Kansas Geological Survey

COMPARISON OF SURFACE AND DOWNHOLE ELECTROMAGNETIC INDUCTION MEASUREMENTS IN THE GREAT BEND PRAIRIE, KANSAS: NOTES ON VERTICAL INTERPRETATIONS OF EM34 MEASUREMENTS

by

David P. Young

Kansas Geological Survey Open-File Report 95-49b

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The Mineral Intrusion Project is a cooperative project between the Kansas Geological Survey and Big Bend Groundwater Management District No. 5, conducted with the support of the Kansas Water Office

Comparison of Surface and Downhole Electromagnetic Induction Measurements in the Great Bend Prairie, Kansas: Notes on Vertical Interpretations of EM34 Measurements

David P. Young

ABSTRACT

Electromagnetic induction (EM) surveys using ground conductivity meters are a relatively quick and inexpensive method of assessing ground conductivity, which is dependent on such factors as clay content and type, soil moisture, and salinity. Downhole EM logs provide superior vertical resolution and depth range, but require a well or borehole of appropriate depth and construction. As part of a study on saltwater intrusion into the Great Bend Prairie aquifer in south-central Kansas, a surface EM survey was conducted at two sites where downhole natural gamma and EM logs were available as ground truth. Both sites have relatively thick (8 to 9 m) near-surface clay zones; the transition from freshwater to saltwater begins at a depth of approximately 10 m at one site and 40 m at the other. Depth of exploration for the Geonics EM34 used in this survey is controlled by the coil spacings and dipole orientations. In theory, the maximum depth of exploration is about 30 m in the horizontal dipole orientation (HDO) and 60 m in the vertical dipole orientation (VDO). In practice, the depth of penetration is dependent on many factors related to the conductivity profile in the subsurface.

Comparison with downhole logs indicates that measurements in the HDO were representative of the conductivity trend with depth, and detected the shallow (10 m) saltwater interface. At least qualitative interpretations can be made directly from HDO measurements. The shallow interface was detected in the deep VDO measurements, but resolution was better in the HDO. Measurements in the VDO did not detect the deeper (40 m) saltwater interface. The lack of detection is attributed to 1) the depth to the interface and 2) the relatively thick near-surface clay, a high-conductivity zone that may dominate the response of the meter. Where such high-conductivity near-surface zones are present, the effective depth of exploration in the VDO may be much less than the theoretical exploration depth of 60 m and more nearly comparable to the HDO exploration depth of 30 m. Measurements in the VDO also are more subject to other uncertainties, such as a severe breakdown of the linear response at high conductivities and sensitivity to misalignment of the coils. While the HDO is effective for shallow interface detection, the VDO may be less reliable, particularly in environments where near-surface high-conductivity zones are present.

INTRODUCTION

As part of the Mineral Intrusion project, an integrated ground conductivity survey was conducted in the Great Bend Prairie. The study consisted primarily of terrain conductivity surveys using electromagnetic (EM) ground conductivity meters. The meters used were the Geonics EM34, with a maximum theoretical exploration depth of 60 m, and the Geonics EM38 for very shallow subsurface measurements. In addition, the specific conductance of surface water was measured in a five-mile stretch of Rattlesnake Creek. Figure 1 shows locations of the surveyed areas, which are in Stafford County.

Detailed site information and EM34 results are presented by Rohs and Kruger (1995); the EM38 survey by Sleezer (1995); and the Rattlesnake Creek survey by Young and Healey (1995). This report compares EM34 measurements with downhole EM logs at the Siefkes and Witt sites. Geohydrologic and other information from these sites may be found in previous Mineral Intrusion project reports.

The use of inductive EM techniques is becoming more common in groundwater studies. Hydrologic applications of the terrain or surface EM method include mapping natural saline intrusions and freshwater/saltwater interfaces (Gillespie and Hargadine, 1994; McNew and Arav, 1995; Stewart, 1982, 1988), and mapping anthropogenic pollution plumes in ground water, particularly at landfill sites and in the oilfield environment (Sweeney, 1984; Newman, 1995).

The primary advantage of surface EM over traditional resistivity techniques lies in the speed in which a reconnaissance survey can be carried out to various depths of exploration (McNeill, 1983). The ground conductivity meters are portable, do not require ground contact, and give direct readout of conductivity in the field. Consequently, lateral changes in conductivity can be assessed quickly over large areas. As with any method, the most useful information can be obtained when EM is used in conjunction with other techniques. Potential benefits of using EM surveying as a first-pass investigation in groundwater studies include fewer and better-located monitoring wells.

A significant disadvantage of inductive EM techniques is that variation of conductivity with depth is not well resolved (McNeill, 1992). According to a technical note from the manufacturer, "The instrument was not designed for detailed sounding of vertical variations of conductivity with depth but will give useful results where the earth can be approximated by a two-layer model. For more complicated vertical variations, conventional resistivity techniques must be used." (McNeill, 1983). As a result of the limited vertical sounding capability, vertical interpretations of the data are difficult.

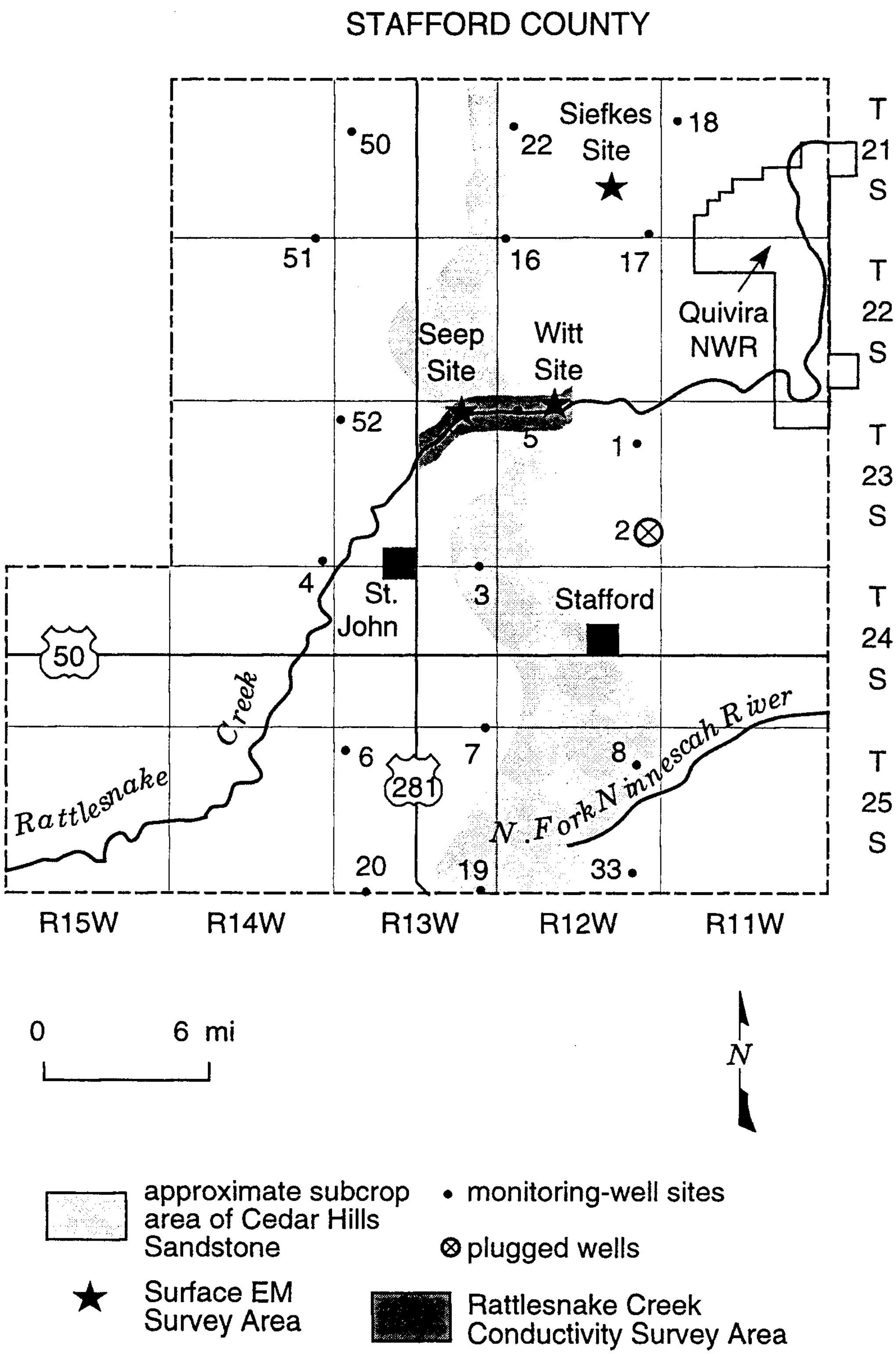


Figure 1. Locations of conductivity survey areas and other physical features.

PRINCIPLE OF OPERATION AND INSTRUMENTATION

Principle of operation and instrumentation are explained in detail by McNeill (1980a). Basically, the surface or terrain EM method uses electromagnetics to measure the apparent ground conductivity, which varies depending on the type of subsurface material and the interstitial water contained within it. The response of the received signal is linearly proportional to ground conductivity based on the assumptions of operation at low induction numbers described by McNeill (1980a), so that the meters give a direct readout of apparent conductivity. An assumption inherent in the method is that the earth consists of horizontal layers of uniform conductivity.

EM instruments measure bulk soil conductivity, which is affected by volumetric water content, salt concentration of the soil water, clay content and type, temperature, and the distribution of these properties in the profile (Cook et al., 1989; McNeill, 1980b). At any given site, unsaturated surface material has lower conductivity than saturated material, and units that contain saltwater are more conductive than units that contain freshwater (McNew and Arav, 1995). In areas where the porewater is not particularly saline, the electrical properties of the soil may be strongly influenced and in some cases completely dominated by the amount and type of clay minerals present (McNeill, 1980b).

