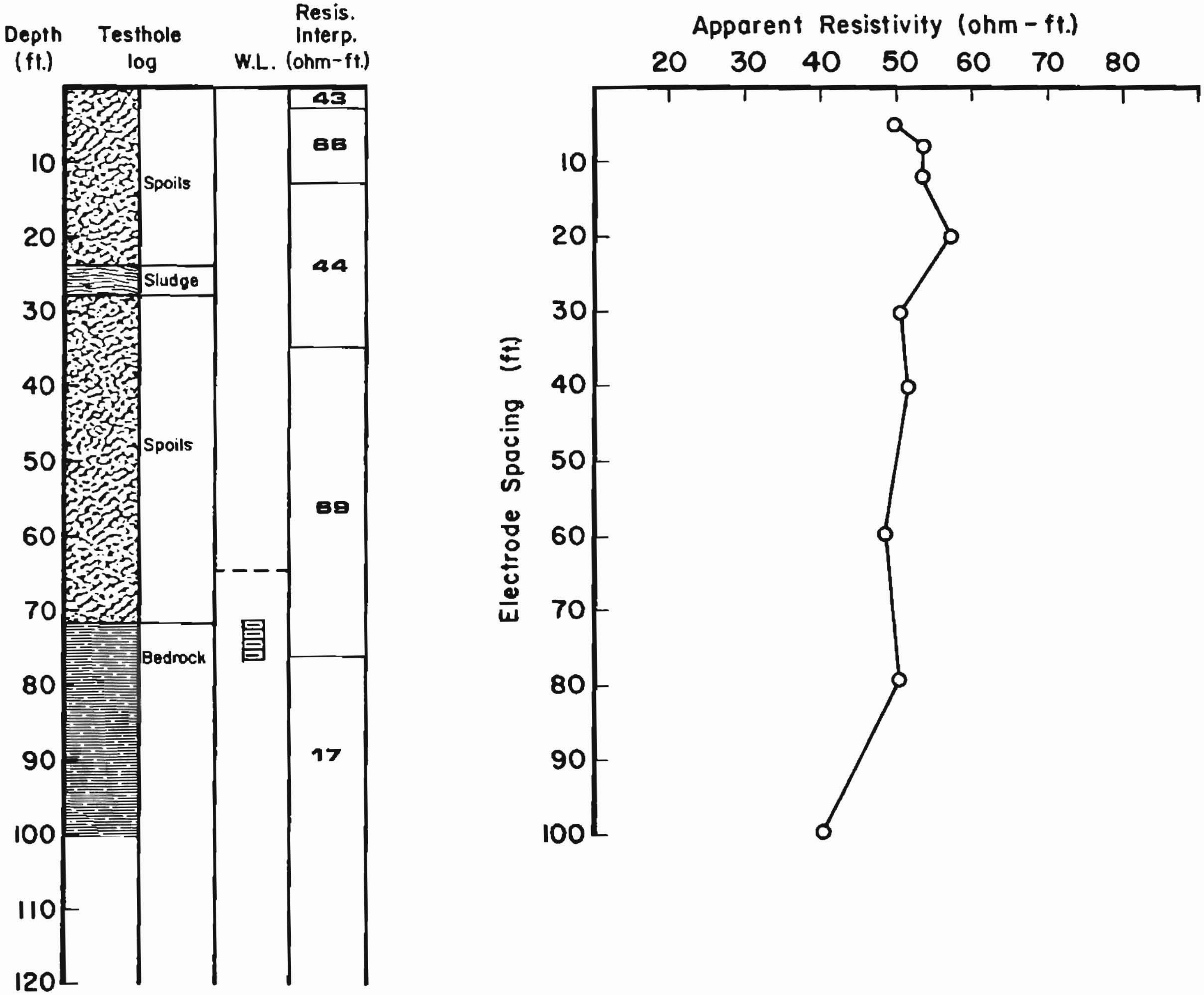



Figure C12. **Center Spoils 90(NE-SW)**

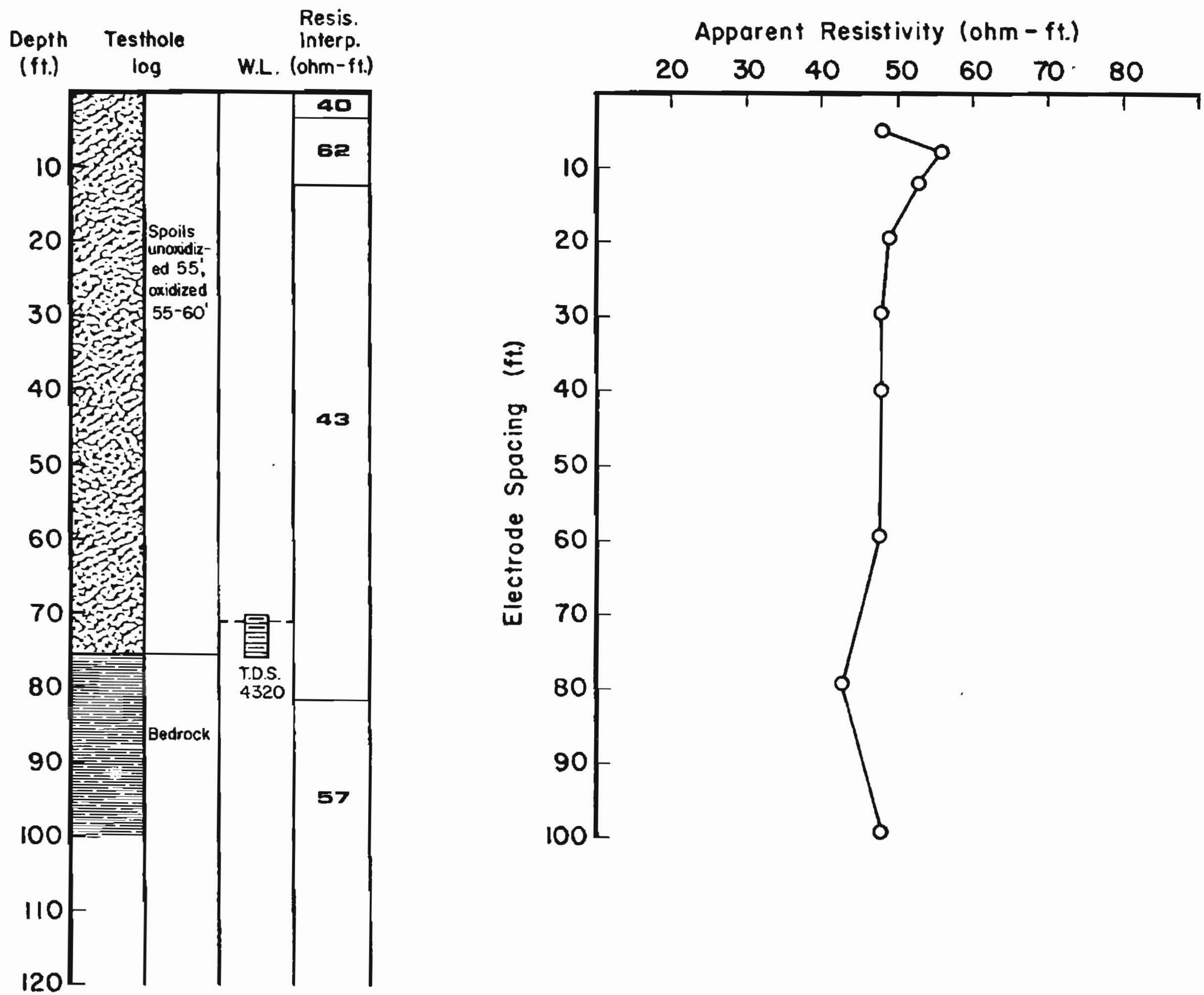



Figure C13. **Center Spoils 91(N-S)**

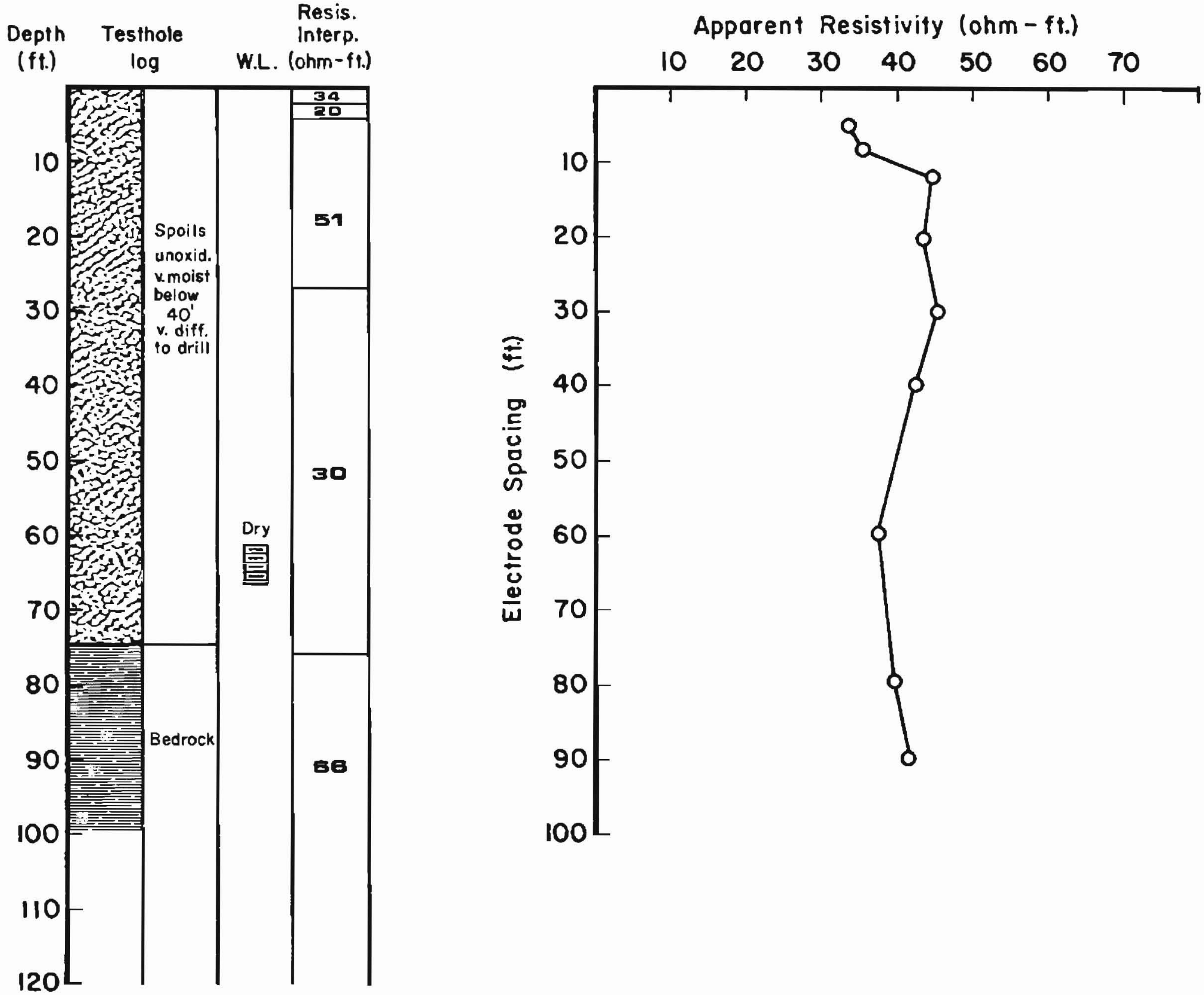



