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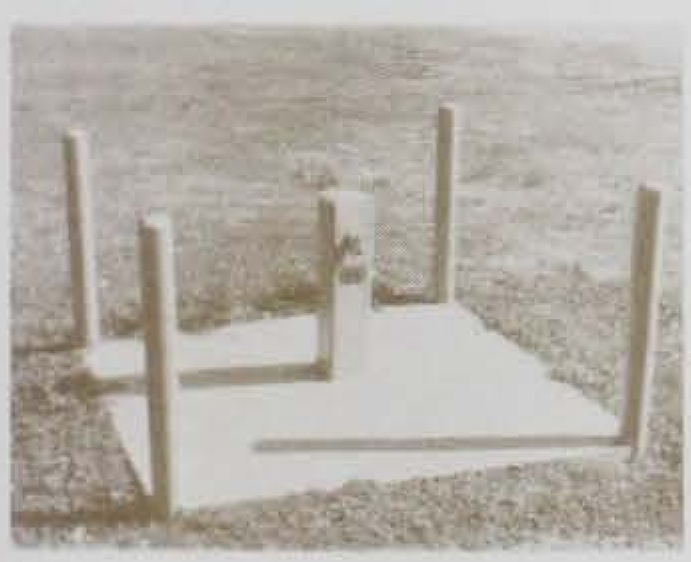

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GEOPHYSICAL INVESTIGATION AT AN EXISTING LANDFILL, BADGER ARMY AMMUNITION PLANT, BARABOO, WISCONSIN

by

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Ground-water contaminants were found in ground-water monitoring wells at the existing landfill. More wells to define the horizontal and vertical extent of the contaminant plume are to be installed. Geophysical techniques (electromagnetic induction, vertical electrical resistivity, and horizontal resistivity profiling) were used to map the extent of the contaminant plume. Using the geophysical, ground-water elevation, and geologic data, five anomalous areas south and east of the landfill were identified as locations for additional ground-water monitoring wells.

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Preface

This investigation was performed by personnel of the Engineering Geology and Rock Mechanics Division (EGRMD) and the Earthquake Engineering and Geophysics Division (EEGD), Geotechnical Laboratory (GL), US Army Engineer Waterways Experiment Station (WES), for the US Army Toxic and Hazardous Materials Agency during the period September 1987 to May 1988.

This report was prepared by Mr. Charlie B. Whitten, EGRMD, and Mr. Keith J. Sjostrom, EEGD, under the supervision of Mr. Don C. Banks, Chief, EGRMD, and Dr. Arley G. Franklin, Chief, EEGD, and under the general supervision of Dr. William F. Marcuson III, Chief, GL. Mr. Donald H. Douglas assisted with the field work. Dr. Dwain K. Butler reviewed the report.

COL Larry B. Fulton, EN, was Commander and Director of WES. Dr. Robert W. Whalin was Technical Director.

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GEOPHYSICAL INVESTIGATION AT AN EXISTING LANDFILL, BADGER ARMY AMMUNITION PLANT, BARABOO, WISCONSIN

Background

1. The US Army Toxic and Hazardous Materials Agency (USATHAMA) is preparing to conduct a remedial investigation/feasibility study (RI/FS) at the Badger Army Ammunition Plant (BAAP), located near Baraboo, Wisconsin (see Figure 1). Chemical data from ground-water monitoring wells at the existing landfill indicate the ground water is contaminated with several contaminants. With the landfill location adjacent to the installation boundary, as shown in Figure 2, a ground-water contaminant plume from the landfill may extend off the installation. USATHAMA requested that the US Army Engineer Waterways Experiment Station (WES) conduct a geophysical investigation at the landfill area to determine if geophysical methods could be used to map the extent of the contaminant plume and determine the possibility of the plume exiting the BAAP facility.

Purpose and Scope

2. The purpose of this site investigation was to detect and assess the migration of a contaminant plume(s) in the ground-water system. The primary objectives were to define the contaminant flow path from the existing landfill and determine the possibility of some contaminants originating at another upgradient source. The deterrent burning area, located 370 m south-southwest of the landfill, was included in the study area. The geophysical techniques used to meet these objectives were electromagnetic (EM) induction, vertical electrical resistivity soundings, and horizontal resistivity profiling surveys. The results of the geophysical surveys will be used to determine locations for the placement of additional monitoring wells to better define the extent of the contaminant plume.

Site History

3. Aerial photographic imagery dating from 1937 through 1986 chronicles the development of the landfill and surrounding area. Presented in Figure 3 are a series of aerial photos showing the changes at the site through time. Stereo pairs of aerial photos were used for the following site descriptions:

a. The 1937 and 1940 aerial photos (see Figure 3) show the landfill area was open farmland prior to the construction of the BAAP in 1942. The 1940 aerial photo is not shown.

b. The 1949 aerial photo in Figure 3 shows open pits located in the landfill and deterrent burning areas. These pits appear to have been used for the excavation of sand and gravel. The size of the pit in the landfill area is approximately 305 m east-west by 90 m north-south; whereas, the pit in the deterrent burning area is 210 m east-west by 75 m north-south. The unused appearance of the roads to these pits indicates little vehicular activity.

c. The condition of the roads in the 1955 aerial photo (see Figure 3) indicates the landfill and deterrent burning areas were in active use during this time period. The landfill area was being used as a borrow pit and/or waste disposal site. Two small pits are visible in the western end of the deterrent burning area. Another small pit is located 152 m east of the deterrent burning area. The purpose of this pit, approximately 30 m square, is unknown. This area will be referred to as Site A throughout the rest of the report.