Using different spacings and coil configurations, operators can vary the depth of exploration of the EM34. The two coil configurations are referred to as the horizontal dipole orientation (HDO) and the vertical dipole orientation (VDO). About 70% of the instrument response comes from material above the exploration depth, which is equal to 0.75s for the HDO and 1.5s for the VDO, where s is the intercoil spacing. In theory, for a uniform earth, increasing the dipole separation and decreasing the frequency increases the depth from which a response will be received as in Table 1 (McNeill, 1980a). In practice, the depth of penetration is dependent on many factors, mostly related to the conductivity distribution in the subsurface (Street and Engel, 1991). Also, the equipment is sensitive to interference by electrical and metal objects such as electrical lines and metal pipelines.

Table 1. Exploration depths for EM34 at various intercoil spacings (from McNeill, 1980a).

	Exploration Depth (m)	
Intercoil Spacing (m)	Horizontal Dipoles	Vertical Dipoles
10	7.5	15
20	15	30
40	30	60

Relative response curves for both dipole orientations are shown in Figure 2 (McNeill, 1980a). These curves describe the relative contribution to the apparent conductivity from material at any depth z. Notice that the x-axis is depth (z) divided by intercoil spacing (s).

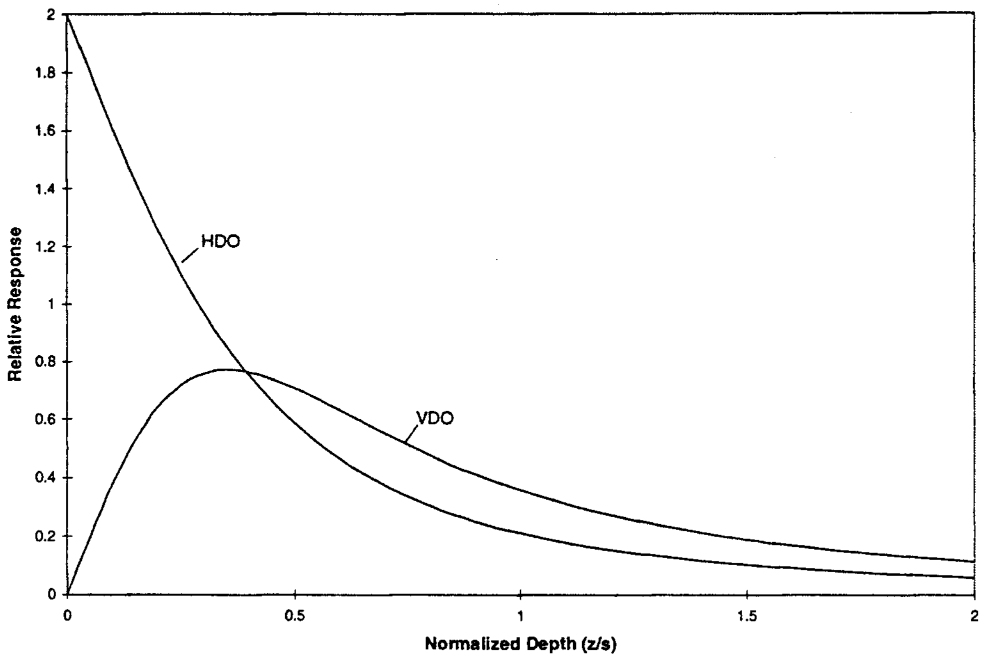


Figure 2. Relative response curves for the EM34 (McNeill, 1980a).

In the VDO, material located at a depth of approximately 0.35s gives the maximum contribution, and near-surface material makes a very small contribution. On the other hand, in the HDO configuration, the relative contribution from near-surface material is large and the response decreases with depth.

At moderately high values of terrain conductivity the linear relationship between indicated conductivity and actual conductivity breaks down. This effect is more severe for the VDO mode of operation (McNeill, 1980a; 1983). Measurements in the VDO are also more sensitive to misalignment of the coils. McNeill (1992) recommends that the EM34 be operated only in the HDO in the conductive conditions generally associated with soil salinity.

In mapping the depth to freshwater/saltwater interfaces, Stewart (1988) found that the VDO is not appropriate for use in high conductivity areas due to the breakdown of the assumption of a linear relationship between terrain conductivity and instrument response. This limits the depth of investigation to 30 m or less. Groundwater studies using the EM34 tend to rely on HDO measurements for vertical interpretations (Goldstein et al., 1990; Paine et al., 1994; Stewart, 1982, 1988; Sweeney, 1984). Stewart (1988) also pointed out problems with interpretations where high-conductivity zones (clay layers) are present within the freshwater zone.

Generally vertical interpretations of EM data make use of layered-earth models (i.e., models consisting of two or more horizontal layers of uniform conductivity). The forward solution, which is commonly used, consists of a system of mathematical equations that will duplicate instrument readings from a given description. It requires the thickness, conductivity, and numbers of layers to be selected. Making these choices with respect to changes in soil type and water quality can be virtually impossible (McNew and Arav, 1995). Layered-earth models are subject to considerable error (Cook and Walker, 1992), not the least of which is the nonuniqueness of model solutions (McNew and Arav, 1995). A conceptual model and judgement are required in the interpretation (even) if layered-earth models are used.

METHODS

Methods and results of the EM34 survey are presented by Rohs and Kruger (1995). Lateral variations in conductivity are discussed in that report. This report compares EM34 measurements with downhole logs at the two sites where downhole logs (natural gamma and EM) were collected as ground truth.

A number of approaches were taken to test for and improve the relation between surface and downhole EM measurements:

Method 1. An attempt at vertical interpretations of the EM34 data was made using 2-layer model solutions proposed by McNeill (1983). In conjunction, a qualitative vertical trend analysis was performed by visually comparing downhole logs with EM34 measurements plotted at their theoretical exploration depths.

Method 2. EM34 measurements were compared with average conductivities (from the downhole logs) to the theoretical exploration depths listed in Table 1.

Because of the poor correlation between VDO measurements and downhole conductivities in Methods 1 and 2, the following approaches were taken in an attempt to improve the correlation in the VDO:

Method 3. Downhole EM logs were weighted using the relative response curve for the VDO (Fig. 2), and EM34 VDO measurements were compared with the mean weighted responses. Weighted responses were calculated by multiplying the relative response by the average downhole conductivity at 1-meter intervals. This was done for all three intercoil spacings. Next the mean weighted response (MWR) down to each theoretical exploration depth was calculated by dividing the sum of the weighted responses by the sum of the relative responses for each spacing.

Method 4. Again using the relative response curve for the VDO, a new concept--the "focused depth range"--was developed, and VDO measurements were compared with average downhole conductivities over different focused depth ranges. If we study the VDO relative response curve (reproduced in Figure 3), we can see the depth range(s) over which the response is most strongly focused. If we examine the curve where the relative response is greater than a certain value (for example, 0.5, for which the figure was produced), a corresponding focused depth range exists. For example, the portion of the curve where the relative response is greater than 0.5 corresponds to a depth range of 0.15s to 0.75s.

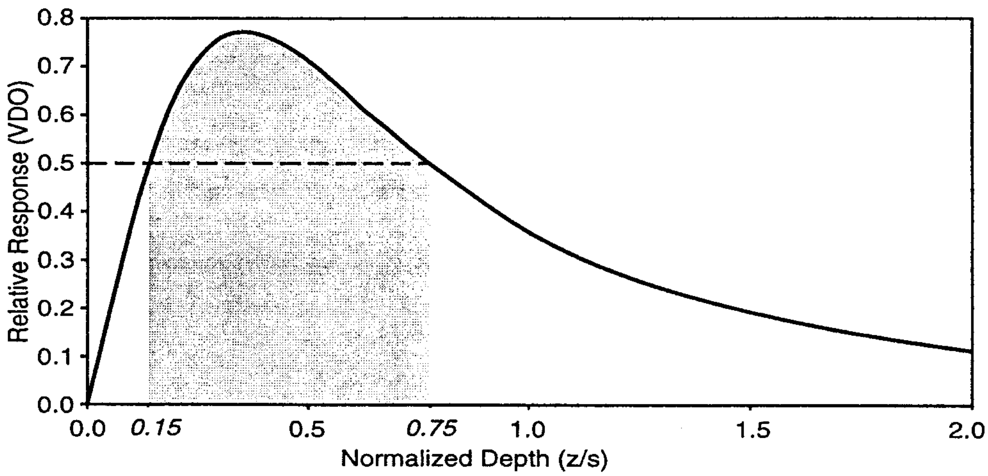


Figure 3. Relative response curve for the VDO highlighting the "focused depth range" where the relative response is greater than 0.5.

From the relative response function, focused depth ranges were calculated for relative responses greater than 0.3, 0.4, 0.5, 0.6, and 0.7. The depth ranges are listed in Table 2. The questions to answer were 1) how did the downhole conductivity over these depth ranges compare with the respective EM34 measurements, and 2) over which focused depth range did the downhole conductivity have the highest correlation with the EM34 measurements. To do this, the EM34 measurements were compared with the average conductivities from the downhole logs over each of the corresponding focused depth intervals (Table 2).

Table 2. Focused depth ranges for VDO based on relative response curve.

	Focused Depth Range (m)		
Relative Response	10 m spacing	20 m spacing	40 m spacing
> 0.3	1-11	2-22	4-44
> 0.4	1.5-9	3-18	6-36
> 0.5	1.5-7.5	3-15	6-30
> 0.6	2-6	4-12	8-24
> 0.7	2.5-5	5-10	10-20

Method 5. EM34 VDO measurements were compared with average downhole conductivities to depths shallower than the theoretical exploration depths.

RESULTS

<u>EM34 measurements.</u> EM34 measurements from the two stations nearest the monitoring wells at the Siefkes and Witt sites, and the two-station averages are listed in Table 3.

Table 3. EM34 apparent conductivity measurements (mmho/m) from stations nearest the monitoring wells at the Siefkes and Witt sites.