Figure C14. **Center Spoils 92 and 93 (N-S)**

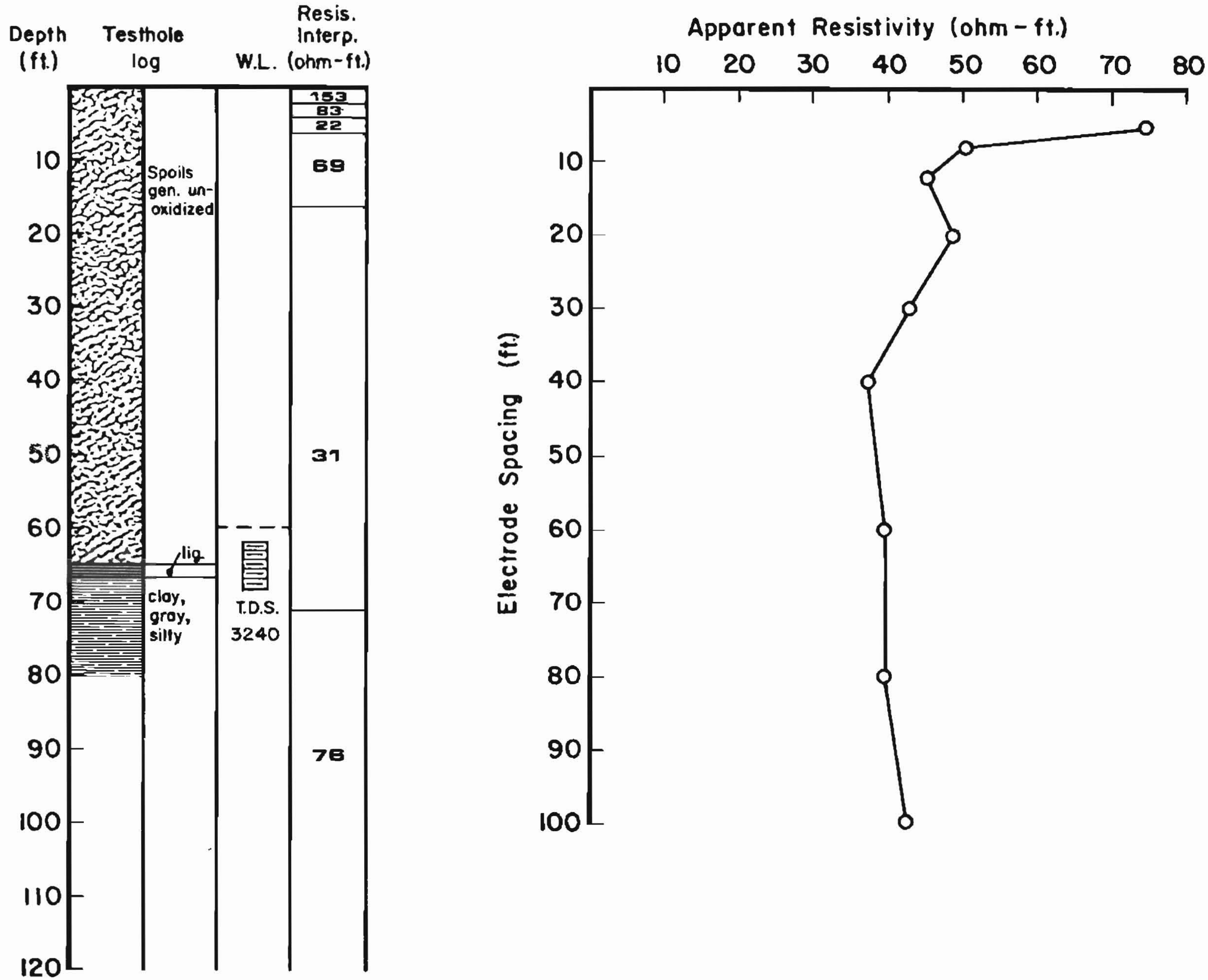



Figure C15. **Center Spoils 97 (E-W)**

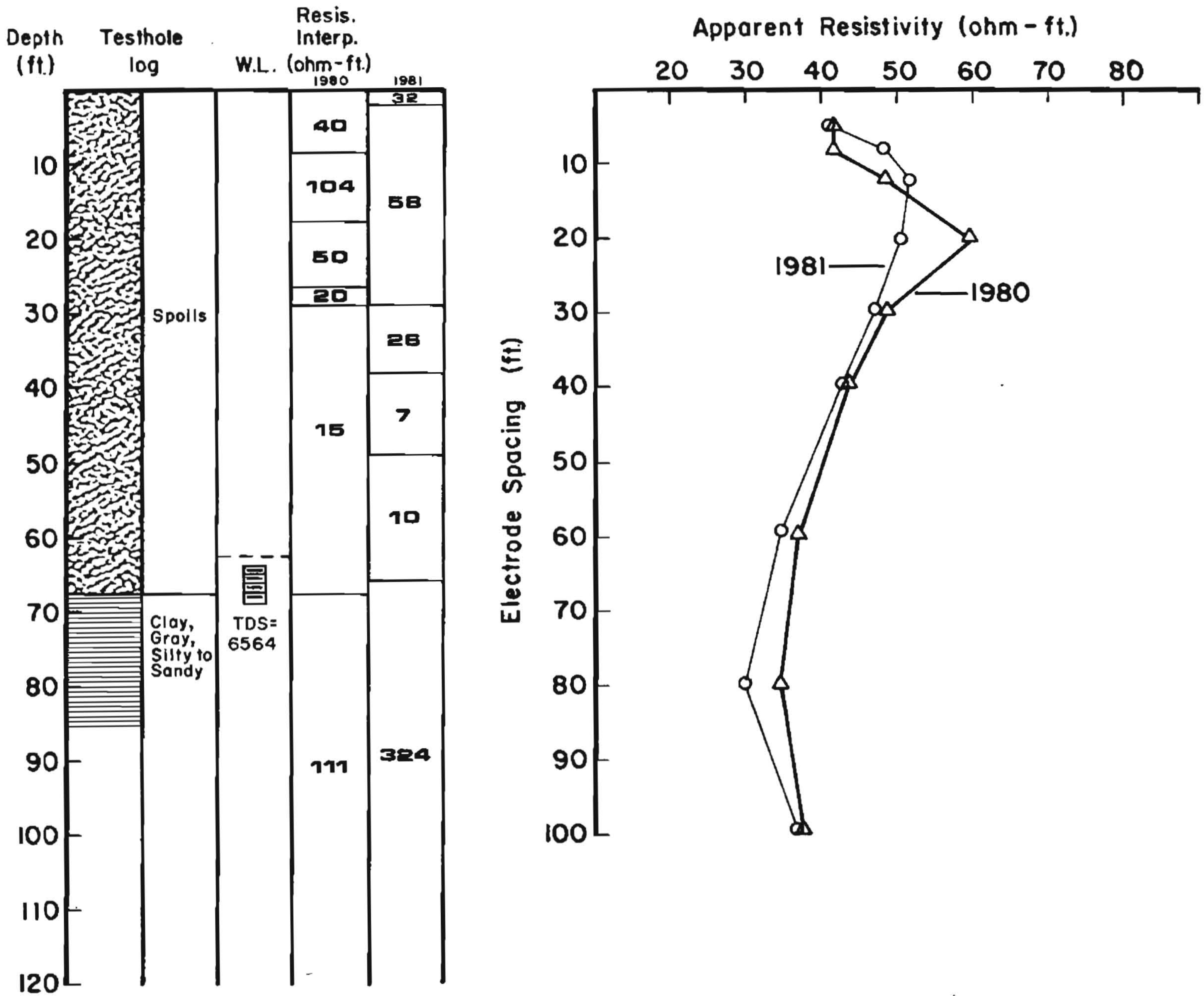



Figure C16. **Center Spoils 99 (E-W)**

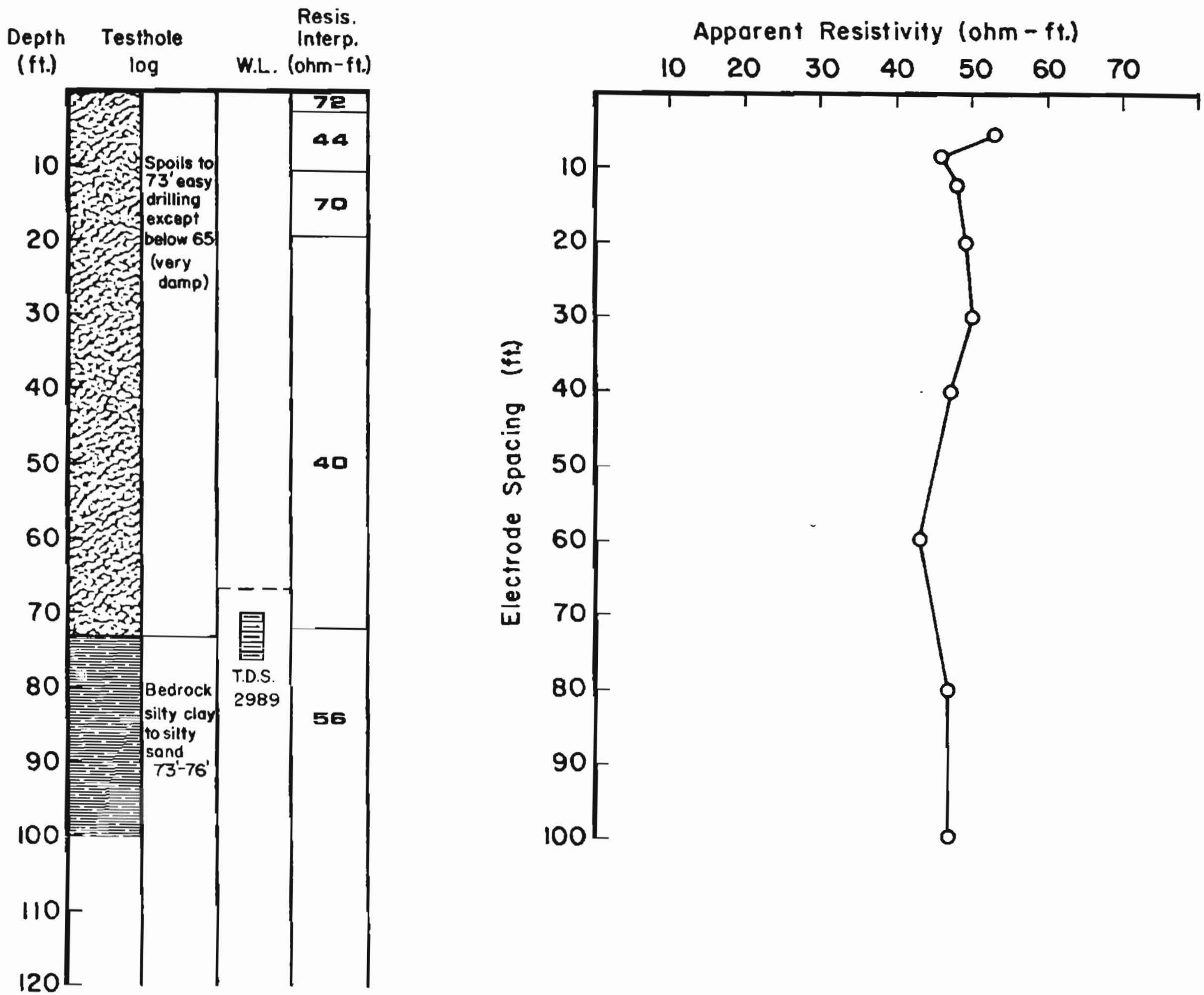



