THE FEASIBILITY OF USING THE SCHLUMBERGER METHOD OF VERTICAL ELECTRIC SOUNDING TO DETERMINE DEPTH TO THE TOP OF THE PERMIAN IN PART OF SOUTHWEST KANSAS

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INTRODUCTION

Surface geophysical methods are becoming more important tools of investigation in hydrogeology, especially as the costs of obtaining subsurface information continue to rise. Resistivity methods have been used successfully in several areas for determining depth to bedrock and locating areas of high total dissolved solids in groundwater systems, particularly where salt-water intrusion or brine contamination is occurring. Often both goals are achieved using the resistivity method.

This study was conducted to determine the feasibility of measuring depth to the top of the bedrock aquifer from Schlumberger electrical soundings under typical geologic conditions in southeast Seward and southwest Meade counties, southwest Kansas. The bedrock aquifer, commonly referred to as the Permian redbeds, underlies much of the shallower unconsolidated aquifer in the study area. The Permian redbeds consist of red and gray shales and siltstones interbedded with evaporites and dolomite and are included in the Upper and Lower Permian Series. The unconsolidated materials above bedrock are collectively referred to as the Ogallala aquifer. These unconsolidated materials consist of variable amounts of sand, gravel, clay, silt, and caliche and are Pliocene to Recent in age. The total thickness of these sediments ranges from less than 100 to over 800 feet. The bedrock aquifer is believed to leak saline water into the base of the unconsolidated aquifer and into the Cimarron River in this part of southwest Kansas. The geoelectric effects of saltwater intrusion from the Permian bedrock on the geoelectric section were not considered in this investigation.

METHODS

Representative well logs for wells drilled in southeast Seward and southwest Meade counties were selected from the water well record files maintained by the Kansas Geological Survey. The locations of these wells are shown in Figure 1. The log of each well showed that the top of the Permian redbeds had been penetrated during drilling. Each log was used to assign thicknesses and reasonable estimates of true resistsivity to each geoelectric layer. The sequence of layer thicknesses and resistivities constitutes the geoelectric section or model for each well site. In some situations the layer thicknesses and resistivities were changed to determine the effect of introduced layers on the simulated vertical electric sounding curve and on the interpretation.

A computer program for the forward calculation of Schlumberger sounding curves (Zohdy, 1979) was used to generate simulated VES curves for each geoelectric model. The Schlumberger array (Fig. 2) was chosen because VES curves generated from the array are minimally affected by near-surface inhomogeneities or natural and man-made electric currents. The input into the model consists of layer depths and resistivities including the resistivity of the geoelectric basement (the infinite layer). The output consists of a listing of simulated apparent resistivities for specified AB/2 distances equally spaced at the rate of six per log cycle.

The output from this program was plotted on log-log paper and the points were connected by a continuous curve. The plotted curve is the simulated VES curve that would be expected for the model geoelectric section at the site. A portion of this simulated VES curve was digitized at a rate of six equally-