	Siefkes Site			Witt Site		
HDO						
Intercoil Spacing	Station 1	Station 2	2-Station AVG	Station 1	Station 2	2-Station AVG
10 m	47	49	48	57	63	60
20 m	47	48	47.5	60	59	59.5
40 m	45	49	47	86	83	84.5
VDO						
Intercoil Spacing	Station 1	Station 2	2-Station AVG	Station 1	Station 2	2-Station AVG
10 m	40	40	40	34	34	34
20 m	36	33	34.5	32	27	29.5
40 m	26	33	29.5	47	47	47

Note: corresponding station numbers in Rohs and Kruger (1995) are listed below.
Siefkes: Station 1=SF1:360, Station 2=SF2:0; Witt: Station 1=WT1:0, Station 2=WT1:20

<u>Downhole measurements.</u> Downhole logs (natural gamma and EM) from monitoring wells at the Siefkes and Witt sites are reproduced in Figures 4 and 5. The monitoring wells were installed by the Mineral Intrusion project primarily to identify and track the freshwater/saltwater transition zone at the sites using focused induction EM logging. The wells are screened in the Permian bedrock at both sites. The logs were collected using a Century 9511 probe. See Buddemeier et al. (1993) for logging methods.

Depth to water in the alluvial aquifer is about 4 m at the Siefkes site and 1 m at the Witt site. At the Siefkes site the freshwater/saltwater transition zone begins at a depth of about 40 m. At the Witt site the transition zone begins at a depth of about 10 m. The groundwater is significantly more saline at the Witt site. The chloride concentrations in the Permian wells are 40,000 and 26,000 mg/L at the Witt and Siefkes sites, respectively. Depth to Permian bedrock is 45 m at the Witt site and 57 m at the Siefkes.

The drop in measured conductivity at bedrock depth (see Figures 4 and 5) is primarily due to the lower porosity of the bedrock. It does not indicate that the water is less saline below these depths. The downhole EM tool, like the surface EM meter,

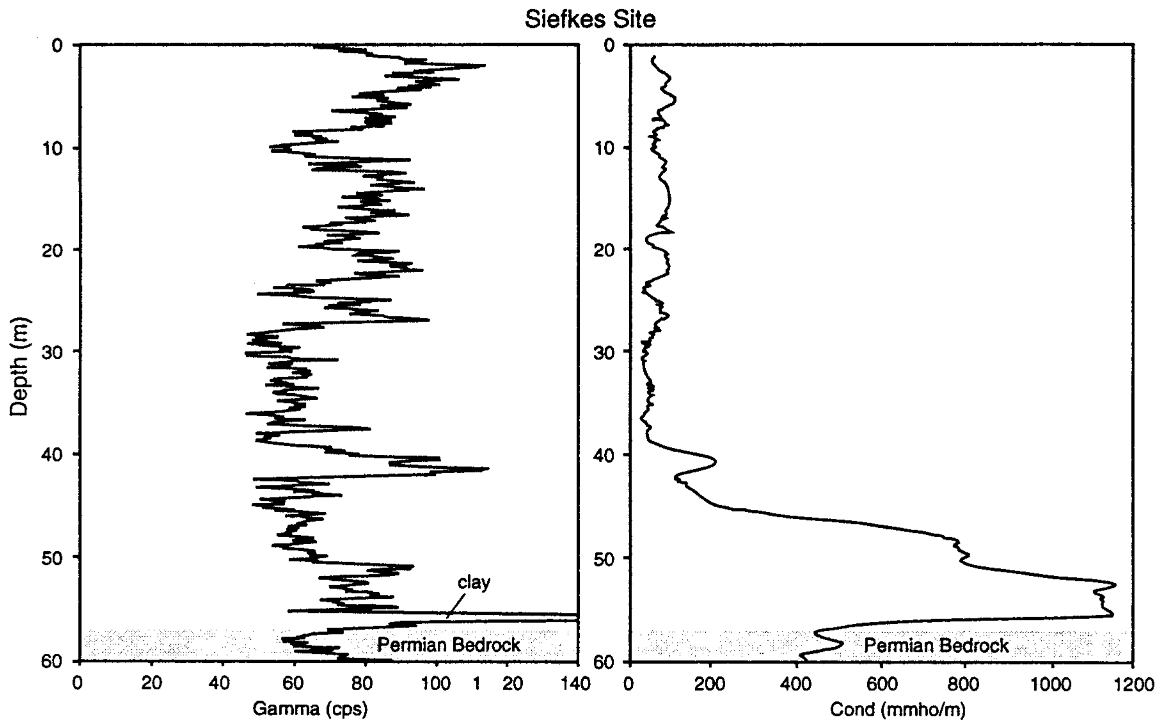


Figure 4. Downhole natural gamma and EM logs from the Siefkes Permian well.

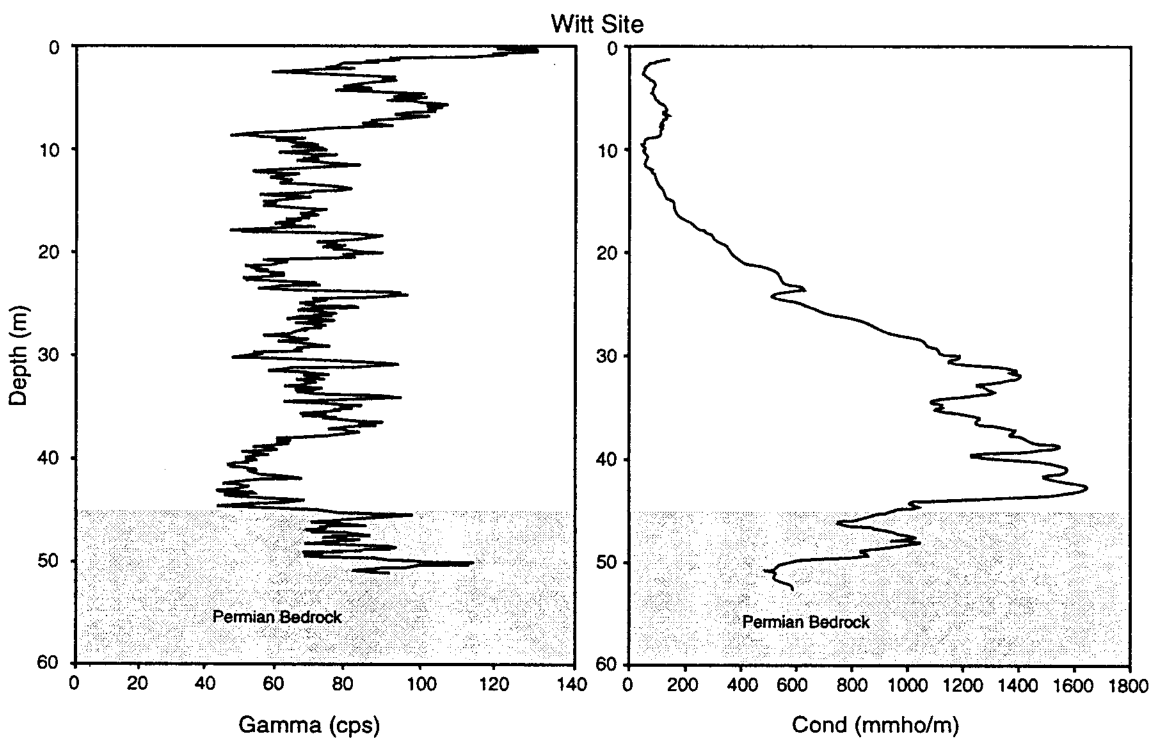


Figure 5. Downhole natural gamma and EM logs from the Witt Permian well.

measures bulk conductivity. At higher salinities, the conductivity of the water overwhelms that of the matrix, which is why freshwater/saltwater transition zones are evident on the downhole logs. Because there is relatively more (nonconductive) rock, less pore space and hence less (salt)water per unit volume in the bedrock formation, the measured bulk conductivity of the bedrock is lower than that of the material above it.

The relatively high-conductivity shallow zone (down to approximately 8 to 9 m) at each site is caused by near-surface clays. This is evident in the cross-correlation between the EM and the gamma log at each site.

Average downhole conductivities over different depth ranges are listed in Table 4. These depth ranges and average conductivities were used for the comparisons in Method 5.

Table 4. Average downhole conductivities over different depth intervals.

Siefkes Site			Witt Site		
Depth Interval (m)		AVG COND (mmho/m)	Depth Interval (m)		AVG COND (mmho/m)
(a)	Top to 7.5	81.7	(a)	Top to 7.5	93.2
	Top to 15	78.0		Top to 15	85.3
	Top to 30	72.5		Top to 30	326.3
(b)	Top to 15	78.0	(b)	Top to 15	85.3
	Top to 30	72.5		Top to 30	326.3
	Top to 60	249.4		Top to Bot	680.4
(c)	Top to 5	79.0	(c)	Top to 5	76.1
	Top to 10	77.4		Top to 10	88.3
	Top to 20	76.3		Top to 20	126.2
(d)	Top to 10	77.4	(d)	Top to 10	88.3
	Top to 20	76.3		Top to 20	126.2
	Top to 40	66.2		Top to 40	574.4

(a) corresponds to theoretical exploration depths for the HDO
(b) corresponds to theoretical exploration depths for the VDO

Method 1. When vertical interpretations of the EM34 measurements were attempted using 2-layer model solutions proposed by McNeill (1983), neither model yielded a satisfactory solution at either site. Shown with the EM logs on Figures 6 and 7 are the EM34 measurements (two-station average) plotted at the theoretical exploration depths given in Table 1. Vertical trend analysis showed that HDO measurements plotted at their theoretical exploration depths were a fairly good representation of the conductivity trend with depth. VDO measurements plotted at their theoretical exploration depths were not representative of the conductivity trend with depth.