d. The 1962 aerial photo in Figure 3 shows that the landfill area was infrequently used during this time period. The two small pits in the western end of the deterrent burning area appear to still be actively used. The pit at Site A has been filled but is still visible.

e. The area along the southwestern edge of the landfill was being used for waste disposal purposes in 1968 (Figure 3). Sand and gravel material from the western end of the landfill is seemingly being used to fill in the western portion of the deterrent burning area. The location of Site A is still visible.

f. Landfilling operations, which had filled 60-70 percent of the landfill site by 1978 (Figure 3), were still active in the northeast portion. The western half of the deterrent burning area has been reclaimed back to the natural ground surface. A small pit is visible in the remaining unfilled portion of the burning area. Site A is no longer visible due to agricultural activity in that area.

g. The 1986 aerial photo (see Figure 3) indicates the area along the northeast section of the landfill was still being used for waste disposal purposes. The deterrent burning area appears to have been inactive for several years.

Geology

General

4. The surface morphology and soils of the BAAP are the result of late Wisconsin stage glaciation. The furthest advance of the westward moving Green Bay Lobe of the Lake Michigan glacier is the Woodfordian Moraine. This north-south oriented moraine divides the BAAP into two regions (Dalziel and Dott 1970). The western third of the BAAP was not overlain by ice but was covered by the glacial outwash deposits, which consist of stratified sand and gravel with minor silt and clay layers. The eastern two-thirds of the BAAP, which includes the location of the landfill and deterrent burning areas, was under the direct influence of glacial ice, giving rise to an undulating topography characterized by knob and kettle-type features. Due to differential melting and movement of the ice front, the glacial deposits in the eastern two-thirds of the BAAP consist of interbedded moraine and outwash deposits.

5. The bedrock geology for this region is shown in Figure 4 (Tsai et al. 1987). The landfill area is located approximately 1 km south of the Baraboo Hills South Range, as shown in Figure 1. The Dresbach Group and Undifferentiated Precambrian basement complex were not encountered in any of the monitoring wells installed at the landfill or deterrent burning areas. The BAAP production well #4, located 550 m west of the landfill, was completed in the Undifferentiated Quaternary glacial deposits at a depth of 57.6 m.

Site

6. The glacial deposits in the area around the landfill consist primarily of sand, silty sand, and sand and gravel with some widely scattered thin silty clay lenses. Figure 5 is a northwest-southeast oriented cross section across the landfill between wells ELN-8201 and S-85-1153 (Warzyn 1982e). Figure 6 is a south-north oriented cross section across the deterrent burning area between wells DBN-8201 and DBM-8202 (Warzyn 1982f). The well logs in Figures 5 and 6 as well as logs from other wells at the sites show silty clay lenses up to 2.7 m thick at or just below the water table. However, the existing data are not sufficient to determine if the silty clay lenses are laterally continuous at the landfill and deterrent burning areas.

Ground Water

7. Ground-water data collected on 22 September 1987 at the landfill and deterrent burning areas are presented in Table 1. The depth to ground water varied from 37.3 m at well ELN-8201 to 44.7 m at well ELN-8203 and the water table elevation varied from 238.1 m at well S-85-1153 to 238.7 m at well ELN-8204.

Table 1

Water Level Data from 22 September 1987

Area	Well No.	Depth to Ground Water m	Ground-Water Elevation m
Landfill area	S1134	42.7	238.3
	S1135	44.2	238.0
	S1136	39.6	238.5
	S-85-1153	38.7	238.1
	*ELN-8201	37.3	238.6
	*ELN-8202	41.0	238.3
	*ELN-8203	44.7	238.2
	*ELN-8204	41.1	238.7
Deterrent burning area	*S1122	38.4	238.2
	DBM-8201	41.9	238.2
	DBM-8202	41.1	**239.4
Other data used for Figure 7	S1130	32.3	254.7
	S1132 ·	40.5	238.5
	S1151	33.7	238.6

* Cluster well site. The water level is from the "A" or upper well.
** This water level datum was not used. The water table is 1 to 1.1 m lower at nearby wells. There is either an error in the data or the well is monitoring a perched water zone.

8. Data collected in the northeast corner of the BAAP indicate the ground-water flow direction to be toward the southeast as shown in Figure 7. The reader should note the change in the ground-water gradient along a line through wells S1130, S1151, and S1135. Well S1130 is located on the flank of the Baraboo Hills while wells S1151 (located near the base of the hills) and S1135 are in the gently rolling glacial terrain. The water table level drops 16.2 m from well S1130 to S1151, a distance of approximately 762 m, while

dropping only 0.6 m from well S1151 to S1135, a distance of approximately 1,036 m. The gradient changed from 0.02 m per m between wells S1130 and S1151 to 0.0006 m per m between wells S1151 and S1135. The change in the ground-water gradient mimics the topographic changes.

9. Weigands Bay, part of Lake Wisconsin, is approximately 1,950 m southeast of the landfill. The water level in Lake Wisconsin is maintained at elevation 235.9 m which is approximately 1.5 m lower than the water table at the landfill. The ground-water gradient from the existing landfill to Lake Wisconsin is approximately 0.0008 m per m.