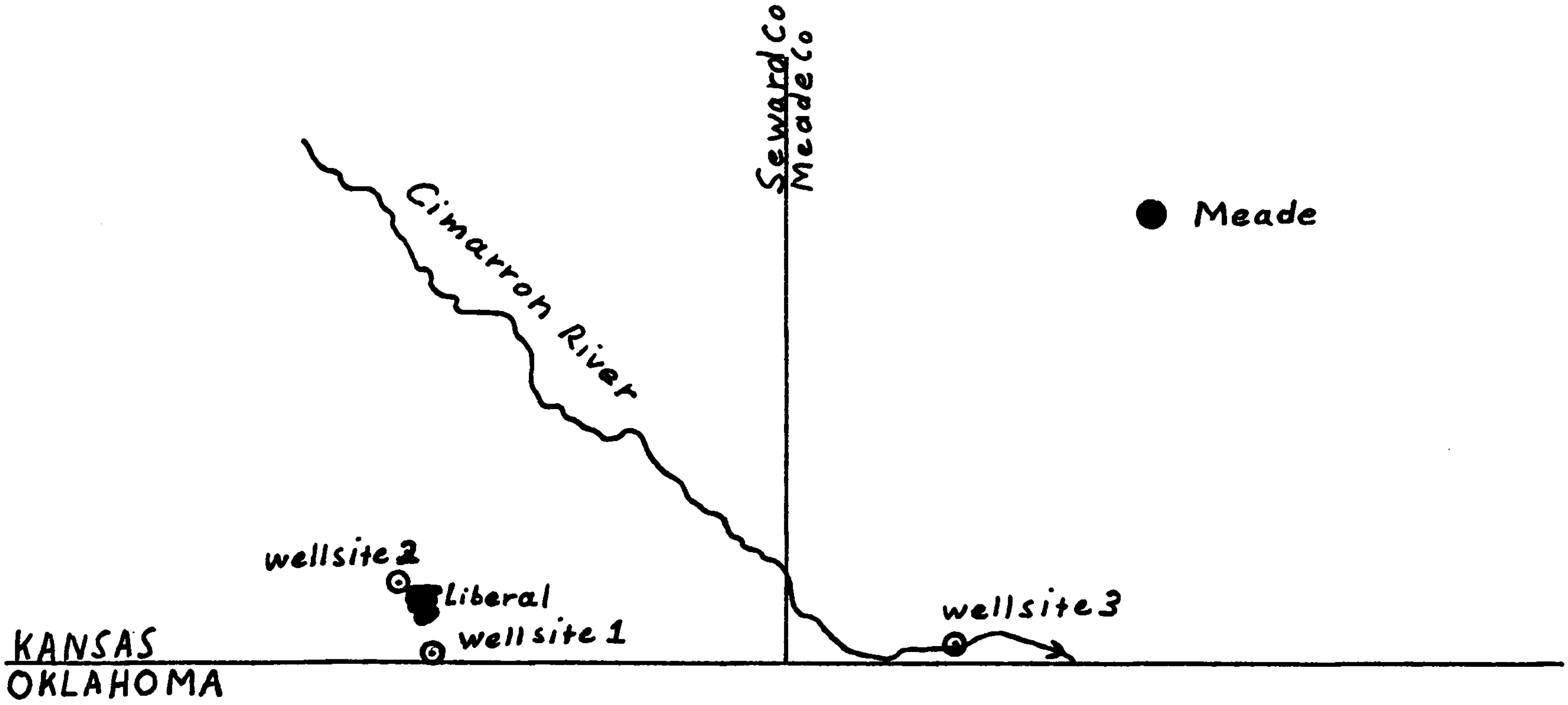

Cimarron River
Seward Co
Meade Co
Meade
wellsite 2
Liberal
wellsite 1
wellsite 3
KANSAS
OKLAHOMA

Figure 1

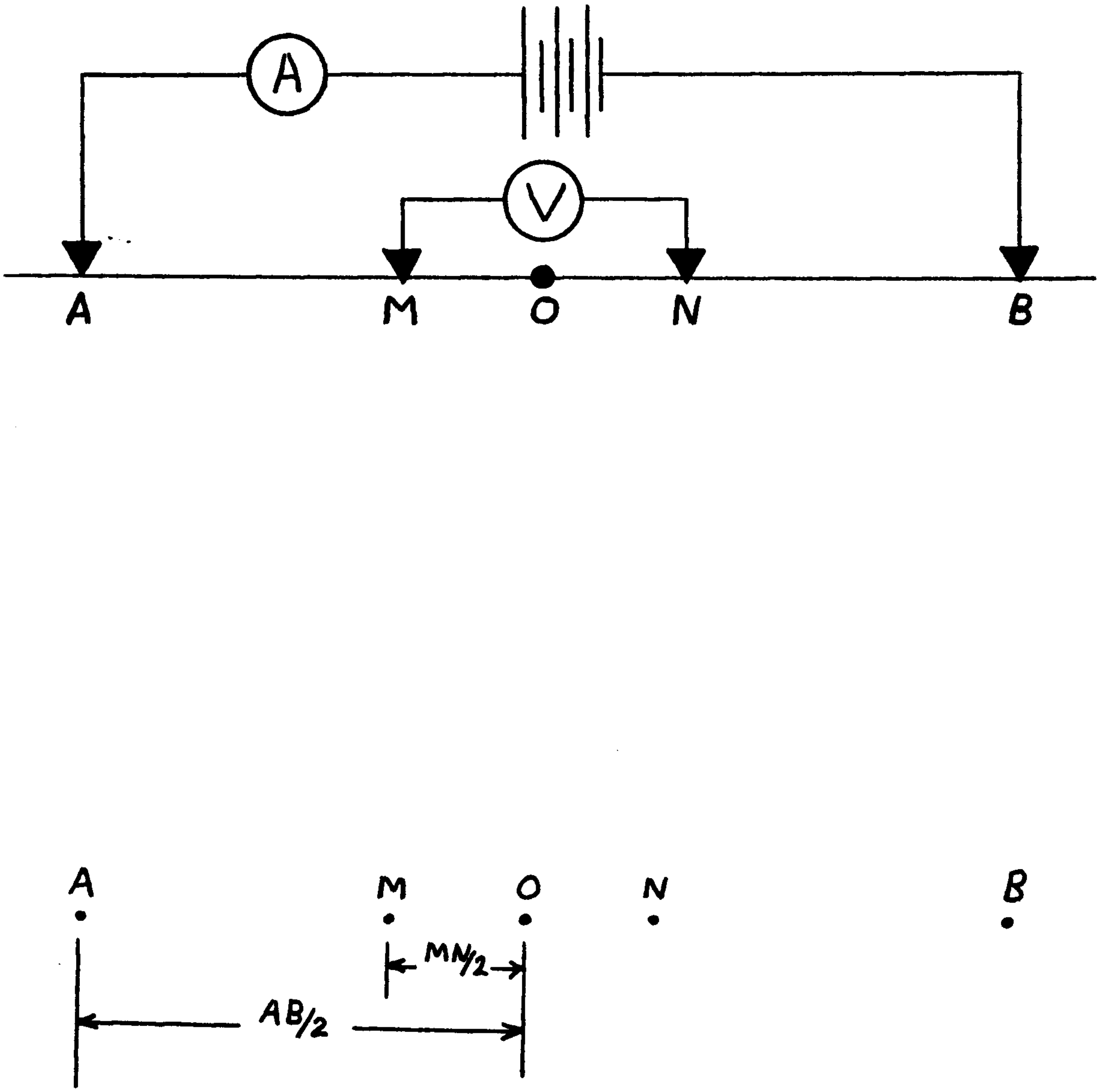


Figure 2.