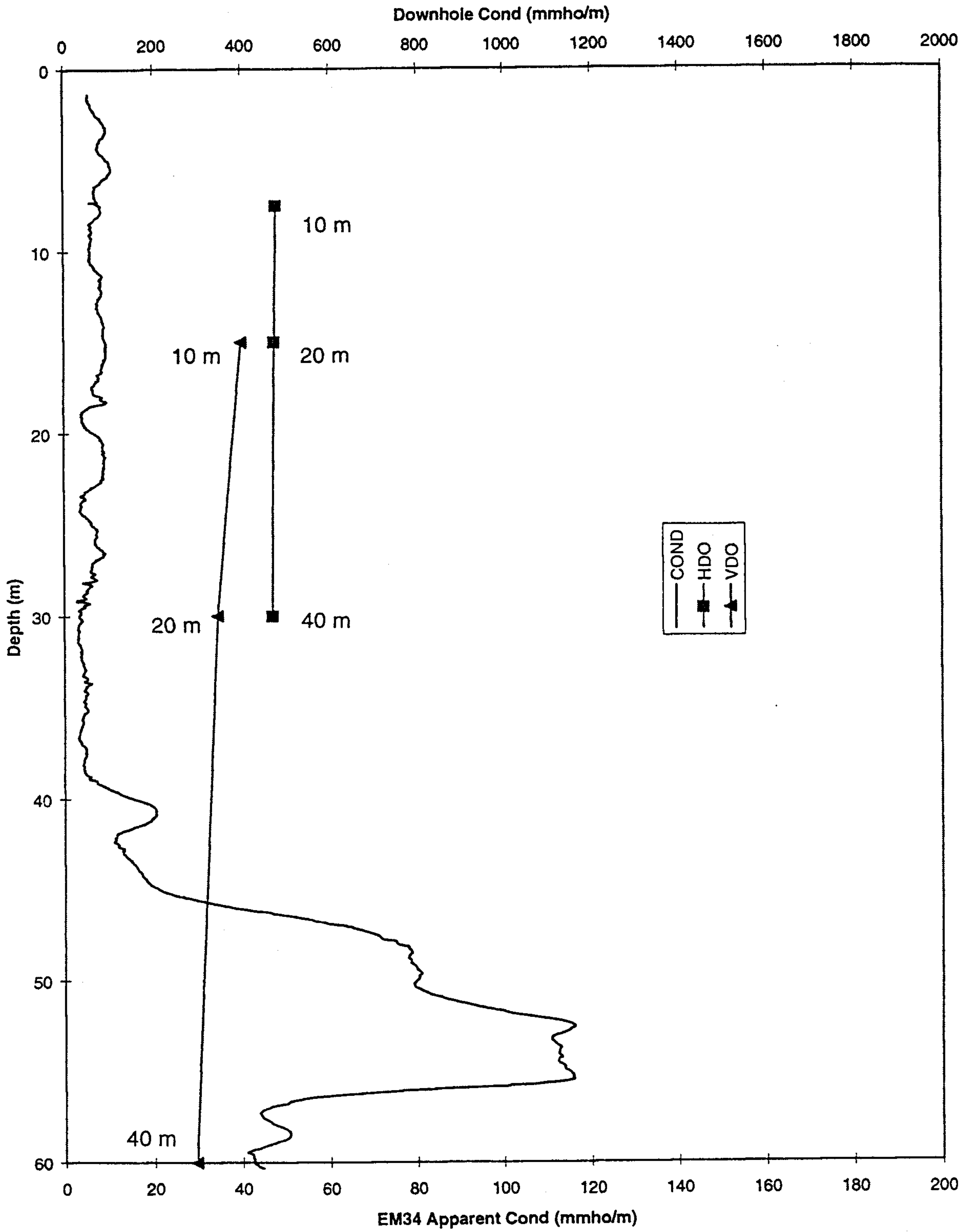


Figure 6. Siefkes site conductivity log shown with EM34 measurements plotted at their theoretical exploration depths.

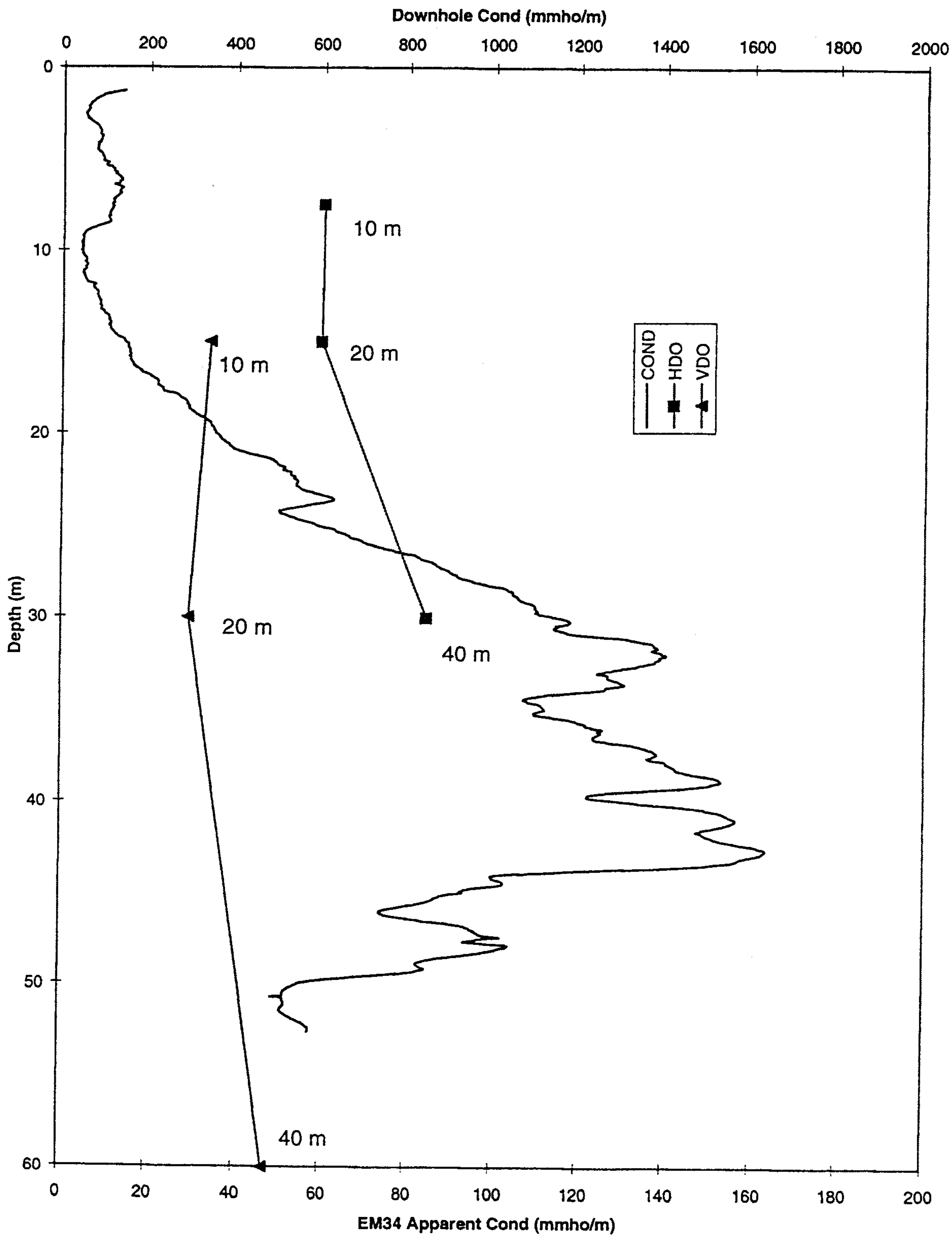


Figure 7. Witt site conductivity log shown with EM34 measurements plotted at their theoretical exploration depths.

Listed in Table 5 are correlation coefficient (r) values for comparisons of EM34 measurements with downhole conductivities via Methods 2-5 discussed above. Correlations were tested at the 10% level of significance. Because the data sets were small, r values are of questionable reliability, however they can be used cautiously to make some qualified generalizations. Also, high correlation coefficients may indicate potentially promising approaches at vertical interpretations of EM34 data that may warrant further testing.

Method 2: Comparison of EM34 measurements with average downhole conductivities to the theoretical exploration depths. HDO measurements generally showed good correlation; VDO measurements showed poor correlation (Table 5). The VDO correlation was negative at the Siefkes site. Figures 8 and 9 show regression lines for HDO and VDO measurements, respectively. The two-station averages from Table 3 were used for these and all other regression plots.

Method 3: Comparison of EM34 VDO measurements with mean weighted responses to theoretical exploration depths. The results and the corresponding VDO measurements are presented in Table 6. VDO measurements still showed poor correlation, including a negative correlation at the Siefkes site (Table 5). Figure 10 shows regression lines for Method 3.

Table 6. Mean weighted responses and corresponding VDO measurements.

Siefkes Site			Witt Site		
Spacing	MWR	VDO	Spacing	MWR	VDO
10 m	71.5	40	10 m	85.8	34
20 m	68.8	34.5	20 m	215.9	29.5
40 m	143.1	29.5	40 m	576.3	47

Method 4: Comparison of EM34 VDO measurements with average downhole conductivities over different "focused depth ranges." There was much better correlation (for the VDO) using this method than any of the above methods (Table 5). In general, the best correlation was found over the focused depth range where the relative response is greater than 0.5. Notice in Table 2 that the lower limits of this "focused depth range" (7.5, 15, and 30 m) are identical to the theoretical exploration depths for the HDO. Regression lines are plotted in Figure 11.

Method 5: Comparison of EM34 VDO measurements with average downhole conductivities to depths shallower than the theoretical exploration depths. In general, the best correlation was found when VDO measurements for the 10, 20, and 40 m spacings were compared with average downhole conductivities to 7.5, 15, and 30 m, respectively (Table 5), which are the same as the theoretical depths for the HDO. Correlation coefficients are comparable to those obtained in Method 4. Regression lines are plotted in Figure 12.

Table 5. Correlation coefficient (r) values for comparisons of EM34 measurements with downhole conductivity via Methods 2-5 described in the text.

Method 2. EM34 measurements vs average conductivity to theoretical exploration depths.

HDO	STATION 1	STATION 2	2-STATION AVG	STATION 1 & STATION 2
Siefkes site	NS (n=3)	NS (n=3)	0.9940 (n=3)	NS (n=6)
Witt site	0.9925 (n=3)	0.9919 (n=3)	0.9999 (n=3)	0.9862 (n=6)
Both sites	0.9393 (n=6)	0.9150 (n=6)	0.9318 (n=6)	0.9243 (n=12)

VDO	STATION 1	STATION 2	2-STATION AVG	STATION 1 & STATION 2
Siefkes site	NS (n=3)	NS (n=3)	NS (n=3)	-0.7451 (n=6)
Witt site	NS (n=3)	NS (n=3)	NS (n=3)	0.7727 (n=6)
Both sites	NS (n=6)	NS (n=6)	NS (n=6)	0.4983 (n=12)

Method 3. EM34 VDO measurements vs mean weighted response to theoretical exploration depth.