Figure C17. **Center Spoils 100 (N 30 E)**

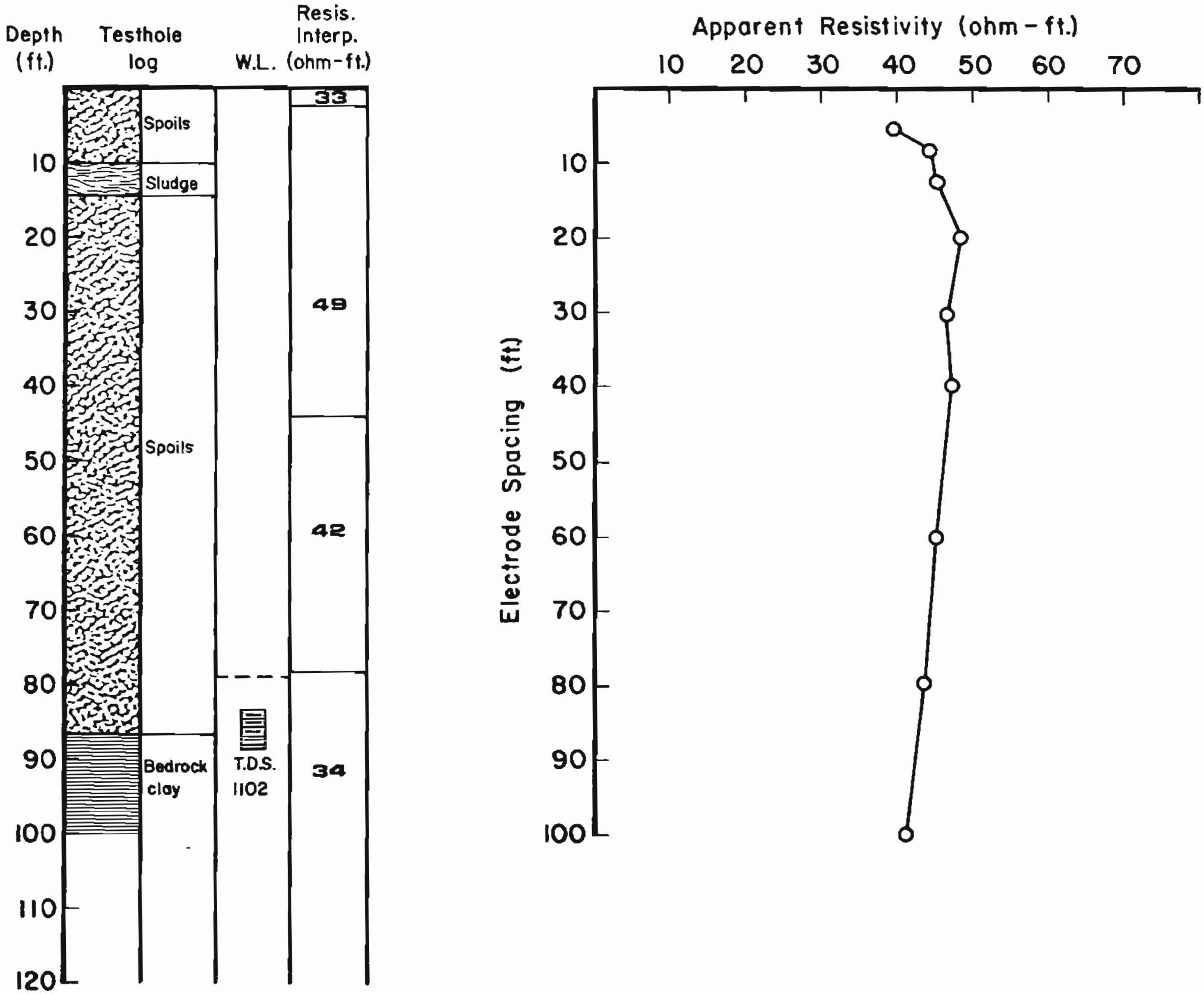



Figure C18. **Center Spoils 76-77 (E-W)**

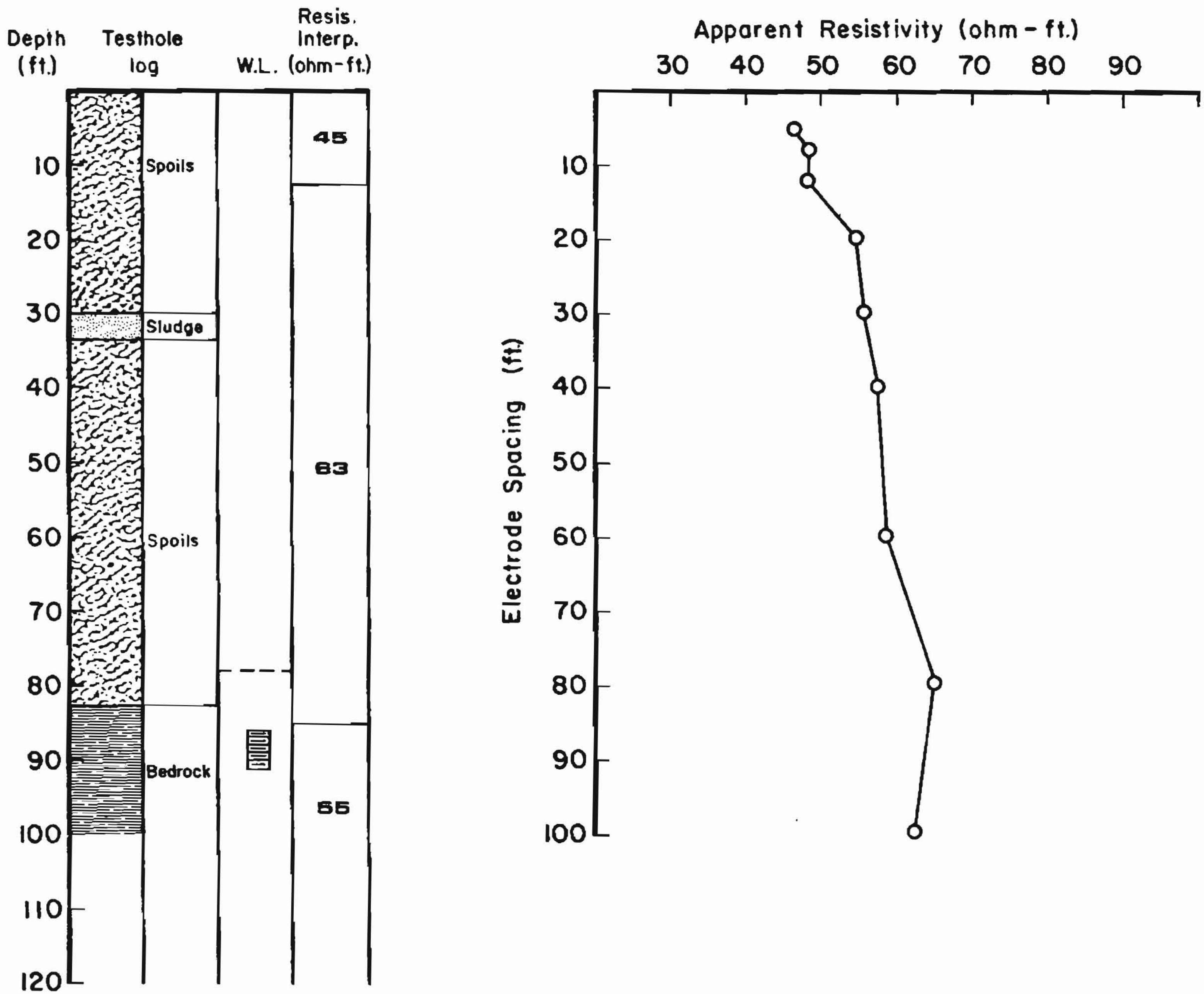



Figure C19. **Center Spoils 82R (E-W)**