10. The 1981 Contamination Survey Report (Envirodyne Engineers 1981) estimated that the ground-water flow velocity at the existing landfill and deterrent burning area ranged from 2.1 to 8.2 m per year. A contamination plume originating from the landfill would have moved approximately 366 m if it is assumed contaminants entered the ground water in 1942, the year the BAAP was constructed, and the ground-water flow velocity is 8.2 m per year. This would place the leading edge of a contaminant plume in the vicinity of the eastern end of the east-west road located south of the landfill (see Figure 2).

Chemical Data

11. Chemical data from the ground-water monitoring wells at the existing landfill show the ground water is contaminated. More monitoring wells are scheduled to be installed to define the vertical and lateral extent of the contaminant plume(s). Geophysical methods, discussed later in the report, were used to define the extent of the contaminant plume(s) and to aid in the placement of new monitoring wells. The geophysical tests may not detect some of the contaminants; however, the techniques can be used to detect the changes in the electrical properties caused by some of the contaminants, such as sulfates. It should be noted that the further a contaminant plume migrates from a source, the more dispersed and dilute the plume usually becomes within the ground-water system. The dilution of the plume, as it moves away from the landfill combined with the great depth to the water table, decreases the ability of the geophysical techniques to detect and/or define the extent of a contaminant plume. Table 2 lists a few of the chemical parameters determined for the ground water. These parameters indicate the electrical properties of

the ground water have been altered by contaminants originating from the landfill or other up-gradient sources. Note the difference between the up-gradient well ELN-8201A and the down-gradient wells ELN-8203A, S1134, and S1135. No contaminants were found in well ELN-8204B, which is located west of the landfill.

Table 2

Chemical Parameters Indicating Changes in the Electrical Properties of the Ground Water

	Range of Concentration (mg/L) in Well Samples				
Parameter	ELN-8201A	ELN-8204B	ELN-8204B	S1134	S1135
Sulfate	31-51	535-792	29-50	448-763	448-593
TDS	270-357	1610-2030	339-402	1280-1650	1390-1560
Hardness	292-342	1290-1530	318-334	436-1173	424-1160
Magnesium	28-39	132-240	30-42	63-140	53-129
Specific Conductance (in mmho/m)	39-52	116-170	41-63	114-150	116-150

Geophysical Methods

Electromagnetic (EM) induction survey program

12. The EM surveys were performed with a ground conductivity system consisting of a transmitter and receiver coil. Measurements are obtained by placing the transmitter coil on the ground and energizing it with an alternating current in the audio frequency range. The coil produces a time-varying magnetic field which induces small currents within conductive material below the ground surface. These currents produce a secondary magnetic field detectable by the receiver coil, located a fixed distance away. The measured quantity is expressed as an apparent conductivity in millimhos per metre (mmhos/m). This conductivity value is dependent on the transmitter frequency, coil spacing, and the ratio between the primary and secondary magnetic fields, which in turn depend on the electrical properties of the subsurface materials.

A detailed discussion of EM theory, survey methods, and data interpretation can be found in McNeill (1980).

13. Eight EM survey lines (EM-1 through EM-8) were located in the vicinity of the landfill site, as illustrated in Figure 8. Survey lines EM-1 through EM-4 were conducted around the perimeter of the landfill. Line EM-5 was conducted parallel to the Perimeter Road from a point approximately 400 m north of the landfill to the road intersection approximately 400 m southeast of the landfill. Line EM-6 was conducted along the east-west oriented gravel road from south of the deterrent burning area eastward to where the road intersects the Perimeter Road. Line EM-7 was conducted approximately 350 m north of the landfill. Line EM-8 was conducted along the eastern side of the deterrent burning area. Measurements were taken at 7.5-m intervals on lines EM-1 through EM-4, the latter part of line EM-6, and EM-8; whereas, 15-m intervals were used for the remaining survey lines. Lines EM-1 through EM-4 were conducted with intercoil spacings of 10, 20, and 40 m in the horizontal dipole mode and 40 m in the vertical dipole mode. The horizontal dipole mode is attained with a vertical orientation of the coils and conversely for the vertical dipole mode. The remaining lines, EM-5 through EM-8, had intercoil spacings of 20 and 40 m in the horizontal dipole mode and 40 m in the vertical dipole mode. Using the horizontal dipole mode, the exploration depths achieved are three-fourths the length of the intercoil spacing used; whereas, with vertical dipoles, the depth of exploration is 1.5 times the coil spacing distance. The advantage of conducting the EM profiles with the coils oriented vertically (horizontal dipole mode) and coplanar is that the coils are less susceptible to misalignment and, therefore, the survey proceeds more rapidly. However, when the survey is performed in this manner, the conductivity readings are much more sensitive to the near surface material which may result in conductivity contrasts at depth being masked. The survey program strategy was to surround the landfill site with survey lines to detect the possibility of contaminants leaching from the landfill and also to conduct EM profiles down-gradient in an effort to map any possible contaminant flow.

Horizontal resistivity profiling program

14. Horizontal resistivity profiling investigates lateral changes in resistivity within the earth's subsurface. This technique is useful in mapping geologic features, soil conditions, and contaminant plumes having resistivity contrasts with the surrounding material. The survey was conducted

using the Wenner array, consisting of two inner potential electrodes and two outer current electrodes equally spaced along a straight line. As a direct current is applied to the earth's surface through the current electrodes, the potential difference is measured between the potential electrodes. The resistivity meter computes and displays the resistance, expressed in ohms, of the subsurface materials in the vicinity of the array. Resistivity for the Wenner array is determined by multiplying the resistance and the geometric factor of the electrode configuration:

$$\rho_a = 2\pi a(R)$$

where

ρ_a = apparent resistivity (ohm-m)
a = electrode spacing (m)
R = resistance (ohm)

This formula calculates resistivity, expressed in ohm-metres, for the ideal case of a completely uniform earth. Since the earth is rarely considered uniform, the above equation is used as a definition and a means of calculating the apparent resistivity of earth material. For more information pertaining to electrical resistivity theory, field procedures, and data interpretation, see Keller and Frischknecht (1966), Mooney (1980), and Engineer Manual 1110-1-1802 (Headquarters, Department of the Army 1979).