	STATION 1	STATION 2	2-STATION AVG	STATION 1 & STATION 2
Siefkes site	NS (n=3)	NS (n=3)	NS (n=3)	-0.7428 (n=6)
Witt site	NS (n=3)	NS (n=3)	NS (n=3)	0.8571 (n=6)
Both sites	NS (n=6)	NS (n=6)	NS (n=6)	0.6247 (n=12)

Method 4. EM34 VDO measurements vs average conductivity over "focused depth ranges" where relative response is greater than listed value (see Table 2 for depth ranges).

Siefkes site Relative Response	STATION 1	STATION 2	2-STATION AVG	STATION 1 & STATION 2
> 0.3	NS	NS	NS	NS
> 0.4	NS	NS	NS	0.7648
> 0.5	0.9992	NS	NS	0.8473
> 0.6	NS	0.9885	NS	0.8376
> 0.7	NS	0.9963	NS	0.8160
	(n=3)	(n=3)	(n=3)	(n=6)

(continued)

Table 5 (continued). Correlation coefficient (r) values for comparisons of EM34 measurements with downhole conductivity via Methods 2-5 described in the text.

Method 4 (continued). EM34 VDO measurements vs average conductivity over "focused depth ranges" where relative response is greater than listed value (see Table 2 for depth ranges).

Witt site Relative Response	STATION 1	STATION 2	2-STATION AVG	STATION 1 & STATION 2
> 0.3	NS	NS	NS	0.9188
> 0.4	0.9885	NS	NS	0.9438
> 0.5	0.9941	NS	NS	0.9544
> 0.6	0.9909	NS	NS	0.9481
> 0.7	NS	NS	NS	0.8644
	(n=3)	(n=3)	(n=3)	(n=6)

Both sites Relative Response	STATION 1	STATION 2	2-STATION AVG	STATION 1 & STATION 2
> 0.3	0.7443	0.7356	0.7729	0.7399
> 0.4	0.7726	0.7752	0.8083	0.7737
> 0.5	0.7803	0.7956	0.8228	0.7877
> 0.6	0.7991	0.8154	0.8429	0.8069
> 0.7	0.7705	NS	0.7770	0.7438
	(n=6)	(n=6)	(n=6)	(n=12)

Method 5. EM34 VDO measurements vs average conductivity to listed depths.

Siefkes site	STATION 1	STATION 2	2-STATION AVG	STATION 1 & STATION 2
To 15, 30, and 60 m	NS	NS	NS	-0.7451
To 10, 20, and 40 m	NS	NS	NS	0.7966
To 7.5, 15, and 30 m	0.9912	NS	0.9906	0.8815
To 5, 10, and 20 m	NS	NS	0.9969	0.8871
	(n=3)	(n=3)	(n=3)	(n=6)

Witt site	STATION 1	STATION 2	2-STATION AVG	STATION & STATION 2
To 15, 30 m and bottom	NS	NS	NS	0.7727
To 10, 20, and 40 m	NS	NS	NS	0.9317
To 7.5, 15, and 30 m	0.9955	NS	NS	0.9577
To 5, 10, and 20 m	NS	NS	NS	0.8680
	(n=3)	(n=3)	(n=3)	(n=6)

Both sites	STATION 1	STATION 2	2-STATION AVG	STATION 1 & STATION 2
To 15, 30, and 60 m (or bottom)	NS	NS	NS	0.4983
To 10, 20, and 40 m	0.7603	0.7547	0.7912	NS
To 7.5, 15, and 30 m	0.7782	0.7974	0.8226	0.7875
To 5, 10, and 20 m	0.7434	NS	0.7505	NS
	(n=6)	(n=6)	(n=6)	(n=12)

n = number of sample pairs.
NS = not statistically significant at 10% level.

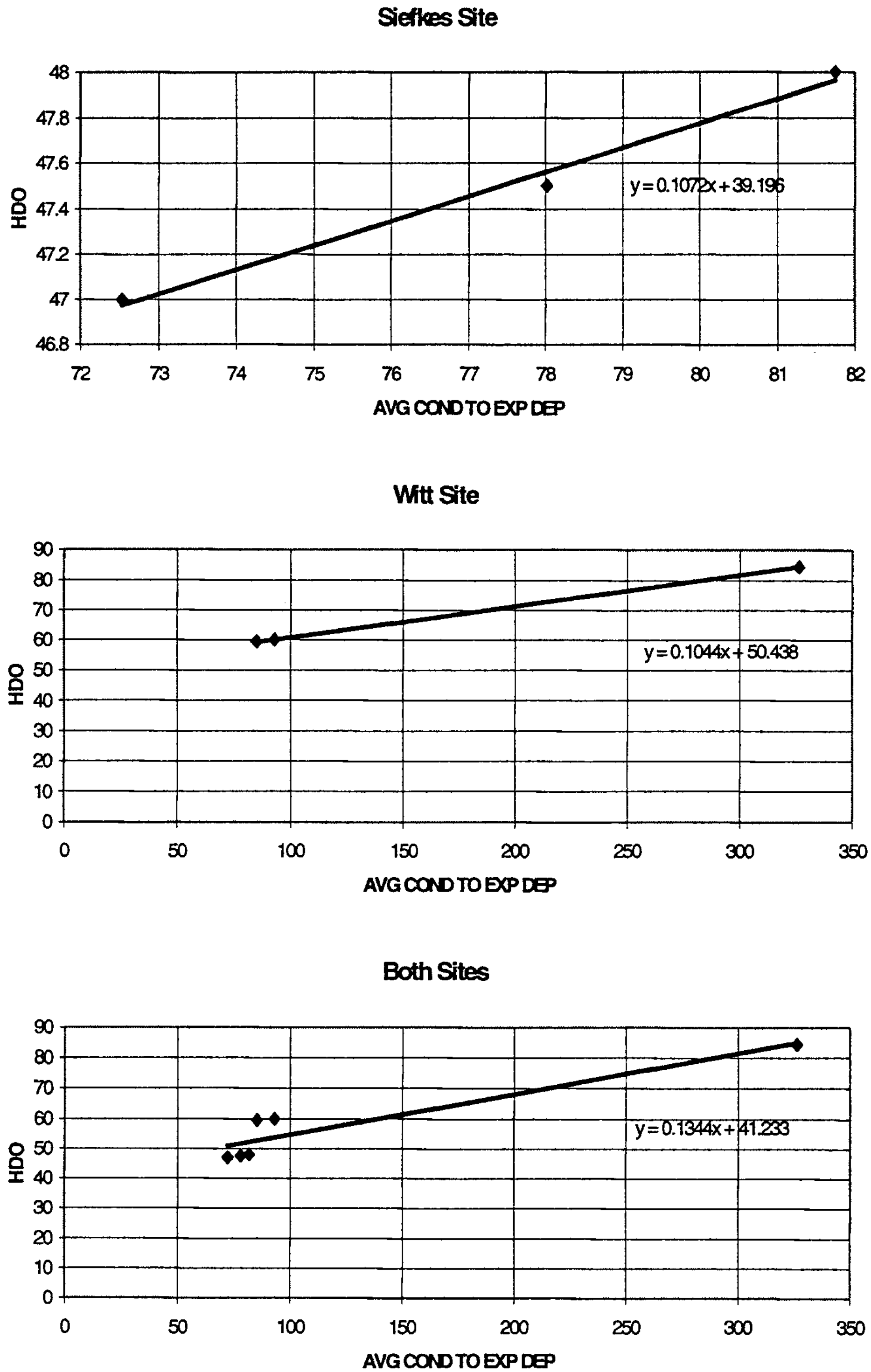
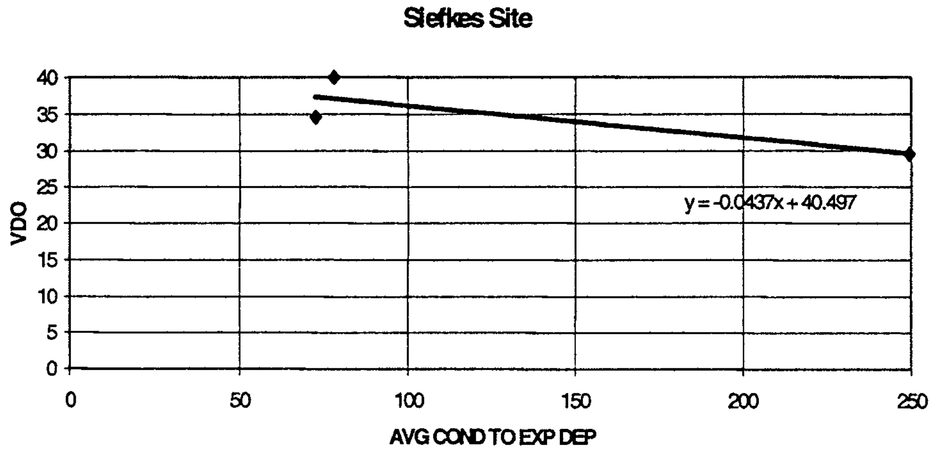
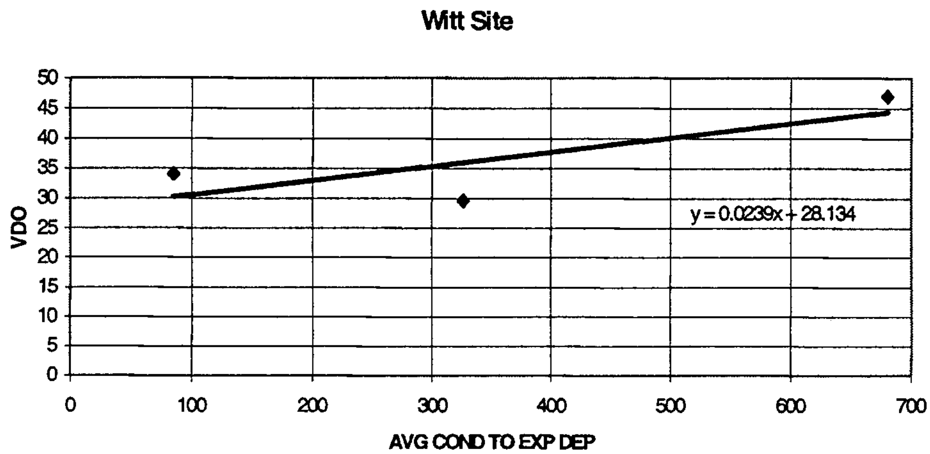


Figure 8. Relation between HDO messurements and the average downhole conductivity to the theoretical exploration depths (Method 2).