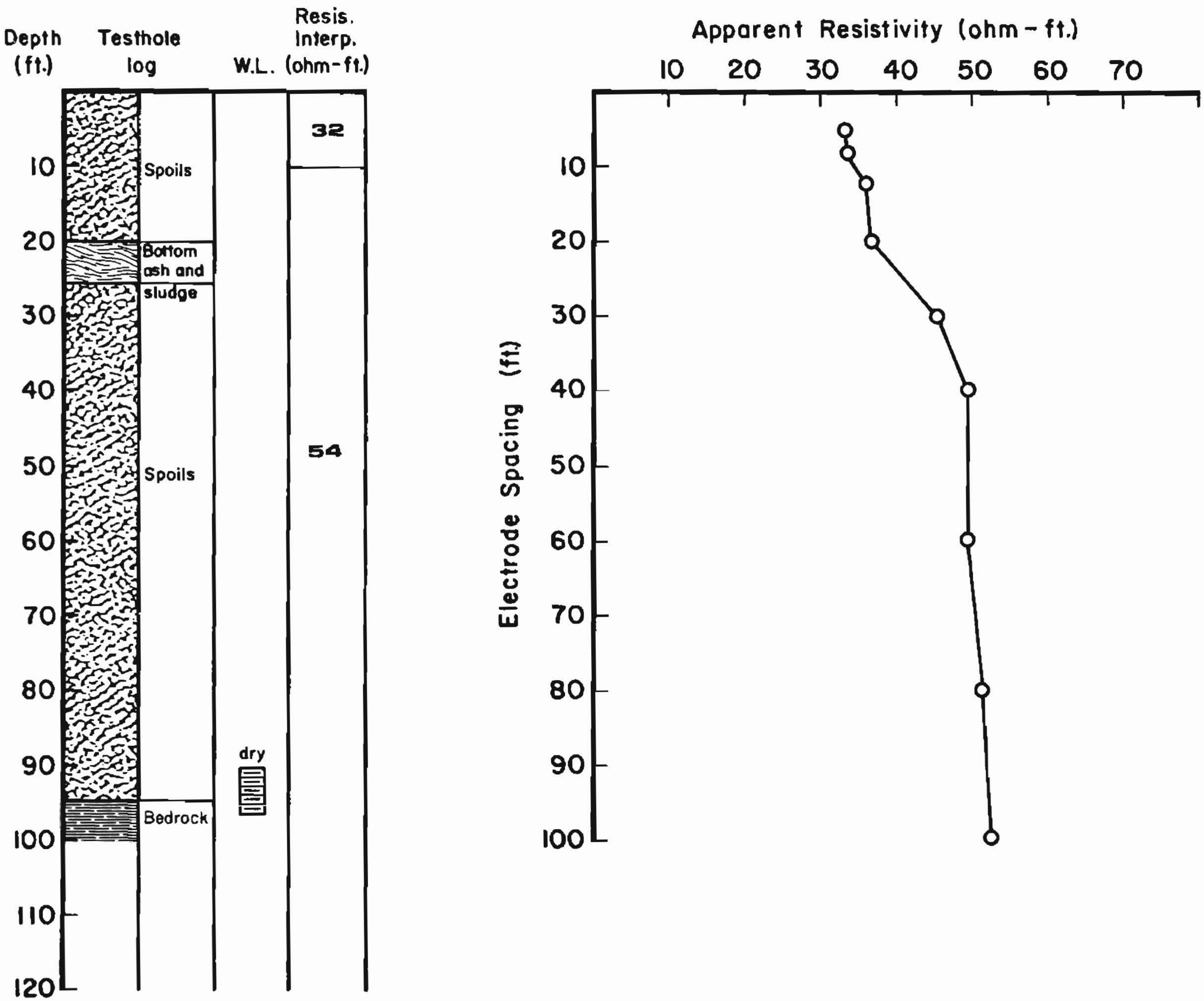



Figure C20. **Center Spoils 143 (E-W)**

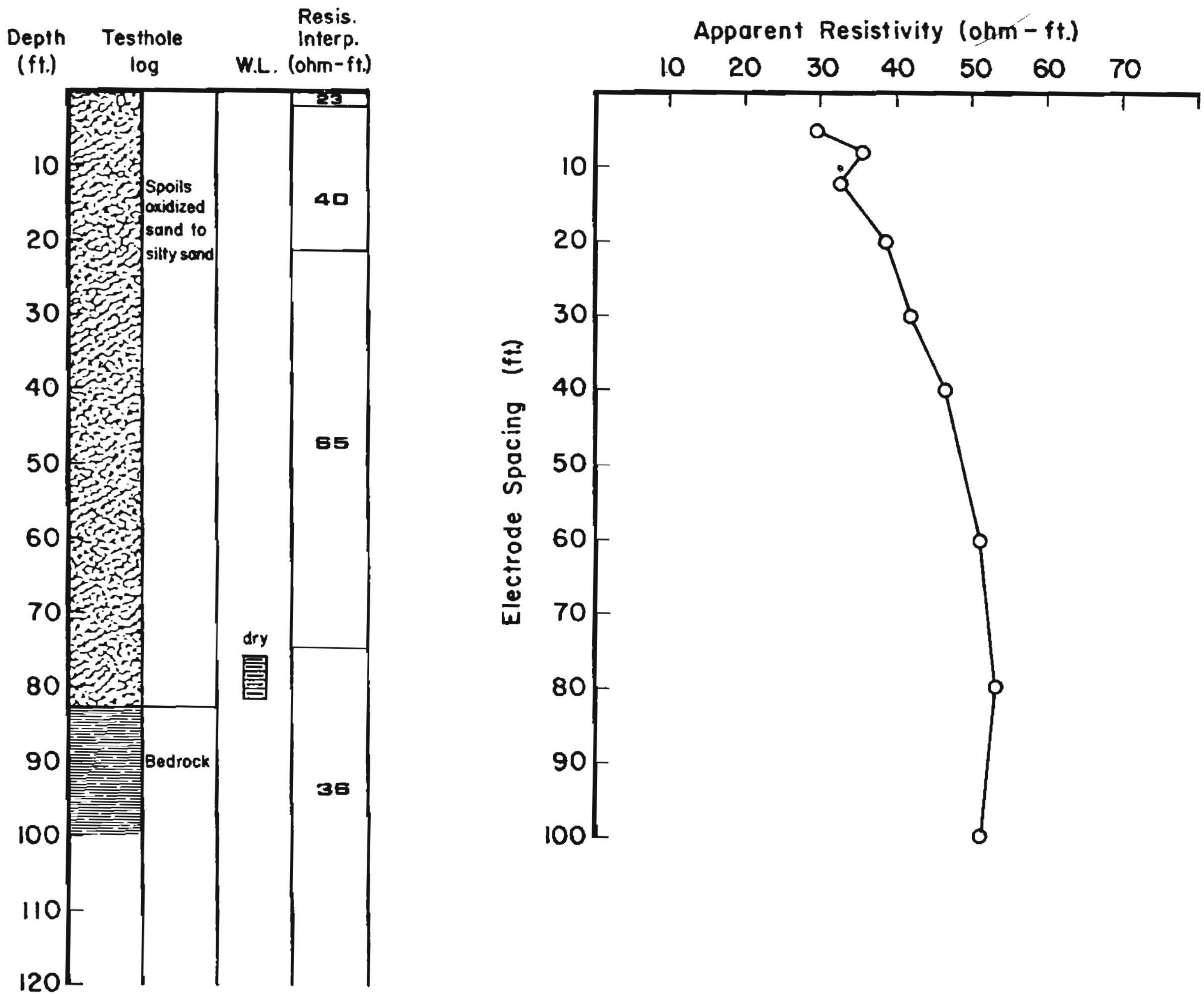



Figure C21. **Center Spoils 145 (E–W)**

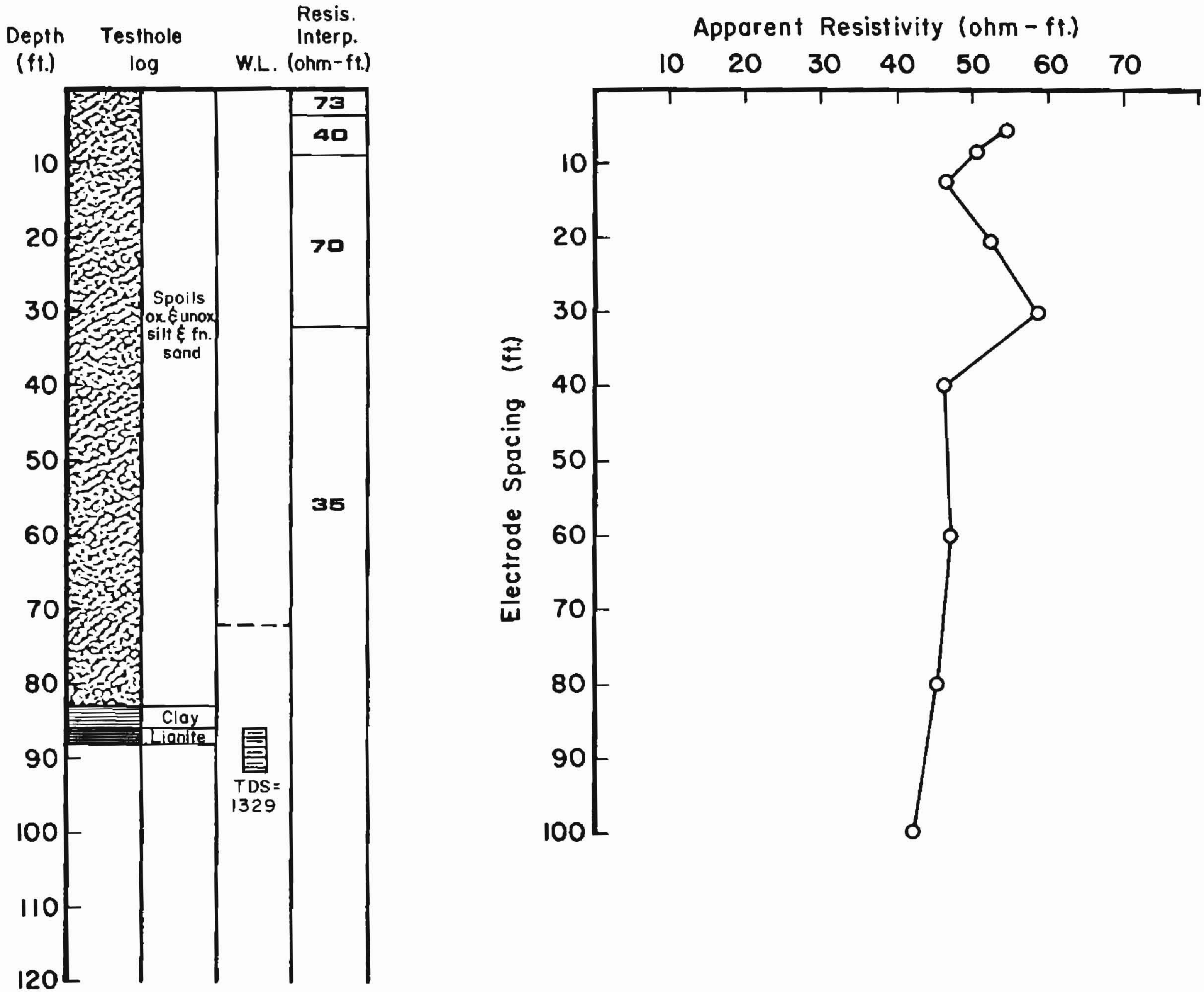