spaced points per log cycle beginning at the far end of the right branch and moving to the left. The digitized points were used as the input into a modified version of Zohdy's (1973) computer program for the inversion of Schlumberger VES curves. Details concerning this automatic inversion technique can be found in Zohdy (1975). The output from this program consists of 1) a detailed layer solution of the interpreted smoothed VES curve, 2) a detailed layering for the site, and 3) a reduced layer solution calculated from the detailed layer solution. The reduced layer solution is calculated by combining some of the layers in the detailed solution into a geoelectrically equivalent but simpler solution.

Each modeled site in the text is summarized graphically and illustrates: 1) the sequence of geoelectric layers showing layer thicknesses and resistivities from the well logs; 2) the simulated VES curve for a Schlumberger array derived from the sequence of geoelectriv layers; 3) the detailed layer solutions to the simulated VES curve from the automatic interpretive program; and 4) the reduced layer solution shown as a segmented horizontal bar showing layer depths and resistivities.

RESULTS

Well Site 1: NW 1/4, NW 1/4, SE 1/4, Sec. 16, T35S, R33W, Seward County

A simulated VES curve for a Schlumberger electrode array was produced by forward calculation using the layer resistivities and thicknesses for this site described in Table 1. The resulting VES curve is shown as a continuous curve from AB/2 = 1 to 3162 feet in Figure 3 along with the original model (solid line bar graph), and the detailed and reduced layer solutions (dashed line bar graph and horizontal bar, respectively). The VES curve has a fairly flat, gently sloped left limb which begins to dip rather steeply downward beginning at AB/2 = 600 feet.

Figure 3. Resistivity model, simulated VES curve and automatic interpretation of the VES curve for Site #1.