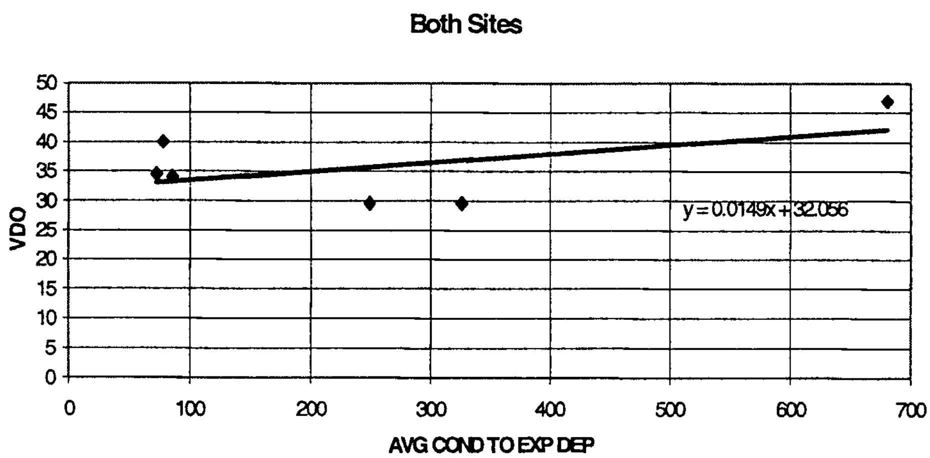


Figure 9. Relation between VDO messurements and the average downhole conductivity to the theoretical exploration depths (Method 2).

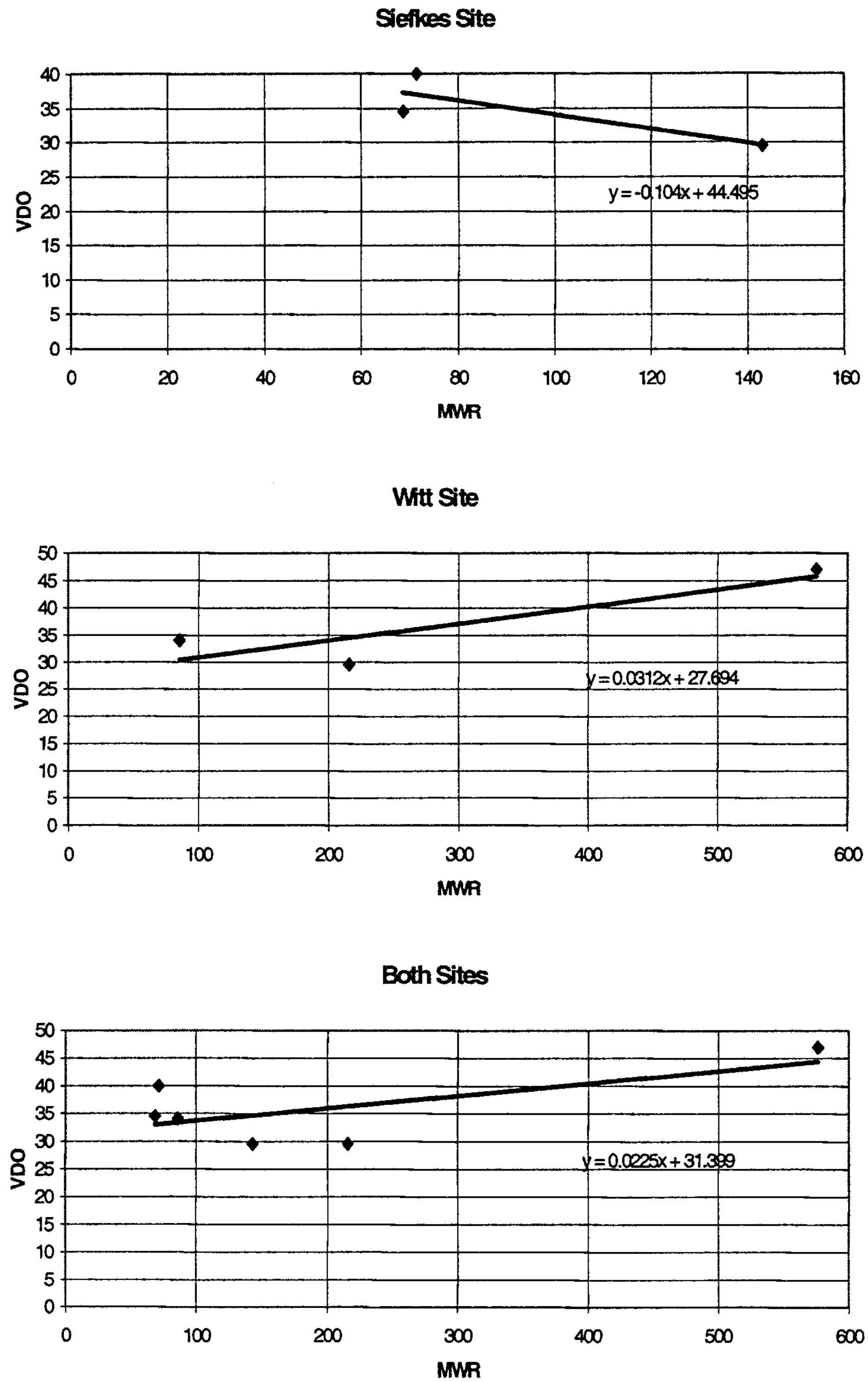


Figure 10. Relation between VDO measurements and mean weighted response (MWR) to the theoretical exploration depths (Method 3).

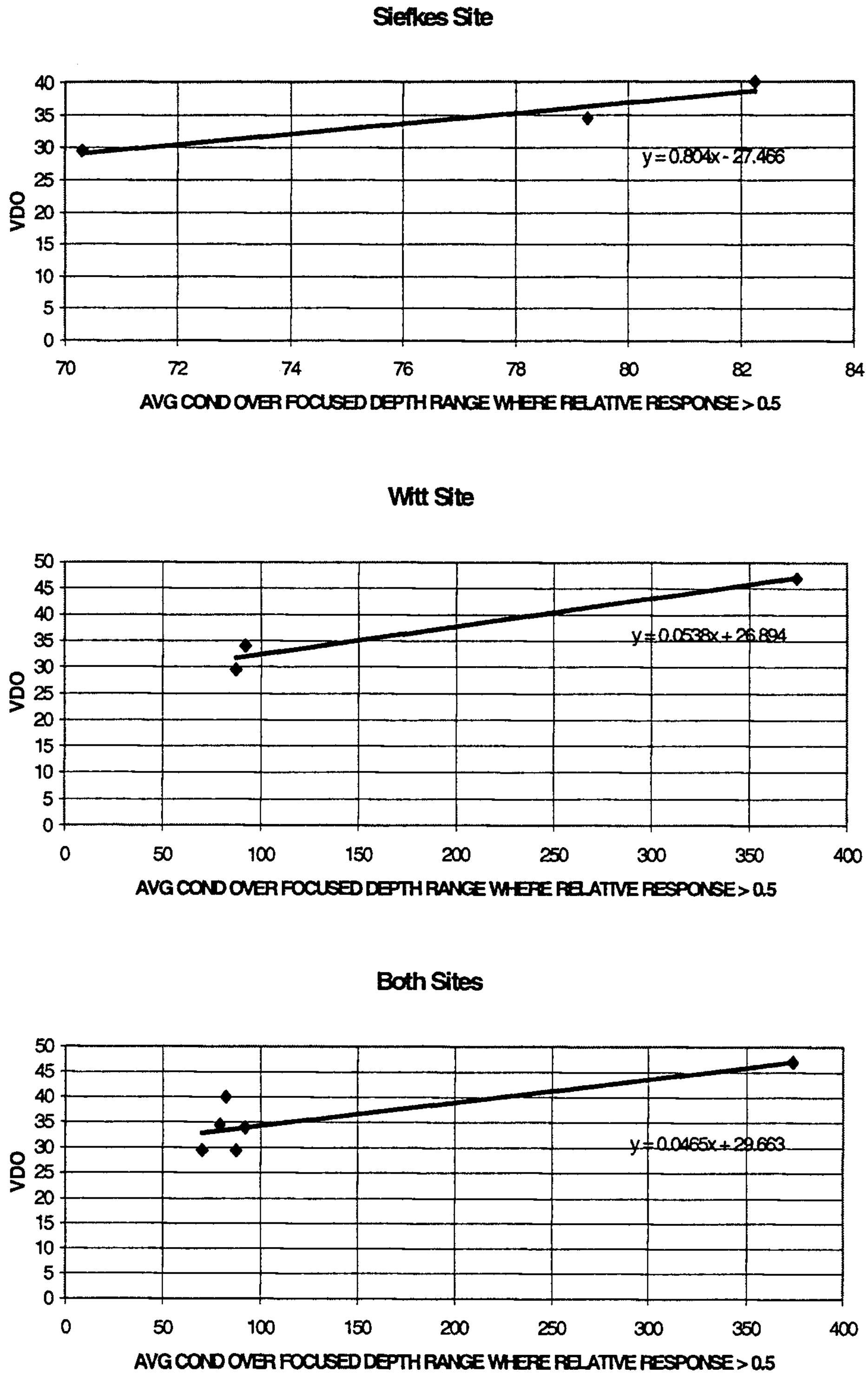


Figure 11. Relation between VDO measurements and average conductivity over the focused depth range where the relative response is greater than 0.5 (Method 4).