Figure C22. **Center Spoils 69(E-W)**

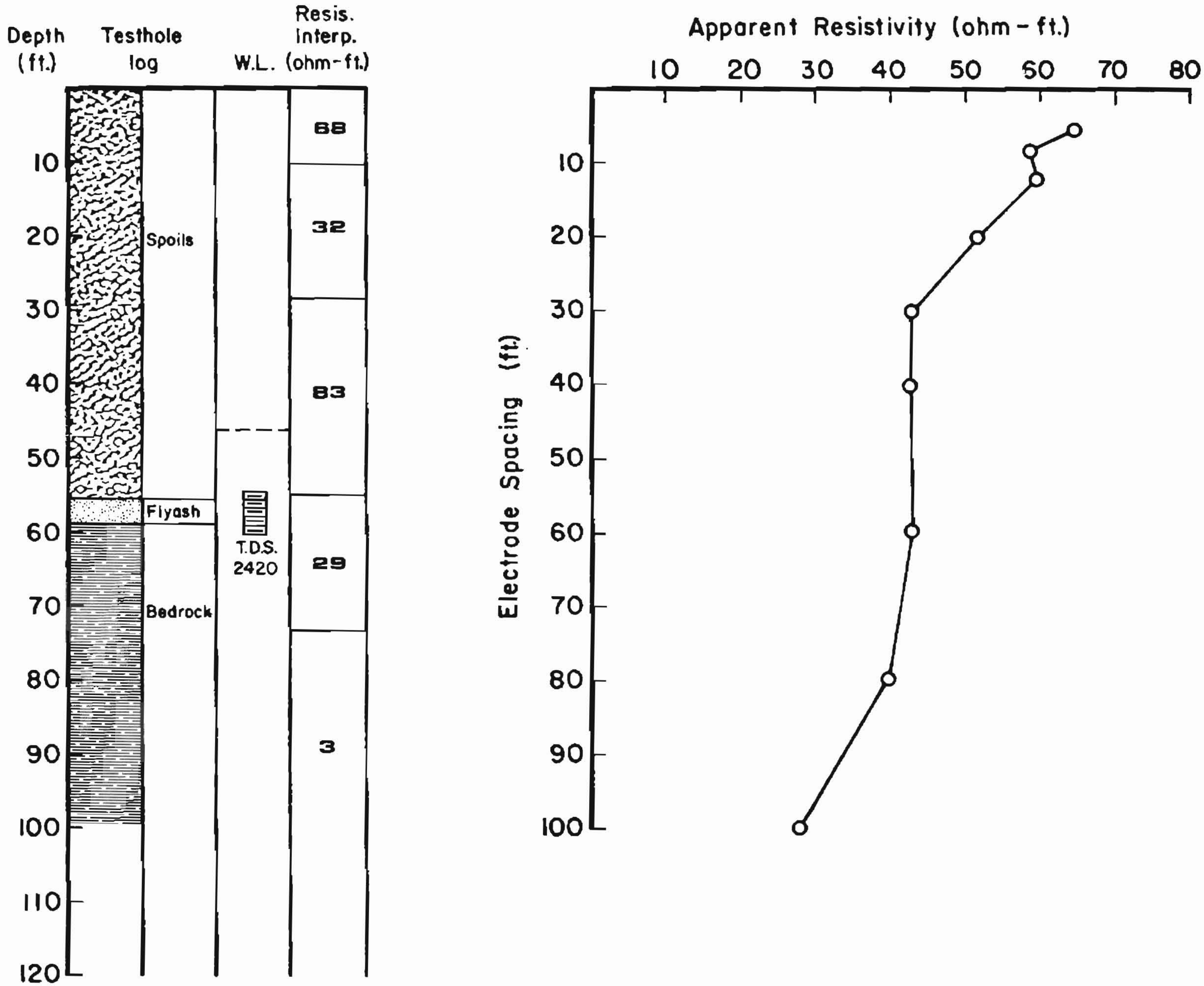



Figure C23. **Center Spoils 119(E-W)**

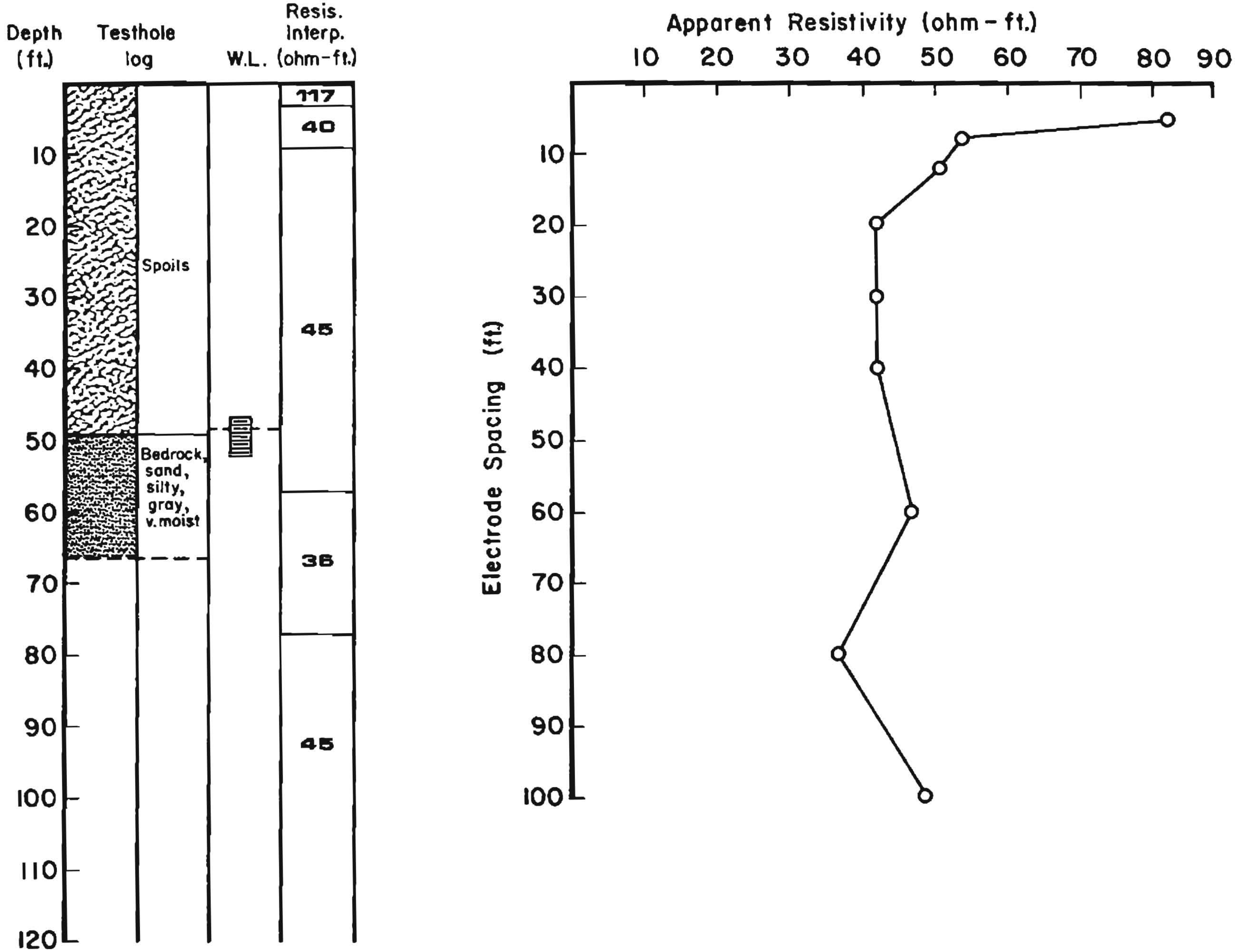



Figure C24. **Center Spoils 133,134 (N-S)**

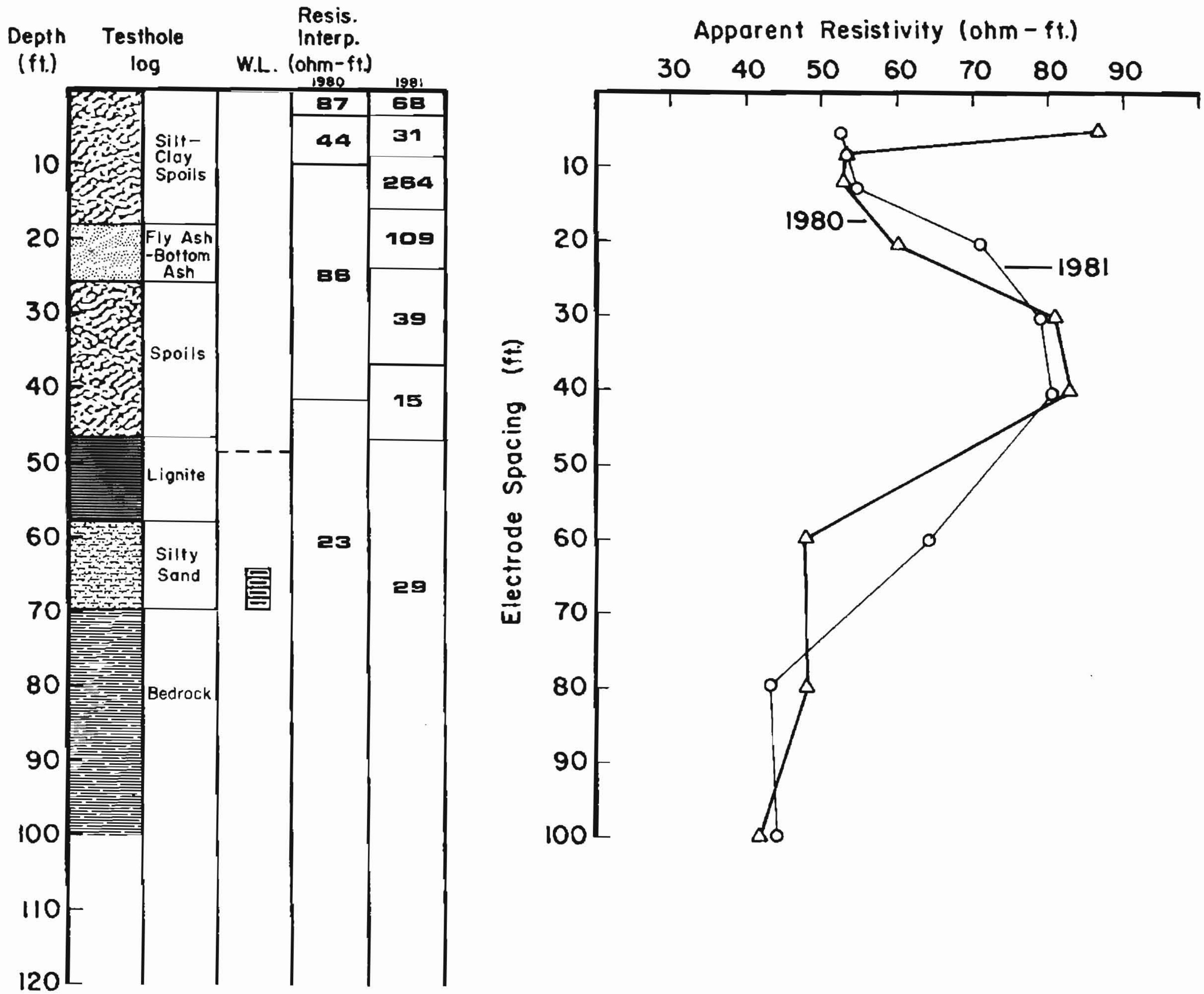