15. Three horizontal resistivity profiles (R1, R5, and R6) were conducted at the site as shown in Figure 8. The purpose of these profiles was to randomly check the validity of the EM data, especially at the shallower depths. An electrode spacing of 35 m was used and measurements were taken at 17.5-m intervals along each profile line.

Vertical electrical resistivity sounding program

16. Vertical electrical resistivity sounding (VES) methods attempt to examine the variation of resistivity with depth. This technique is primarily used in detecting layers of earth material having significant resistivity contrasts with surrounding zones. The tests were conducted using the Schlumberger array which consists of two closely spaced potential electrodes located midway between two current electrodes. The electrode arrangement is

symmetric about the point of investigation and remains so throughout the data collection process. Normal field procedures entail leaving the potential electrodes fixed and logarithmically increasing the distance L between the current electrodes and center point. A measurement of the resistance is made for each new electrode configuration. As the distance L increases, the measured potential difference rapidly decreases and eventually surpasses the measuring capabilities of the resistivity meter. This can be corrected by increasing the distance A between the potential electrodes.

17. The potential difference is measured and resistance computed in the same manner as explained in the description of horizontal resistivity profiling. The resistivity, expressed in ohm-metres, is calculated using the formula shown below:

$$\rho_a = \pi AR[(L/A)^2 - 0.25]$$

where

L = distance between current electrodes and center point (m)

A = distance between potential electrodes (m)

The equation multiplies the resistance and the geometric factor for the Schlumberger array configuration to yield the resistivity representative of a uniform earth. Because of the heterogeneous nature of the earth, the above equation is used as a definition and technique for calculating the apparent resistivity of the subsurface material. For further information concerning electrical resistivity theory, procedures for VES surveying, and methods of data interpretation, see the sources noted in the explanation of horizontal resistivity profiling.

18. Three VES surveys (VES-1, VES-5a, and VES-5b) were conducted at the landfill site and a fourth (VES-6) was positioned along survey line EM-6 south of the landfill. The location of each VES is shown in Figure 8. For VES surveying to a desired depth of exploration D , the electrode spacing L for the current electrodes should range from a minimum of D/5 to a maximum of 4-6 times D to obtain adequate coverage for interpretation purposes (Mooney 1980). The desired depth of exploration for these tests was to the water table. The logarithmically spaced current electrode distances L ranged from 2 to 200 m, resulting in 30 apparent resistivity values per survey which should provide sufficient data within the depth of interest.

Results

Electromagnetic (EM) induction survey program

19. Data acquired from the EM surveys are displayed in conductivity versus distance plots which are shown in Figures 9 through 16 for lines EM-1 through EM-8, respectively.

20. Line EM-1. Line EM-1 was conducted on the south side of the landfill along a line connecting wells S1134, ELN-8203, and S1135, as shown in Figure 8. The results of this survey are shown in Figure 9. Between 40 and 105 m, an area of low conductivity was detected near the surface. This region exists in an area where the top soil has been disturbed by recent agricultural activity. An increase in soil porosity and the sandy composition of the soil likely contribute to produce the lower readings. Higher conductivity readings are also recorded in this area using the 40-m intercoil spacing in the vertical dipole mode. These readings may be influenced by nearby transmission lines. An overhead power line and an underground telephone cable cross the survey line at 160 m. The data measured on either side of this point show the influence of the transmission lines. There is a large high conductivity anomaly from 165 to about 315 m that may be due to subsurface contaminants. Two areas of higher conductivity were detected near the surface with the 10- and 20-m intercoil spacings. These areas are located between 265 and 320 m and at 390 m. There are some piles of asphalt debris on the surface near between 255 and 300 m.

21. Line EM-2. Line EM-2, located on the western side of the landfill as shown in Figure 8, was conducted toward the south-southeast along a line beginning at well ELN-8201 and ending at survey line EM-1. The results are presented in Figure 10. A high conductivity anomaly is detected by the 10- and 20-m intercoil spacings between 45 and 75 m. The electrical interference of the power line and buried telephone cable is evident about a point 232.5 m from the start of the line. Two low conductivity anomalies are also detected. The first is located between 30 and 70 m and is detected by the 40-m intercoil spacing in the vertical dipole mode. This anomaly occurs at depth and overlaps the interval where a near surface high conductivity anomaly exists. The second, detected using the vertical coil orientation, is a decreasing conductivity trend located over the last 20 m of the survey line. The area

occurs in a region of recent agricultural activity and may be due to higher soil porosities.