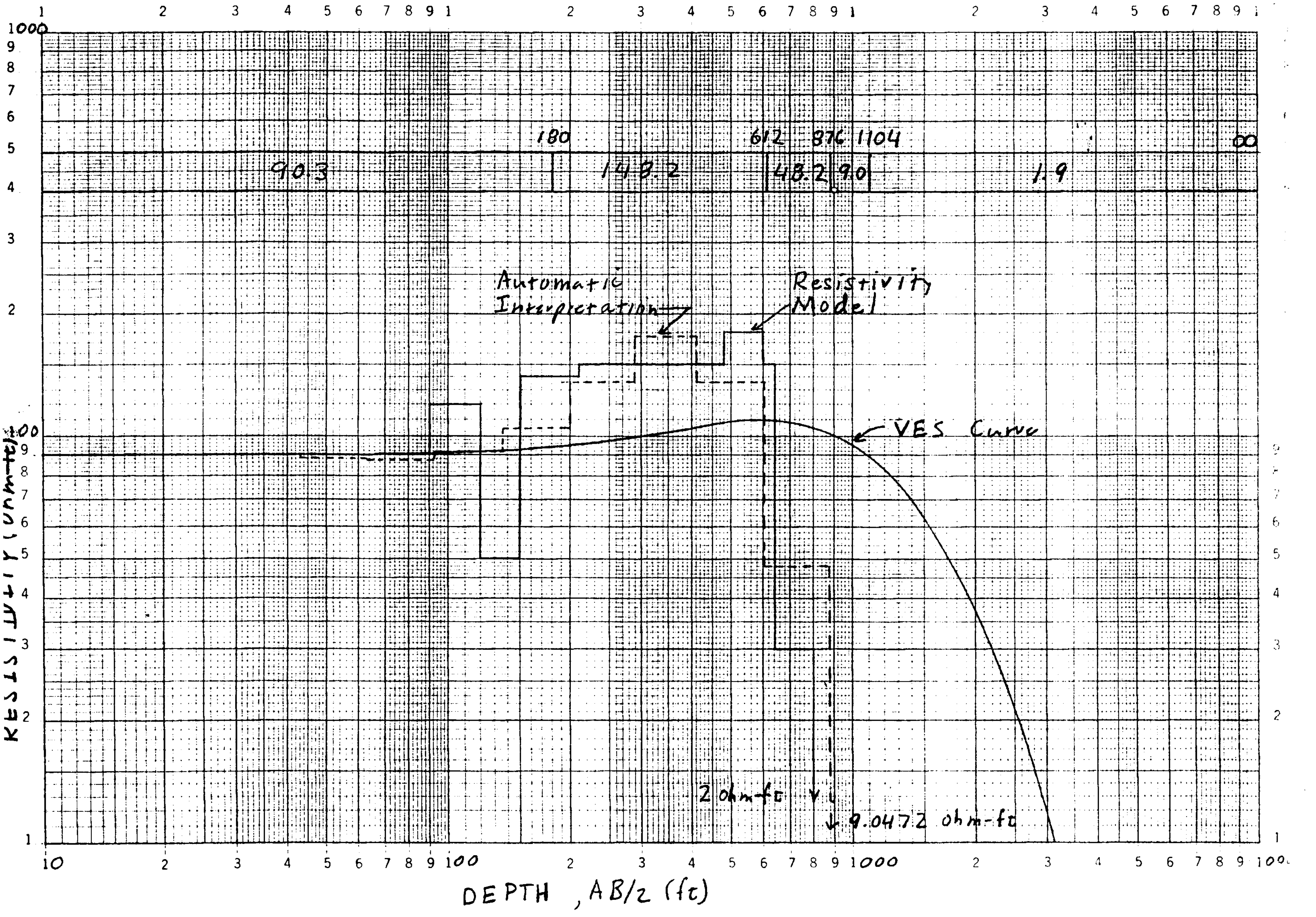


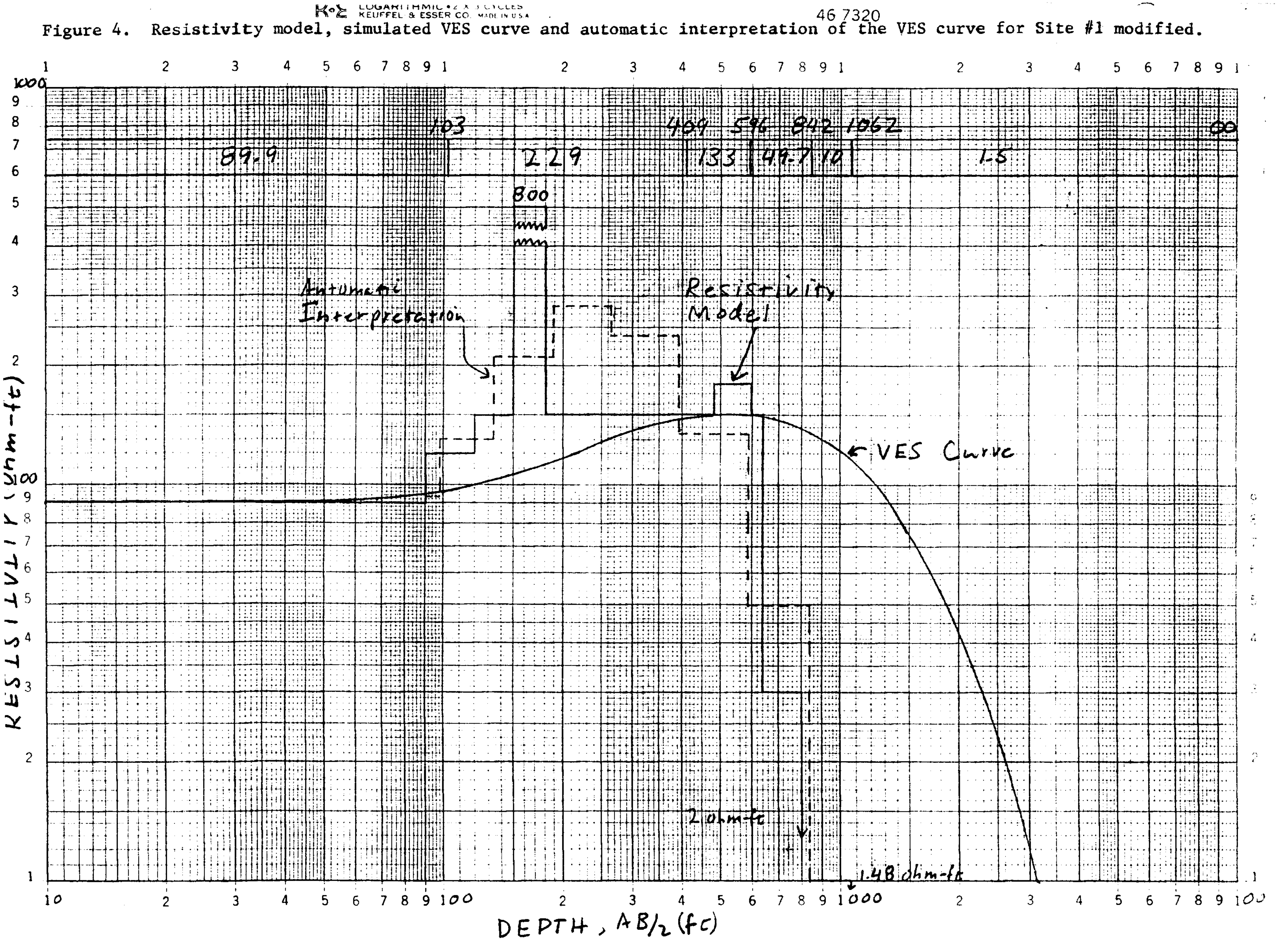
Table 1. Drillers' log, layer depths, and model resistivities at well site 1, NW 1/4, NW 1/4, SE 1/4, Sec. 16, T35S, R33W, Seward County