Figure C25. **Center Spoils 136-137 (N-S)**

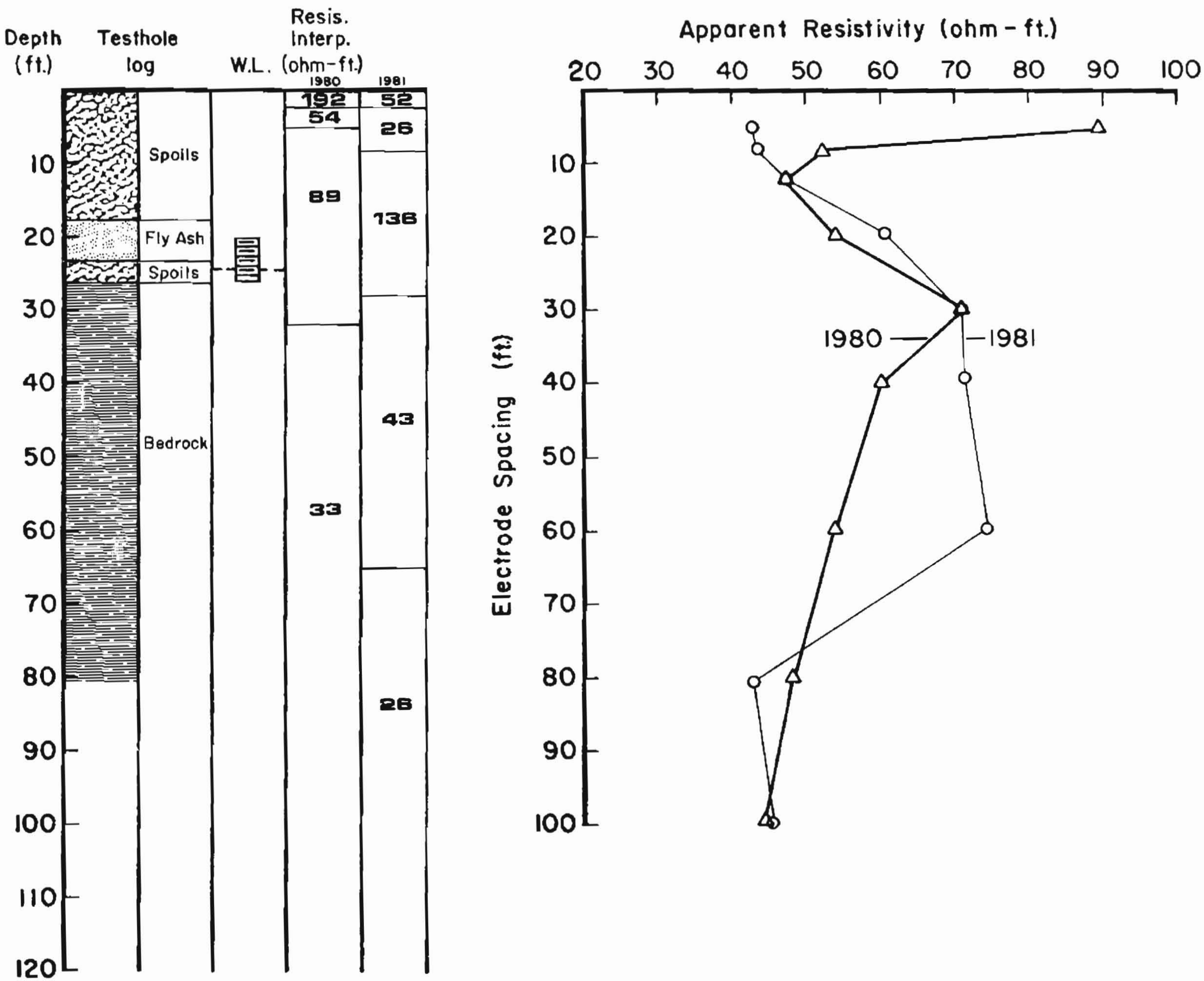



Figure C26. **Center Spoils 140 (N-S)**

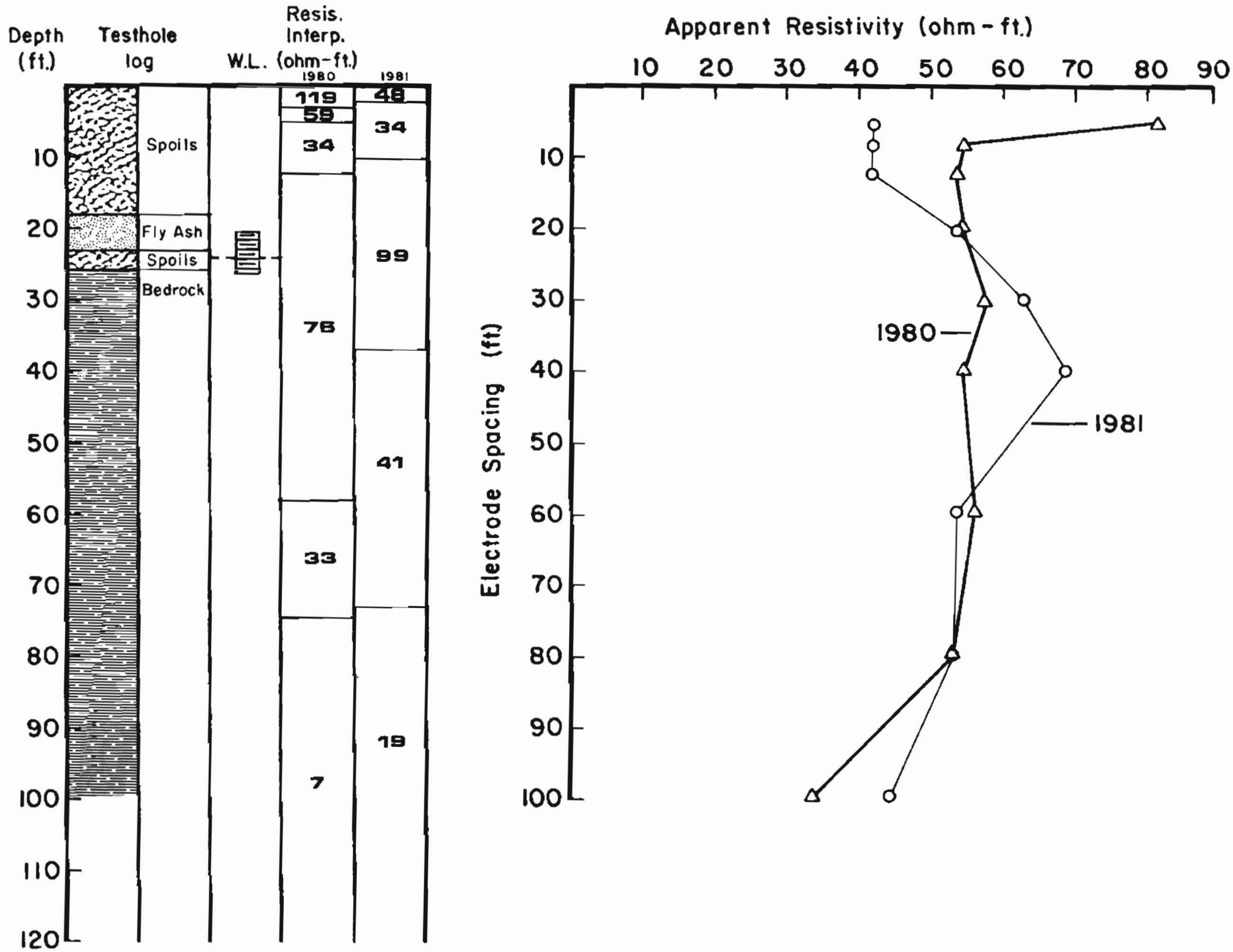



Figure C27. Center Spoils 140 (E-W)