22. Line EM-3. Line EM-3 is located along the north side of the landfill site, as illustrated in Figure 8. The results are presented in the conductivity versus distance plot shown in Figure 11. Between 50 and 110 m, an area of slightly high conductivity readings were detected with the 10, 20, and 40-m intercoil spacings with the coils orientated vertically. Within this area, partially exposed pieces of sheet metal are scattered along the surface, suggesting that buried material located near the surface is causing the higher readings. Beginning at a distance of 140 m, the survey line descends a steep embankment (elevation difference roughly 6 m) to the unfilled portion of the landfill. A low conductivity anomaly is detected using the 10- and 20-m coil spacings during this descent. Along the bottom of the landfill, between 170 and 225 m, the conductivity increases as the survey progresses. A zone of high conductivity is detected beginning at 225 m and extends for 40 m and is likely caused by recently buried materials. Located nearby were two truck loads of refuse material containing paint cans, wire, creosoted railroad ties, treated lumber, and other construction material. Using the 10-m coil spacing, a region of low conductivity is detected near the surface between 260 and 320 m. Beyond 320 m, there is an overall high conductivity trend in the data.

23. Line EM-4. Figure 12 shows the results of line EM-4 which is situated along the Perimeter Road on the eastern side of the landfill, as illustrated in Figure 8. The conductivity readings acquired using the 40-m intercoil spacing in the vertical dipole mode are much higher than those obtained using the horizontal dipole mode. A chain link fence located 18 m away and parallel to the survey line is believed to create the higher readings but not the recorded fluctuations as shown in the results. These variations are due to conductivity contrasts in the subsurface. A prominent region of high conductivity, detected near the surface as well as at depth, is located between 50 and 135 m near well ELN-8202 and another is detected at depth between 130 and 200 m by the vertical dipole method.

24. Line EM-5. Line EM-5 was conducted 35 m west of and parallel to the Perimeter Road, as shown in Figure 8. The results are presented in Figure 13. Two high conductivity anomalies are detected by the EM survey. The first area is located between 465 and 585 m which is the segment of the survey traversing the landfill. This anomaly is caused by buried conductive

materials; failure of the 40-m coil spacing in the vertical dipole mode to reflect this high anomalous area cannot be readily explained. The second is located between 750 and 800 m where the power line and underground telephone cable cross the survey line. Areas of conductivity variation were detected at depth using the 40-m intercoil spacing in the vertical dipole mode.

25. Line EM-6. Line EM-6 was conducted along the east-west road located south of the landfill as indicated in Figure 8. The western portion of the survey line was conducted along the southern boundary of the deterrent burning area. The conductivity versus distance plot for this line is shown in Figure 14. The increasing conductivity trend at the end of the survey line is possibly due to the influence of a nearby power line, located parallel to the Perimeter Road. Numerous anomalies are located along the survey line and of these, only the ones occurring near 165 m may be caused by cultural features. The dramatic conductivity high detected using the 40-m coil spacing in the vertical dipole mode at the end of the survey line is likely due to a nearby fire hydrant and associated water line.

26. Line EM-7. Line EM-7 is located approximately 350 m north of the landfill, as illustrated in Figure 8. The results are presented in Figure 15. An area of high conductivity is detected using the 40-m coil spacing in the vertical dipole mode at the end of the survey line. No other anomalous areas are detected along the survey line.

27. Line EM-8. Figure 16 shows the results of line EM-8 which was conducted along the eastern edge of the Deterrent Burning Area, as shown in Figure 8. No anomalous areas are detected along this survey line.

Horizontal resistivity profiling program

28. Measurements from the horizontal resistivity profiling program are presented in apparent resistivity versus distance plots. These plots are shown in Figures 17, 18, and 19 for profiles R-1, R-5, and R-6, respectively. Data collected for profiles R-5 and R-6 were erratic and at times varied as much as 500 ohm-m between data points, making interpretation difficult. To help with the analysis, the data were smoothed by averaging over adjacent data points, a method described by Bevington (1969).

29. Profile R-1. Resistivity profile R-1 was conducted along the same investigative path as survey line EM-1 (see Figure 8). The results of this profile are shown in Figure 17. A distinct high resistivity (low conductivity) anomaly is detected between 35 and 80 m. This portion of the survey line

traverses an area which has undergone recent agricultural activity. For the most part, however, the resistivity varies between 250 and 450 ohm-m with the lower readings occurring between 175 and 300 m.

30. Profile R-5. Resistivity profile R-5 is located along line EM-5, as illustrated in Figure 8. Figure 18 displays the smoothed resistivity results of this profile. A decreasing trend in resistivity occurs from the start of the profile to the northern edge of the landfill. The landfill is indicated as the distinct region of lower resistive material located between 420 and 600 m. South of the landfill, the resistivity increases and varies between 650 and 900 ohm-m. The erratic data recorded during the test are dominated by the topography. Some of the high resistivity readings can be correlated with topographic highs, reflecting less silty soil and generally lower moisture content.

31. Profile R-6. Resistivity profile R-6 is located south of the landfill along survey line EM-6 and the averaged results are presented in Figure 19. An increasing resistivity trend was detected from the start of the profile to 400 m. Low resistivity readings occur near the Perimeter Road. An anomalous zone of higher resistivity was detected between 90 and 135 m, which is south of the deterrent burning area. Data collected between 385 and 500 m and 630 and 750 m may be affected by topographic fluctuations.

Vertical electrical resistivity sounding (VES) program

32. Data acquired from VES are displayed in Schlumberger sounding curves which display the apparent resistivity versus electrode spacing. The graphs are shown in Figures 20 through 23 for soundings VES-1, VES-5a, VES-5b, and VES-6, respectively. Computer algorithms utilizing an inverse modeling technique were used to analyze the data and produce models of the subsurface at the sounding positions. These models yield the thickness, depth to the interface, and apparent resistivity for each layer.