Drillers' Log	Depth to the Bottom (feet)	Model Resistivity (ohm-feet)
top soil, clay	90	90
clay, fine sand	120	120
clay	150	50
sand, clay	210	140
fine sand	480	150
fine sand	600	180
fine sand	640	150
Permian redbeds	800	30
geoelectric basement	∞	2

A section of this VES curve was digitized from AB/2 = 10 to 2,000 feet and interpreted using the inversion program. The detailed and reduced layer solutions show several interesting features when compared with the original geoelectric section. The depth to the top of the Permian redbeds is overestimated by approximately 60 feet (+9.4%). Layer 2 of the model is not discriminated in either the detailed or reduced layer sections. Also the thickness of the higher resistivity (greater than 100 ohm-feet) portion of the model is thinner and has been assigned a slightly higher true resistivity in the interpreted section.

In the second model for this well site layers three and four of the original model have been given higher true resistivities (150 and 800 ohm-feet, respectively) and the thickness of layer 4 has been reduced from 60 to 30 feet (Fig. 4). Such layers might correspond to a thick gravel layer. The simulated VES curve has the same general shape as the original model but peaks at a higher apparent resistivity value in the vicinity of AB/2 = 550 feet.

Figure 4. Resistivity model, simulated VES curve and automatic interpretation of the VES curve for Site #1 modified.



The simulated VES curve was digitized from AB/2 = 10 to 2,000 feet and inverted using the modified inversion program. The detailed and reduced geoelectric layer solution are presented in Figure 4 as a dashed line and horizontal bar respectively. Neither method of layering shows the presence of the 800 ohm-feet layer. However, since higher resistsivity layers appear in the detailed solution below the high resistivity layer, the inversion process seems to have calculated an alternate electrically equivalent solution to the simulated VES curve. also, the depth to the top of the Permian bedrock is underestimated by 44 feet (-6.9%).

Well Site 2: SE 1/4, SE 1/4, SW 1/4, Sec. 30, T34S, R33W, Seward County

A 14-layer earth model was used to describe the subsurface layering at this site (Table 2). Figure 5 shows the resulting simulated VES field curve produced forward calculation of apparent resistivity with a Schlumberger array. This curve gently undulates up to approximately AB/2 = 700 feet before the curve begins to descend.

The detailed and reduced layer solutions of this simulated VES curve from AB/2 = 10 to 2,000 feet is shown in Figure 3. The inversion program interprets six layers at this site. Depth to the top of the Permian redbeds is overestimated by 199 feet (+29.7%). Quite possibly digitizing the remainder of the field curve out to AB/2 = 3,000 feet would correct the overestimation of depth. Notice also that the 25-foot thick, 300 ohm-foot layer does not appear in the interpretation. It appears as though the effective relative thickness of this layer is not sufficient for detection.

In the next run, the resistivity of the last layer was changed from 10 to 500 ohm-feet. This would correspond to zones in the Permian redbeds where

Figure 5. Resistivity model, simulated VES curve and automatic interpretation of the VES curve for Site #2.