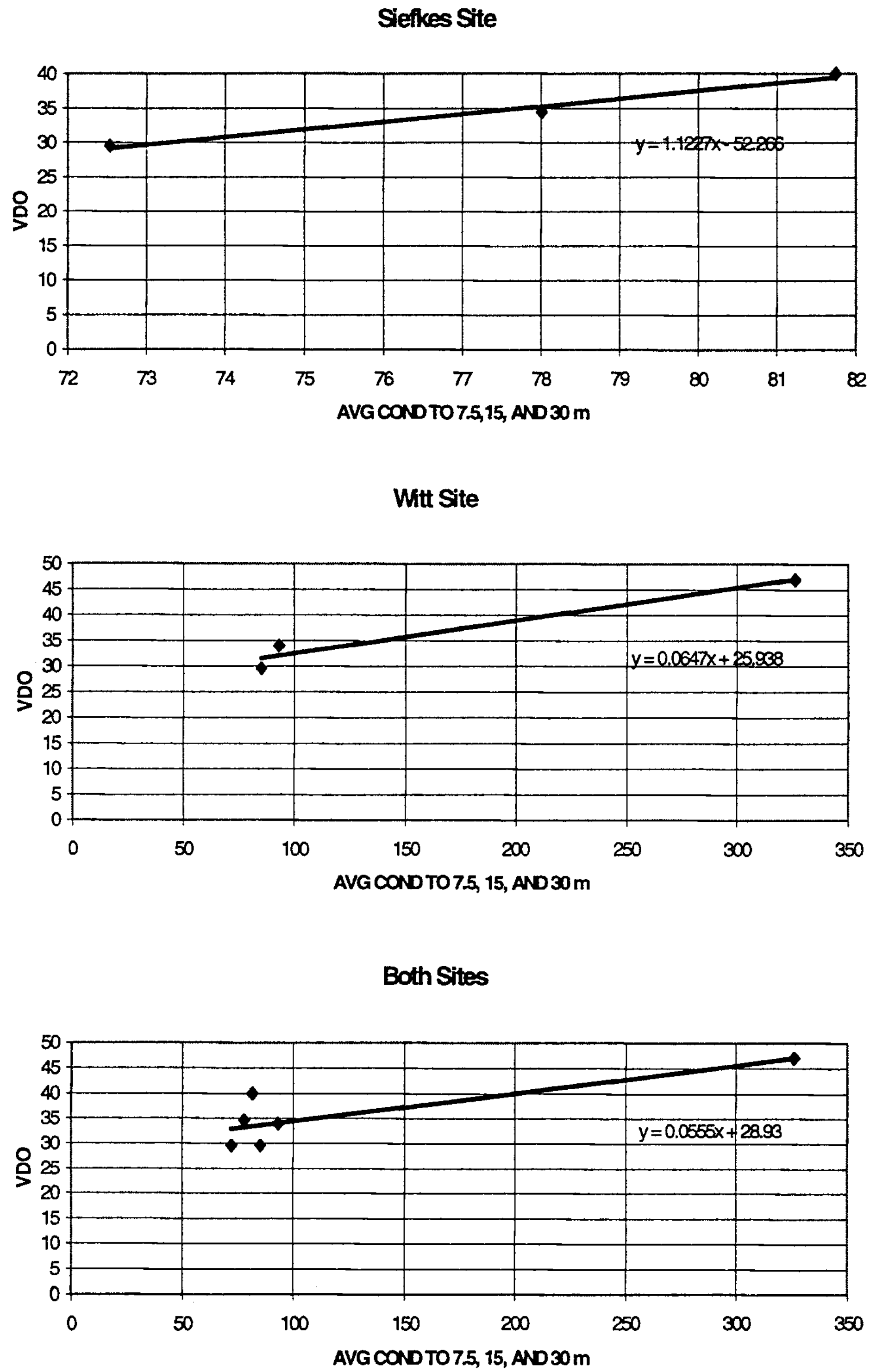


Figure 12. Relation between VDO measurements at 10, 20, and 40 m spacings and average conductivity to 7.5, 15, and 30 m, respectively (Method 5).

DISCUSSION

It is evident from the lack of a satisfactory 2-layer model solution that the earth does not exhibit simple two-layer characteristics at either of the surveyed sites. This is also evident in the downhole logs. The sites do not exhibit sharp freshwater/saltwater interfaces, they exhibit transition zones. Another complication is that the near-surface clays may dominate the EM34 response. This section discusses the analyses intended to improve and refine the interpretational approach, particularly in the VDO.

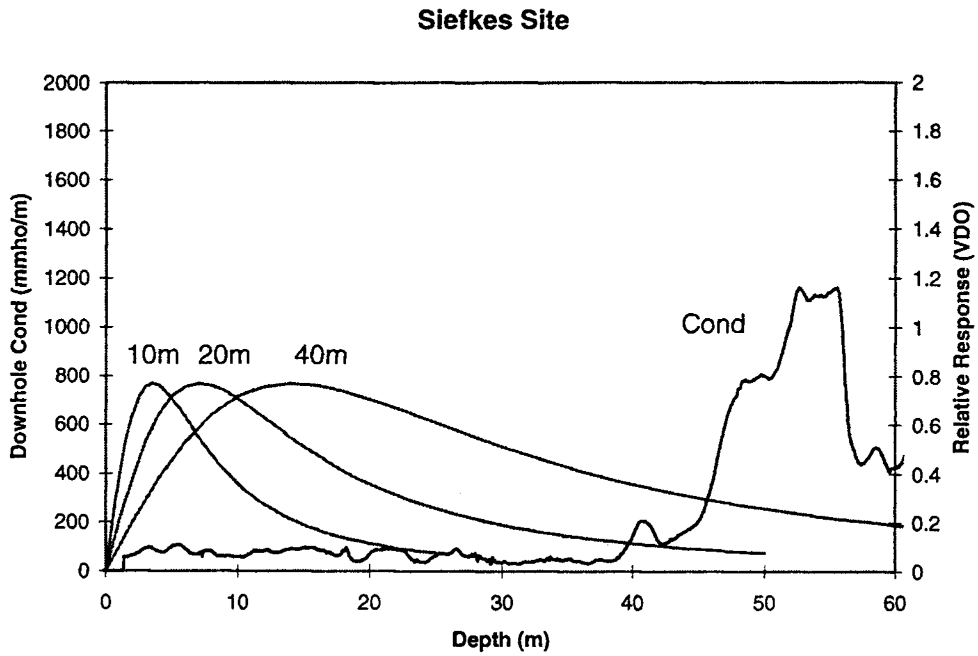
HDO measurements. Vertical trend analysis showed that HDO measurements were representative of the qualitative trend of the downhole logs at the theoretical depths (Figs. 6 and 7). Similarly, when EM34 measurements were compared with average conductivities above corresponding exploration depths (Method 2), the HDO data showed fairly good linear relationships (Table 5; Fig. 8).

At the Siefkes site the conductivity is relatively uniform with depth down to about 30 m, as are the HDO measurements (Fig. 6; Tables 3 and 4). The HDO measurements are indicative of near-surface clay and not much salt content down to about 30 m. At the Witt site the 40 m HDO measurements are significantly higher than the 10 and 20 m measurements (Fig. 7; Tables 3 and 4), and indicate that considerable saltwater is present between 15 and 30 m. The HDO data also show that the ground conductivity is higher at the Witt site compared with the Siefkes site.

The measurements in HDO mode, whose response is strongest for near-surface material, are a fairly good representation of the conductivity trend down to the 30 m exploration depth at both sites. The theoretical exploration depths for the HDO (Table 1) seem reasonable. Based on the limited amount of data available, at least qualitative interpretations can be made using the HDO measurements.

VDO measurements. VDO measurements plotted at the theoretical exploration depths (Table 1) do not appear to be good representations of the downhole trends (Figs. 6 and 7). The poor relation between the VDO measurements and the average conductivities to the theoretical exploration depths (Method 2) is evident in Table 5 and in Figure 9. Weighting the conductivity logs (Method 3) did not improve the VDO correlation appreciably. Recall that Methods 2 and 3 yielded a negative relation at the Siefkes site (Table 5). Apparently the EM34 is not "seeing" the conductive saltwater zone below 40 m.

Some of the discrepancy in the VDO may be explained by examining the relative response curves for the VDO, which are superposed on downhole logs from the Siefkes and Witt sites in Figure 13. Although 70% of the signal comes from material above 1.5s (the theoretical exploration depth), the highest relative response is at about 0.35s, which is equivalent to depths of 3.5, 7 and 14 m for 10, 20, and 40 m VDO spacings. These depths of maximum contribution are much lower than the theoretical exploration depths of



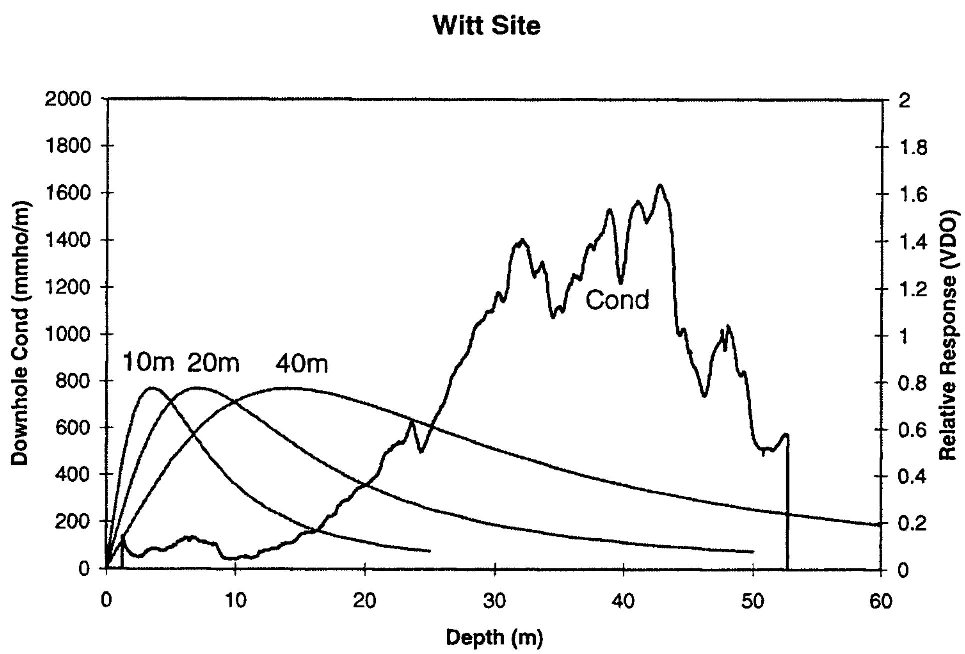


Figure 13. Relative response curves for the VDO superposed on downhole conductivity logs.