33. Sounding VES-1. Sounding VES-1 was located along survey line EM-1 approximately 15 m east of well S1134, as indicated in Figure 8. The data are illustrated in the Schlumberger sounding curve presented in Figure 20. Of the many computer models generated it was determined the four-layer model best represented the data. The depths to the interfaces and apparent resistivities for this sounding position are shown below:

Layer	Apparent Resistivity, ohm-m	Depth to the Interface, m	Thickness, m
1	24	0.0	1.5
2	392	1.5	9.7
3	232	11.2	15.4
4	700	26.6	?

The results show a thin layer of material with low resistivity underlain by a layer of moderate resistivity about 9.7 m thick. Layer 3 is a lower resistive layer detected at a depth of 11.2 m. The fourth layer is a zone of high resistivity.

34. Sounding VES-5a. Sounding VES-5a was located south of survey line EM-1 and positioned along line EM-5, as shown in Figure 8. The data acquired are presented in the Schlumberger resistivity sounding curve in Figure 21. The apparent resistivity, depths to the interface, and thickness of each layer were calculated using the computer algorithm and a four layer model best represented the data. The results are shown below:

Layer	Apparent Resistivity, ohm-m	Depth to the Interface, m	Thickness, m
1	29	0.0	1.1
2	692	1.1	8.4
3	874	9.5	20.9
4	525	30.4	?

The computed information indicates that layer 1 is a thin zone of low resistivity representing the near surface material. Layers 2 and 3 are zones with greater thickness and higher apparent resistivity. Layer 4 has moderate resistivity and extends to an undetermined depth.

35. Sounding VES-5b. Sounding VES-5b is located along survey line EM-5 and is positioned on top of the landfill, as indicated in Figure 8. The acquired data are displayed in the Schlumberger sounding curve shown in Figure 22. The apparent resistivity, thickness, and depth to each layer were computed using a computer modeling program. A four-layer profile best suited the data and the results are presented below:

Layer	Apparent Resistivity, ohm-m	Depth to the Interface, m	Thickness, m
1	41	0.0	1.1
2	53	1.1	9.4
3	1154	10.5	25.2
4	199	35.7	?

The first layer is a thin zone of low resistivity corresponding to the material used to cover the landfill. The second layer has slightly higher resistivity (53 ohm-m) and is 9.4 m thick. This layer likely represents the resistivity and thickness of the buried material within the landfill. Layer 3 is a highly resistive, thick zone of material detected at a depth of 10.5 m. Layer 4 is a lower resistive zone detected at a depth of 35.7 m.

36. Sounding VES-6. Sounding VES-6 is located along survey line EM-6, as indicated in Figure 8. Data collected from this test are displayed in the Schlumberger sounding curve shown in Figure 23. Using a computer algorithm to calculate the apparent resistivity, thickness, and depth to each layer, a four-layer model was generated to fit the data. The computed results are shown below:

Layer	Apparent Resistivity, ohm-m	Depth to the Interface, m	Thickness, m
1	27	0.0	0.6
2	820	0.6	14.2
3	5631	14.8	16.6
4	587	31.4	?

The first layer, representing the near surface material, is a thin zone of low resistivity. Layer 2 is a zone of high resistivity with a thickness of 14.2 m and layer 3, with a slightly larger thickness, has a much higher resistivity value. Layer 4 is a zone of moderate resistivity extending to an undetermined depth.

37. Generalization of sounding results. The computed results for the four resistivity soundings have been presented above. With these data, the site may be generalized into a single four layer model. The ranges of apparent resistivity, depth to interfaces, and thickness are shown below:

Layer	Apparent Resistivity Range, ohm-m	Depth to the Interface, m	Thickness Ranges, m
1	24-41	0.0	0.6-1.5
2	53*, 392-820	0.6-1.5	8.4-14.2
3	232**, 874-5631	9.5-14.8	15.4-25.2
4	199-700	26.6-35.7	?

Note: * = Apparent resistivity value of the material buried within the landfill.
** = Apparent resistivity value of possible contaminant plume south of the landfill.

Layer 1 is characterized as a thin surface layer of soil with low resistivity. Layer 2, a zone of more resistive material (except where noted), is detected at depths ranging from 0.6 to 1.5 m and has thicknesses varying from 8.4 to 14.2 m. Layer 3 is a zone of high resistivity, except for the apparent resistivity value calculated for sounding VES-1, with thicknesses ranging between 15.4 and 25.2 m. Layer 4, detected at depths ranging from 26.6 to 35.7 m, is a zone of low to moderate resistivity. The depth to and resistivity of this layer may represent the water table since the depths correlate with the water level at well S1134. Overall, the correlation between all four soundings is good considering the geological environment and the distance between the sounding locations.

Summary of Geophysical Results

38. Based on the results obtained from the EM, VES, and horizontal resistivity profiling surveys, 14 anomalous areas were determined and are designated as A-1 through A-14 in Figure 24. High conductivity (low resistivity) anomalies are caused by a variety of different reasons. Three of the more common are buried conductive materials, inorganic contaminants such as acids and bases, and conductive cultural features, which include electrical transmission lines and metal fences, located near the investigative surveys. On the other hand, low conductivity (high resistivity) anomalies may be caused by some of the following: soil type, low moisture content, high soil porosity, or by the presence of organic contaminants. It will be noted that anomalous areas created by organic contaminants are often difficult to detect in field testing.