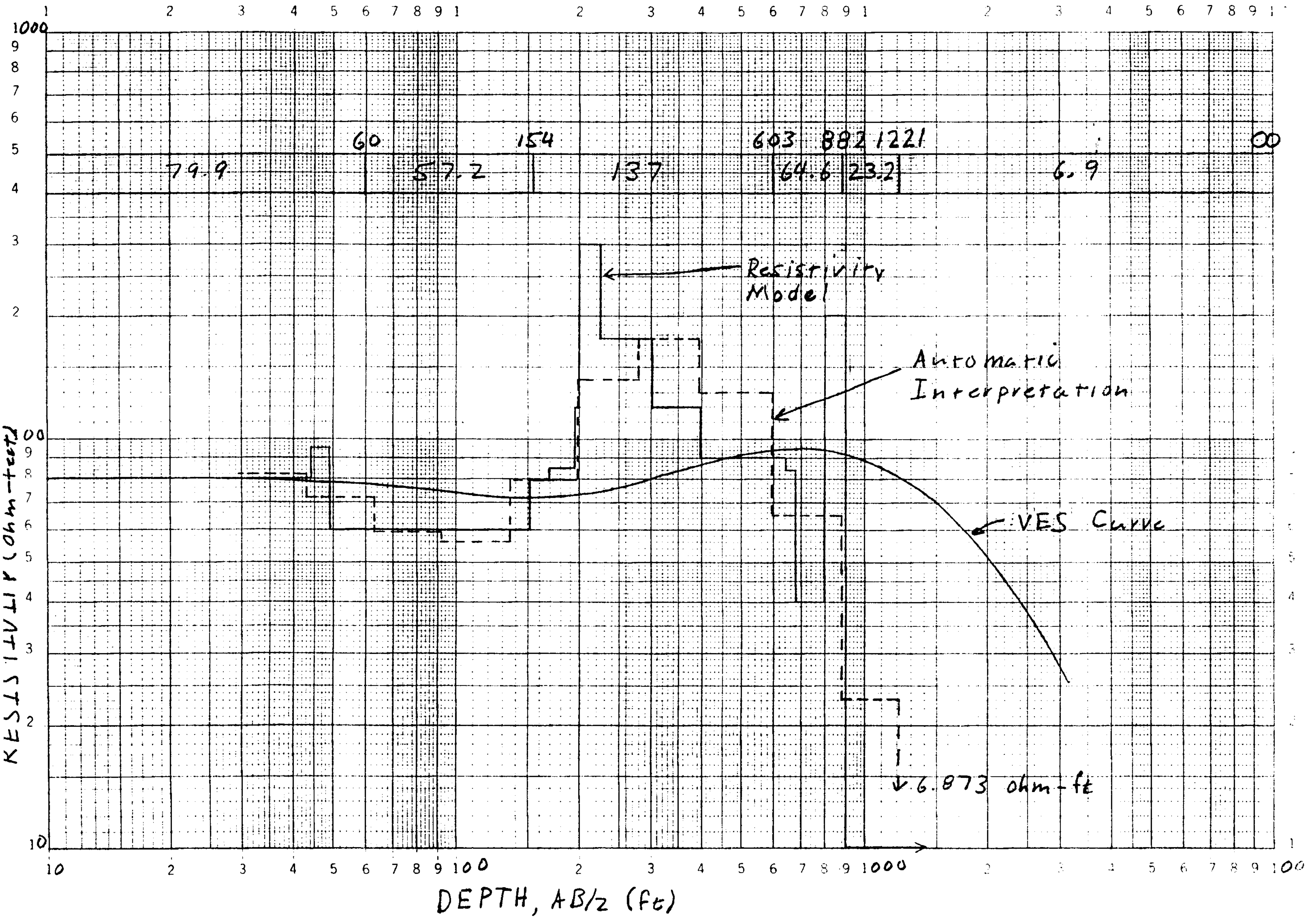


Table 2. Drillers' log and model resistivities at SE 1/4, SE 1/4, SW 1/4, Sec. 30, T34S, R33W, Seward County

Drillers' Log	Depth	Model Resistivity
top soil	4	80
fine sand and clay	49	95
tan clay	153	60
white clay; caliche	168	80
tan clay; caliche	196	85
fine sand	200	120
coarse sand	224	300
clay and sand	301	175
fine sand	396	120
fine sand	636	90
fine sand; clay	670	85
Permian redbeds	800	40
Permian redbeds interbedded with evaporites and dolomite	900	200
geoelectric basement	∞	10

interbedded evaporites and dolomite are present some distance below the top of the subcropping Permian (Fig. 6). Ths salient feature of this VES curve is a steadily rising right limb for AB/2 > 1,000 feet.

The automatic interpretation of a section of the curve from AB/2 = 10 to 2,000 feet shows that the top of the Permian redbeds cannot be determined from the VES curve (Fig. 6). Instead shallower higher resistivity layers have been substituted. Also the depth to the high resistivity basement is overestimated by 417 feet (+46.3%). Possibly a better depth estimate might be obtained if the remainder of the right-hand portion of the curve is added to the interpretation.

Well Site 3: NE 1/4, NE 1/4, NE 1/4, Sec. 13, T35S, R30W, Meade County

A six layer resistivity model was used to simulate the Schlumberger sounding at this site (Table 3). The simulated field curve is asymmetrical, has steeply sloped left and right limbs, and peaks at AB/2 = 600 feet (Fig. 7). The simulated VES curve shows asymptotic behavior beginning at AB/2 = 400 feet.

Table 3. Drillers' log, layer depths (ft.) and model resistivities (ohm-ft) at well site NE 1/4, NE 1/4, NE 1/4, Sec. 13, T35S, R30W, Meade County.

Drillers' Log	Depth	Model Resistivity
soil	4	80
gravel	18	600
gravel and sand	38	400
gravel and clay	78	300
Permian redbeds	300	40
geoelectric basement	∞	20

The detailed and reduced resistivity layer interpretations are shown in Figure 7. The depth to the top of the Permian redbeds is overestimated by 27 feet (+34.6%). The true resistivities of the shallow layers (less than 10 feet in depth) are not correctly interpreted possibly because the simulated field curve was not digitized below 10 feet. Also the thickness of the highly resistive 600 ohm-feet layer is reduced somewhat in the detailed and reduced interpretations. It is also interesting that a relatively low resistivity (approximately 26 ohm-feet) layer appears in the detailed solution below the base of the gravel and a relatively thin very high resistivity layer (1066 ohm-feet) is interpreted within the gravel.

Figure 6. Resistivity model, simulated VES curve and automatic interpretation of the VES curve for Site #2 modified.