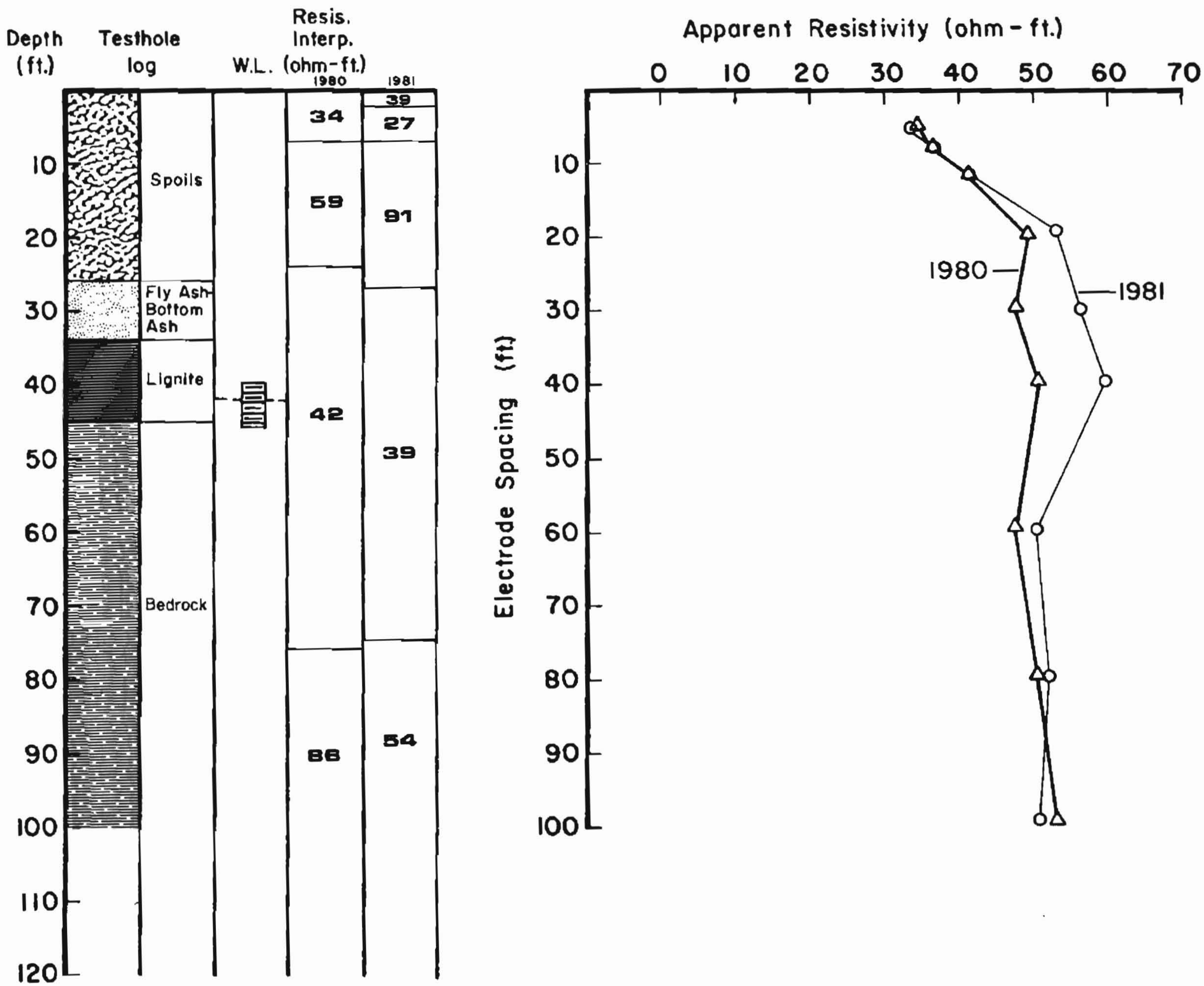



Figure C28. **Center Spoils 141, 142 (E-W)**

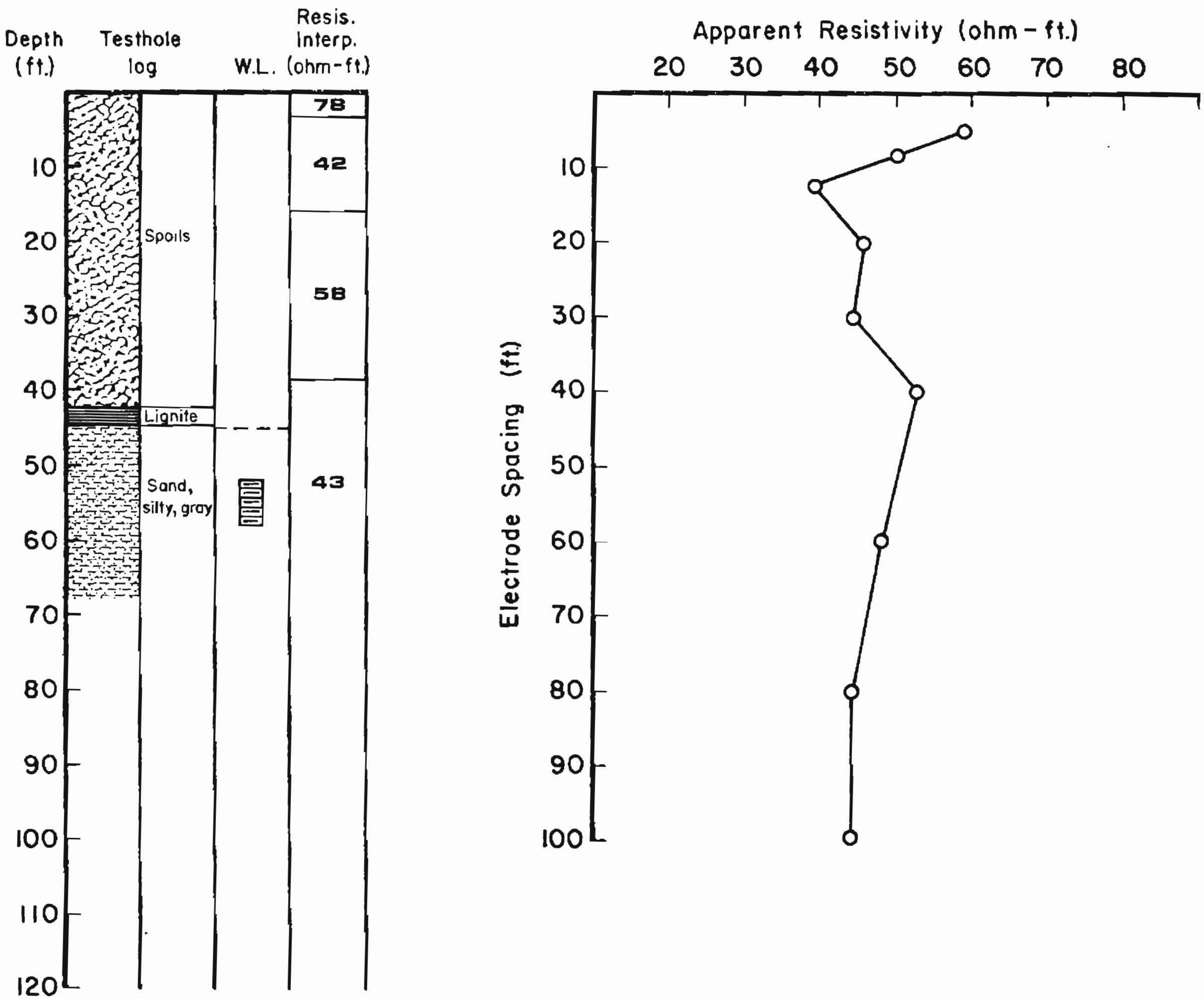



Figure C29. **Center Spoils 129-130(E-W)**