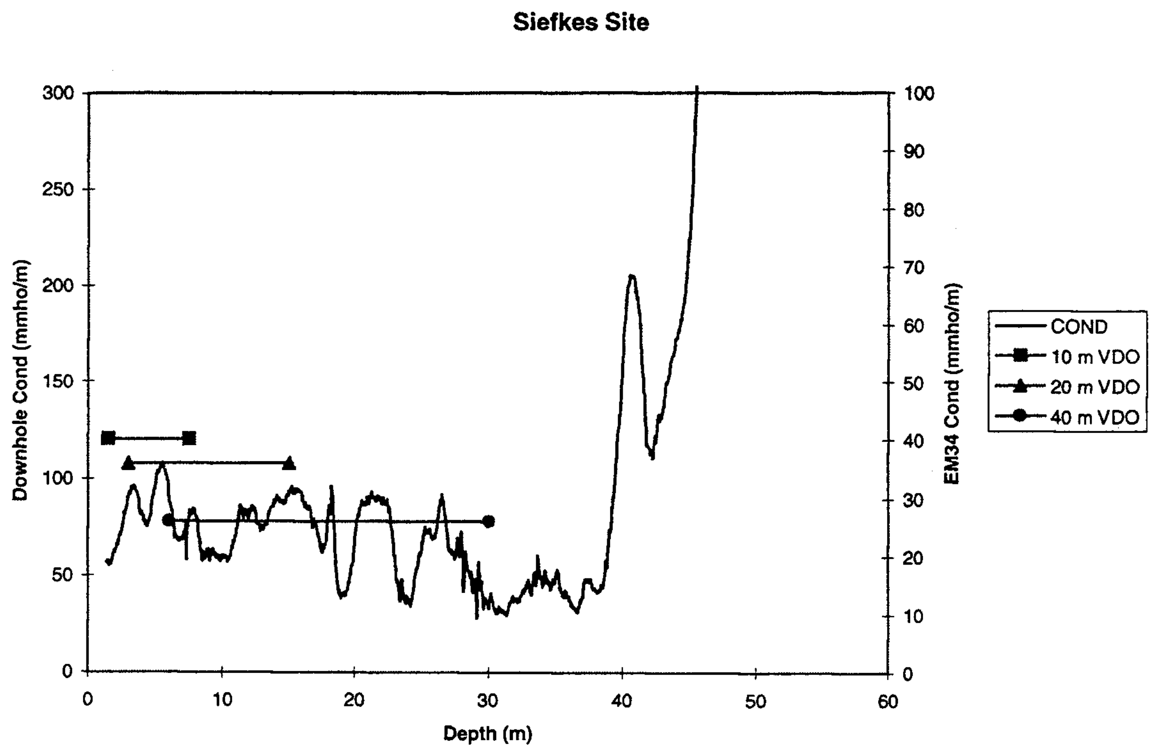
15, 30, and 60 m for the same spacings. This may lead one to wonder if VDO measurements are actually reading as deep as theoretical depths would suggest. It is conceivable that actual exploration depths in the VDO could be much less than the theoretical exploration depths, particularly if high-conductivity clay zones are present in the zone of maximum response. At the Siefkes and Witt sites, high-conductivity near-surface clay layers are present.

The considerable improvement in r values (Table 5) using the "focused depth range" concept (Method 4) suggests that the actual depth of exploration in the VDO may indeed be much less than the theoretical exploration depths and more nearly comparable to the HDO exploration depths, at least at these two sites. It also suggests that the "focused depth range" may be more useful in vertical interpretations of VDO data than the traditional "exploration depth." The results of Method 5 further support this concept of a shallower exploration depth for the VDO.

It should be stressed that this is based on a very small data set and that more samples and more downhole comparisons are needed for verification, but it makes at least qualitative sense at these two sites. EM logs from the Siefkes and Witt sites are shown in Figure 14 along with EM34 VDO measurements at their theoretical focused depth ranges. Notice that the scales are different for the different sites. At the Siefkes site VDO measurements decrease with increased spacing (or depth). If the focused depth ranges are accurate, this would indicate that the 10 m reading is focused on the the near-surface clay (high-conductivity zone), while the measurements at the greater spacings represent increasingly less focus on the clay and more focus below in the less-conductive zone. At the Witt Site, the deep (40 m) VDO measurement is significantly higher than the shallower measurements (Table 3). Again, if the focused depth ranges are accurate, this would indicate that the 40 m measurement is focused in the highly-conductive saltwater, while the 10 and 20 m readings are focused above the saltwater.

At these sites the depth of exploration for the VDO appears to be similar to that of the HDO, but it may be deeper at sites where the near-surface is not conductive. As McNeill (1980a) puts it, EM systems prefer to look through an insulator to a conductor rather than through a conductor to an insulator. In other words, if the top layer is more conductive, the depth of exploration will be lesser, and vice versa. In our case (both sites with a near-surface conductor) it appears that the depth of exploration is effectively limited to about 30 m whether the VDO is used or not.

This gets back to the fact that EM measurements are inherently site specific--they depend on the subsurface conductivity profile, which is influenced by many factors, as discussed previously. To a certain extent, EM measurements, their variations and correlations with downhole data are site specific. For vertical interpretations, each individual measurement must first be considered with respect to other measurements at that site. An implication of this is that statistical analyses utilizing such parameters as means and deviations may not be valid when data from two or more different sites are combined.



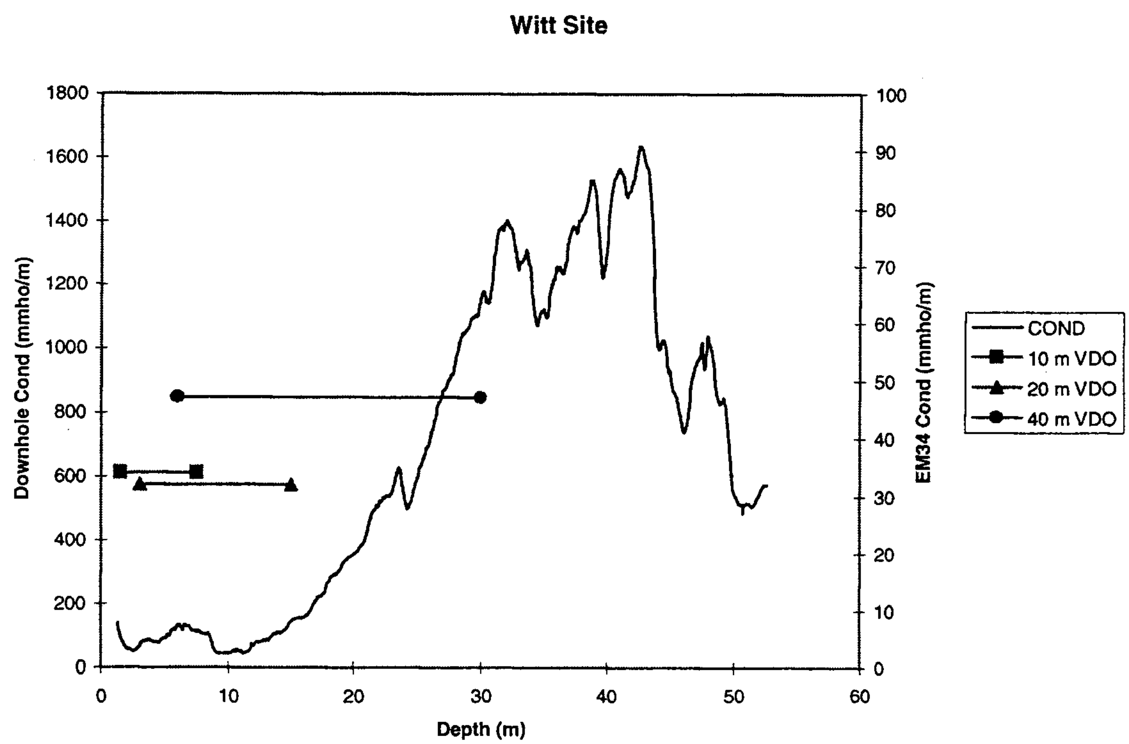


Figure 14. Downhole conductivity logs shown with EM34 VDO measurements plotted at their theoretical focused depth ranges (Method 4).

CONCLUSIONS

Comparison with downhole logs shows that EM34 measurements in the HDO are effective for shallow saltwater interface detection. A transition from freshwater to saltwater at a depth of about 10 m was detected because it is sufficiently shallow (and because the conductivity of the saltwater is much greater than that of the near-surface clay). Based on the data available, at least qualitative interpretations can be made directly from HDO measurements.

Correlation of VDO data with downhole data (using theoretical exploration depths) was poor at best. A saltwater zone at about 40 m was not evident in the EM34 measurements. This is attributed to the depth to the transition zone and the fact that the high-conductivity near-surface clay may dominate the response of the meter and decrease the depth of investigation.

Based on the relative response curve for the VDO, a concept of the "focused depth range" was introduced which may be more useful than theoretical exploration depths in vertical interpretation of VDO data. Results presented in this report suggest that the effective depth of exploration in the VDO may be much less than the theoretical exploration depths, depending on conditions at the site. More data must be collected at more sites where ground truth (in the form of downhole logs) is available to test this concept.

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Thanks to R. W. Buddemeier and R. O. Sleezer for reviewing this report and providing useful comments and suggestions. Also, thanks to M. Schoneweis for assistance with figures and M. Miller for assistance in the final preparation. The Mineral Intrusion Project is funded by the Kansas Water Office.

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