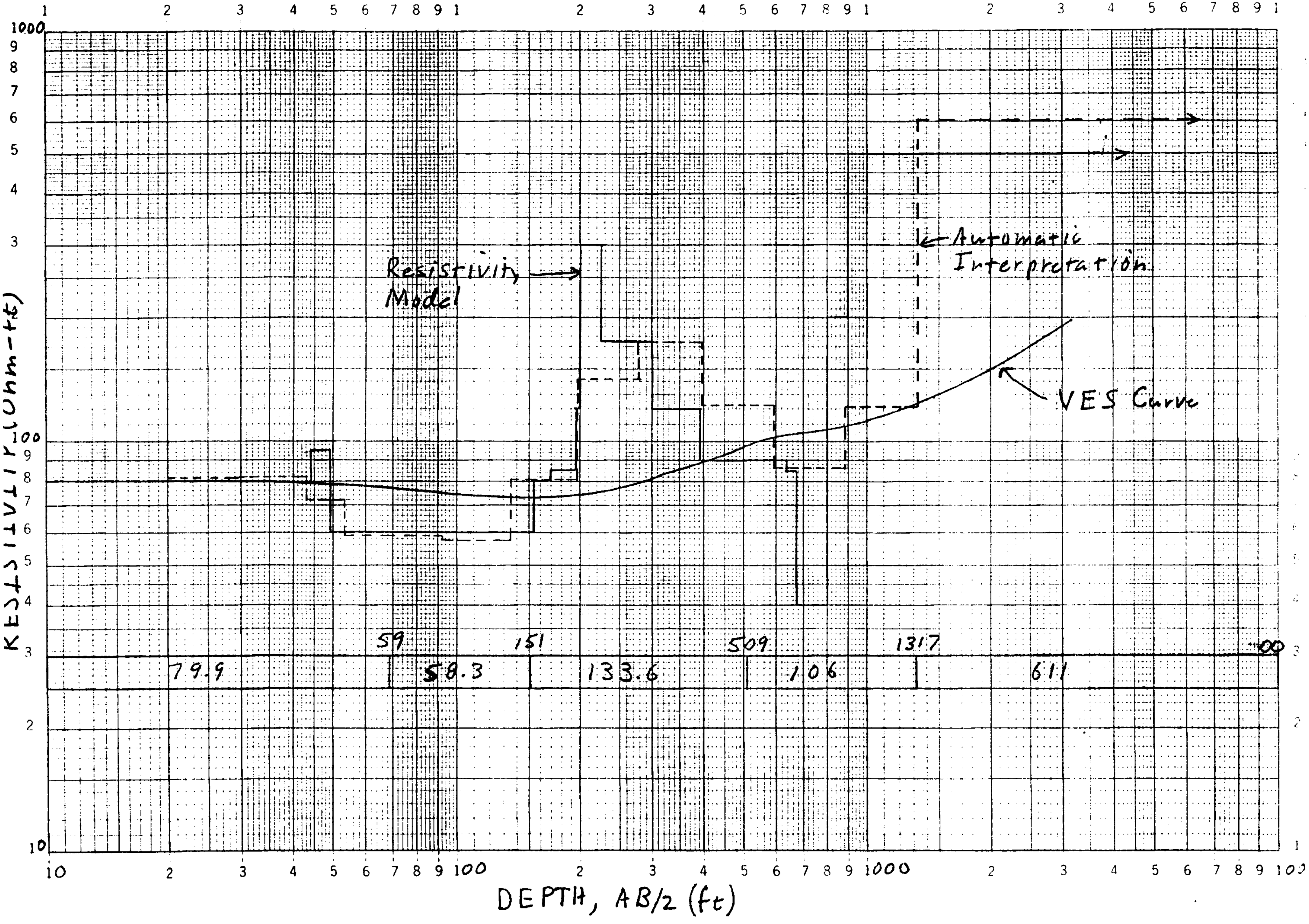
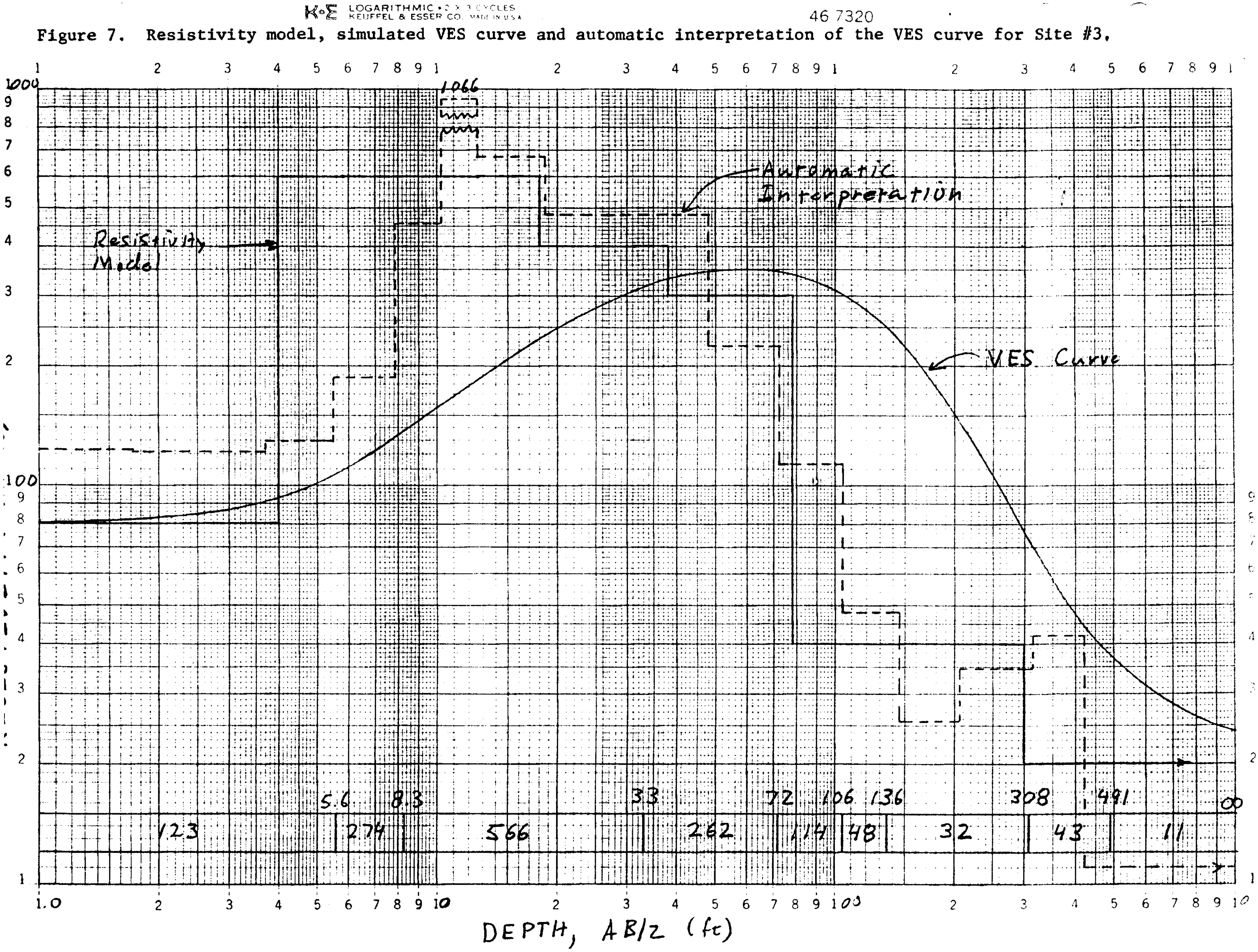