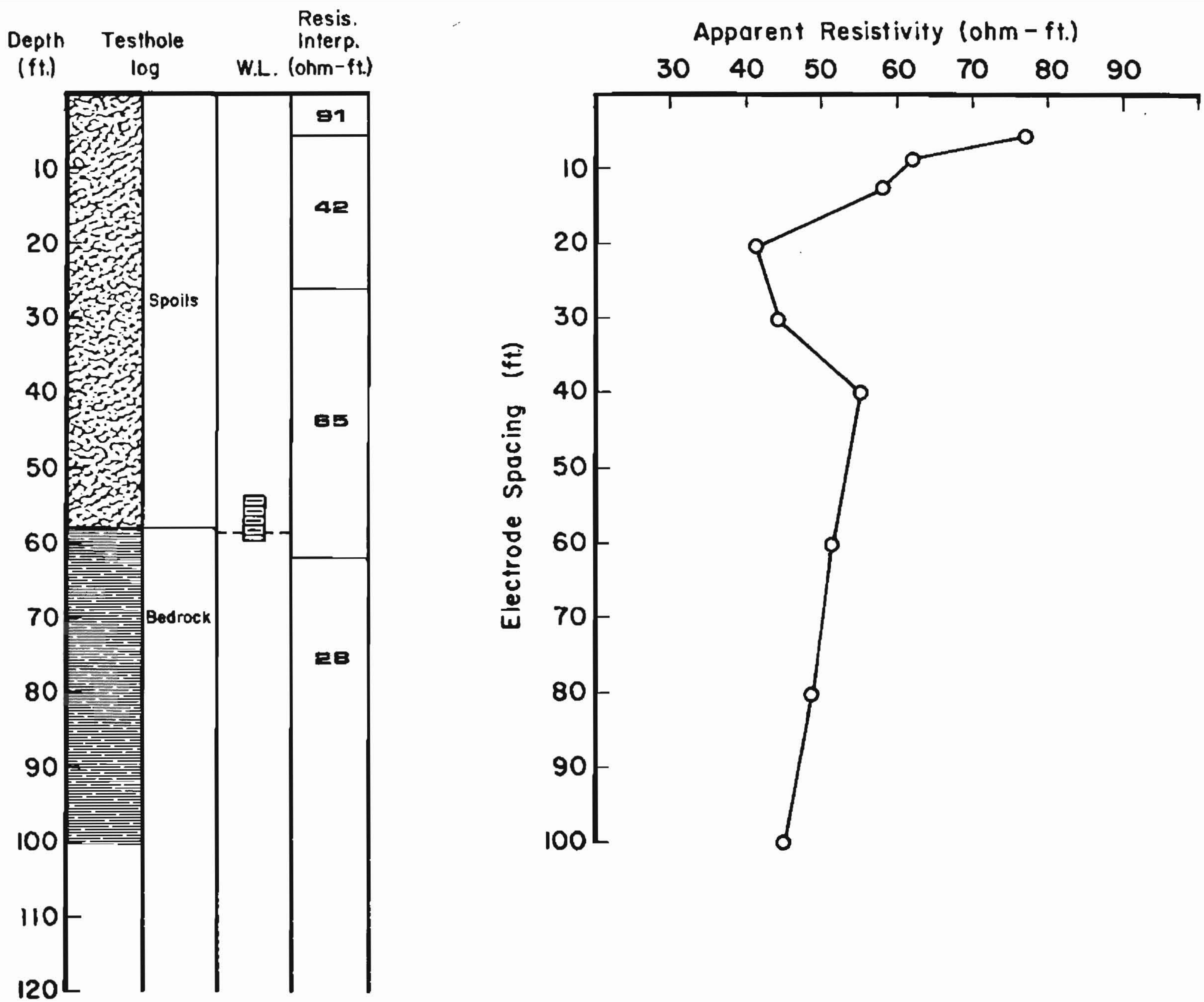



Figure C30. **Center Spoils 124(N-S)**

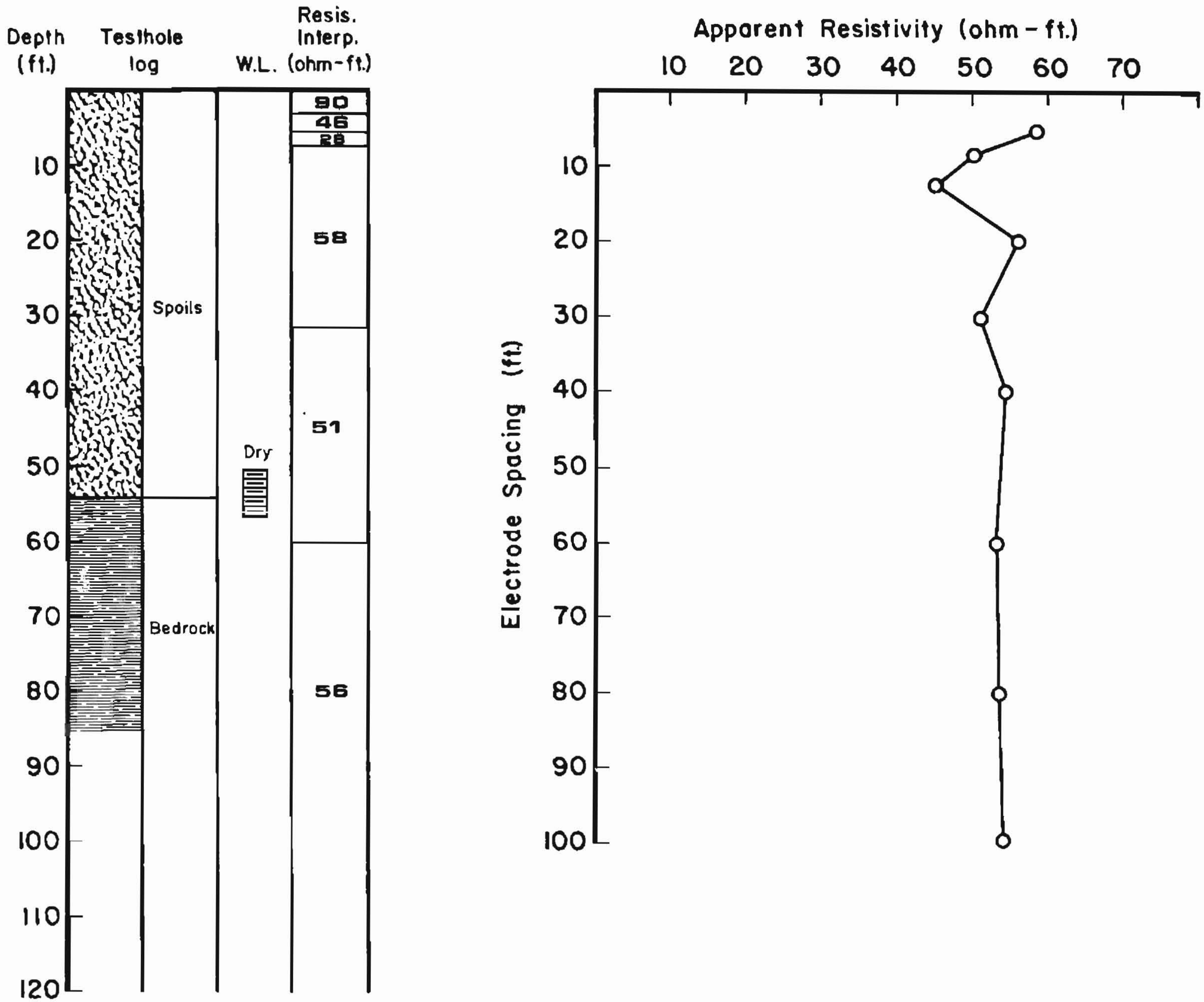



Figure C31. **Center Spoils 128(N-S)**