Figure 7. Resistivity model, simulated VES curve and automatic interpretation of the VES curve for Site #3.



DISCUSSION OF RESULTS

The purpose of this short study was to evaluate the feasibility of using Schlumberger electrical soundings to determine the depth to the top of the Permian redbeds in southeast Seward and southwest Meade counties in Kansas. In order to ascertain feasibility, VES curves of several geoelectrical models of layered sequences reflecting a range of geologic conditions in the subsurface were interpreted and compared with the original models. Only the portion of the VES curve from AB/2 = 10 to 2,000 feet (or in one case, to 800 feet) was used in the inversion process. This assumes that only these portions of the curves were available for digitizing. In the field readings are usually taken beginning at AB/2 = 10 feet and AB = 2000 feet was considered to be the maximum spread length for the array.

Generally where the thickness of unconsolidated sediments ranges from 600 to 800 feet an AB/2 = 2,000 to 3,000 feet should be sufficient to determine the depth to the top of the Permian redbeds in the area under study. Electrical resistivity methods seem to be able to discriminate the top of the Permian redbeds quite well, even though shallow high resistivity layers may be present. These layers might be sand and gravel, gravel, or other material, but are generally not seen on the interpreted sections. Also, the top of the Permian can be discriminated even if there is a highly resistive, relatively thin layer near the top of the Permian redbeds. However, the resistivity of the infinite layer (geoelectric basement) below the highly resistive layer must approach zero. The top of the Permian redbeds cannot be discriminated where the geoelectric basement has a higher resistivity value than the next to the last layer. Furthermore, the accuracy of the depth to the top of the Permian depends upon the thickness and resistivity of layers introduced into the geoelectric sequence by the automatic interpretation process. At well site 1 the top of the Permian was estimated to be 104 feet shallower when high resistivity layers were introduced into the sequence. In such cases, the layering can be changed to an electrically equivalent solution if other geologic or geophysical information is available.

Automatically interpreted VES curves will seldom correspond to the original models for two reasons. The digitized VES curve may not be extended far enough to the left or right to approach asymptotic values of resistivity or to have a complete terminal branch. This usually causes over or underestimation of depth and resistivity of the first and last layers in the interpreted section at the least. Often other layer boundaries and resistivities are affected. The automatic inversion technique can also interpret alternate solutions which are quite different from reality. This can occur because the geoelectric effect of thin relatively high or low resistivity layers in a given sequence may be suppressed or because the inversion technique calculates an electrically equivalent section.

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