39. The landfill, indicated by the outlined areas in Figures 8 and 24, was detected by EM survey line EM-5, resistivity profile line R-5, and sounding VES-5b. The landfill area has significant conductivity and resistivity contrasts with the surrounding subsurface material as can be seen by the test results.

Anomaly A-1

40. Anomaly A-1 is an area of high conductivity (low resistivity) detected along survey line EM-1 between wells S1134 and S1135, shown as the shaded area in Figure 24. The anomaly was detected by all three geophysical tests and based on the chemical data from the above monitoring wells. This anomaly was caused by contaminants that may be emanating from the landfill. The higher readings occur between wells S1134 and ELN-8203. Using the results from sounding VES-1, an estimated depth to the contaminant plume was found to be approximately 11 m below the surface and 15 m in thickness. It should be noted that the southern boundary of the landfill cannot be visually distinguished on the surface. Therefore, the distance between the landfill and the location of the geophysical surveys is unknown and the readings may reflect an influence from buried material within the landfill.

Anomaly A-2

41. The higher conductivity readings detected near well ELN-8202 along line EM-4 is designated anomaly A-2. This region is indicated by the shaded area in Figure 24. Data from the monitoring wells indicate that subsurface contaminants are present in this area. These subsurface contaminants, as detected by the EM survey, exist near the surface and extend to depths exceeding 30 m. It is also possible that the EM results reflect some influence from the buried material since the landfill boundary is unknown in this area.

Anomaly A-3

42. Anomaly A-3 is located along survey line EM-4 as shown by the shaded area in Figure 24. This region of highly conductive material is detected by the EM survey at depths exceeding 30 m and is likely due to contaminants leaching from the landfill. There is also a possibility that the EM data may reflect some influence from the landfill material since the distance to the landfill is unknown.

Anomaly A-4

43. Anomaly A-4, shown as the shaded area in Figure 24, is located along line EM-2 approximately 50 m south of well ELN-8201. An area of high

conductivity is detected within 15 m of the surface and may be caused by buried conductive materials. Evidence of buried material is detected a short distance away along line EM-3 (see Results, Line EM-3) and can be seen visually to the southeast less than 30 m away. This, however, does not rule out subsurface contaminants as a source of this anomaly. A zone of lower conductive material, detected at a depth greater than 30 m, also exists at this location.

Anomalies A-5 through A-11

44. Anomalies A-5 through A-10 are located north of the landfill, as illustrated by the shaded areas in Figure 24. Anomaly A-11 is located southeast of the landfill along survey line EM-5 and is also illustrated in Figure 24 by a shaded area. Each anomalous area is a region of higher conductive material located at depths exceeding 30 m. Anomaly A-11 is possibly due to contaminants migrating from the landfill in the ground water. Anomalies A-5, A-9, and A-10 may be caused by the diffusion of conductive material from the landfill. It is also a possibility that all of the anomalous zones north of the landfill may be caused by contaminants in the ground-water system originating from another upgradient source, but the results from survey line EM-7 are unable to confirm this possibility. Variations in soil types and properties could be additional causes of the anomalies.

Anomaly A-12

45. Anomaly A-12 is located along survey line EM-6 southeast of the deterrent burning area as indicated by the shaded area in Figure 24. This area is a region of lower resistive (higher conductive) material detected to depths of 30 m. The most likely cause of this anomaly would be subsurface contaminants originating from the deterrent burning area and filtering through the soil to the ground-water table. There are also numerous cultural features in the area but their effects on the resistivity/conductivity data are not believed to be significant. Variations in soil types and properties should also be considered as a possible cause.

Anomaly A-13

46. Anomaly A-13 is located at a distance of 520 m along survey line EM-6. A shaded area indicates the location in Figure 24. This high conductivity (low resistivity) region is detected within 30 m of the surface. Possible causes of this anomaly include mounding of the ground water level, changes in soil properties, or the presence of subsurface contaminants. The

latter hypothesis is supported by the 1955 aerial photo (Figure 3) of the area which indicates the location of a surface pit, designated Site A, approximately 200 m to the northwest.

Anomaly A-14

47. Anomaly A-14 is actually a cluster of three separate anomalous zones detected within 200 m of each other. They are located at the end of survey line EM-6 and within the shaded area shown in Figure 24. Two high conductivity anomalies are located at a distance of 670 and 790 m and are detected within 30 m of the surface. The third is a high conductivity (low resistivity) anomaly located at 690 m and exists at depths greater than 30 m. Without any visible cultural features or evidence of buried material in the area, it is possible the presence of subsurface contaminants from upgradient sources or changes in soil properties caused these anomalous areas.

Conclusions and Recommendations

48. The electromagnetic and resistivity tests performed cannot positively confirm the presence of contaminant plumes in the ground-water system, but can locate areas of concern. The results of this investigation should help determine the location of additional monitoring wells at the landfill site and surrounding area. The suggested locations for additional monitoring wells are the following anomalous areas:

- a. A-11: Ground-water flow at the landfill site is to the southeast. Anomaly A-11 is southeast of the landfill and monitoring wells S1135 and ELN-8203. Contaminants have been consistently found in both of these monitoring wells. The limited data available for well S-85-1153, located approximately 45 m to the north-northeast of A-11, does not indicate any ground-water contamination. A well should be installed along the Perimeter Road a distance of 50 to 75 m southeast of well S-85-1153 to determine if the ground water exiting the installation boundary in that area is contaminated.
- b. A-14: Anomaly A-14 is downgradient of the landfill near the intersection of Perimeter Road and the east-west road south of the landfill. Ground-water flow velocities from previous studies indicate ground-water contaminants from the landfill may have migrated to this area. A well should be installed approximately 140 m west of the road intersection in the area where higher conductive material is detected at depths exceeding 30 m.
- c. A-13: Anomaly A-13 is located due south of the eastern end of the landfill. With the ground-water flow to the southeast,

anomaly A-13 may be situated along the western edge of a contaminant plume originating from the landfill. Ground-water flow may also be changing to a more southerly flow as it gets closer to Lake Wisconsin, as indicated in Figure 7. However, there are insufficient water level data in this area to determine if the ground-water flow direction will change. A well should be installed at anomaly A-13 to determine if the ground water is contaminated and the flow is changing direction. Note that Site A, a possible source area, is located approximately 150 m northwest of this anomaly. Other than its location, nothing else is known about this site at this time.

d. A-3: Anomaly A-3 is located along the eastern edge of the landfill near the BAAP boundary. A strong conductivity high was detected at depth in this area. A well should be installed along the eastern side of the Perimeter Road in this area to determine if contaminants from the landfill are migrating into the ground-water system and off the installation.

e. A-12: Anomaly A-12 is not likely caused by the landfill. If the ground water in this area is contaminated, the deterrent burning area is the probable source. A monitoring well should be installed at this location to determine if contaminants are present in the ground water.

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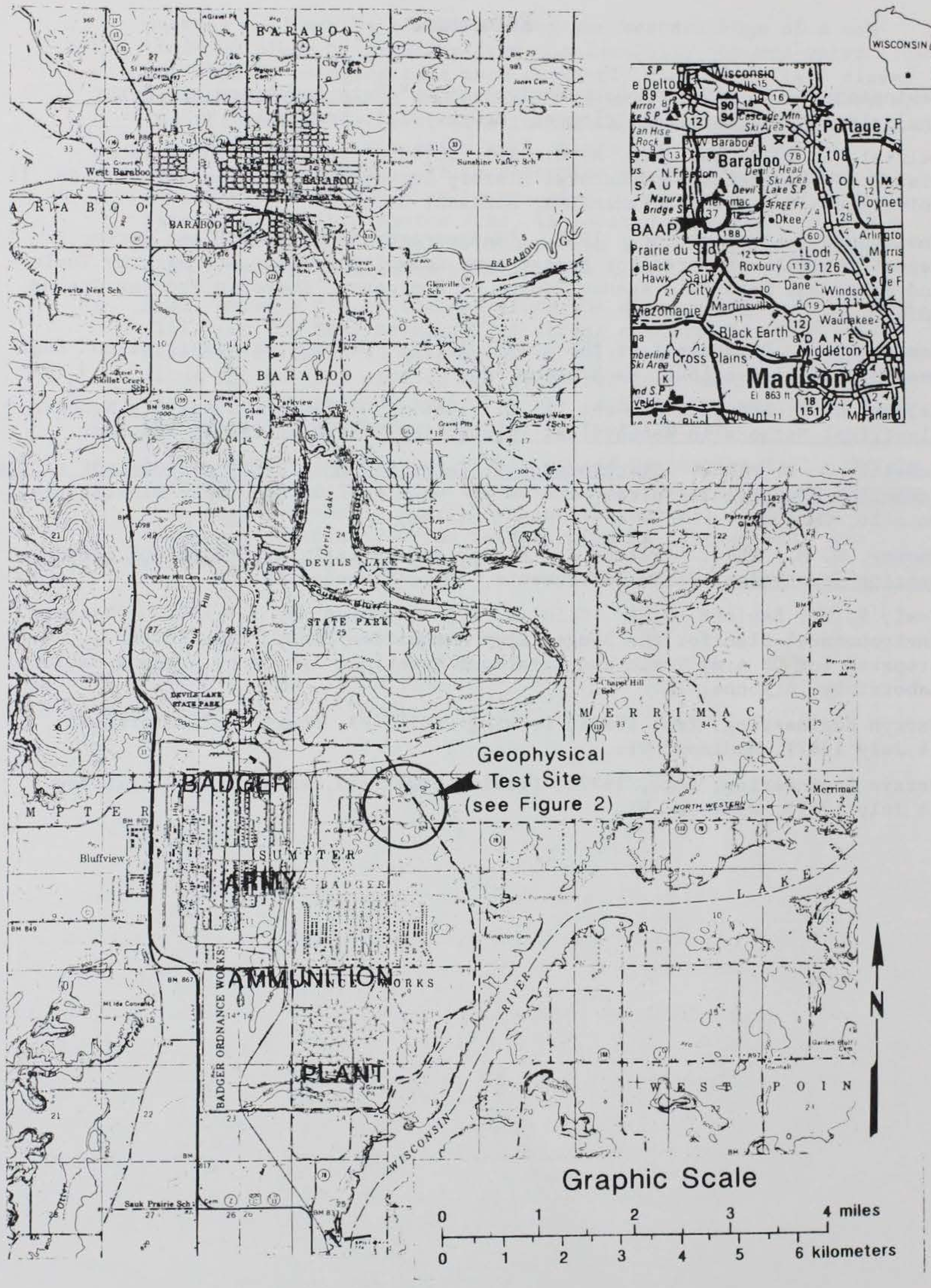

Figure 1. Site map showing the location of the geophysical test site, Badger Army Ammunition Plant, Wisconsin

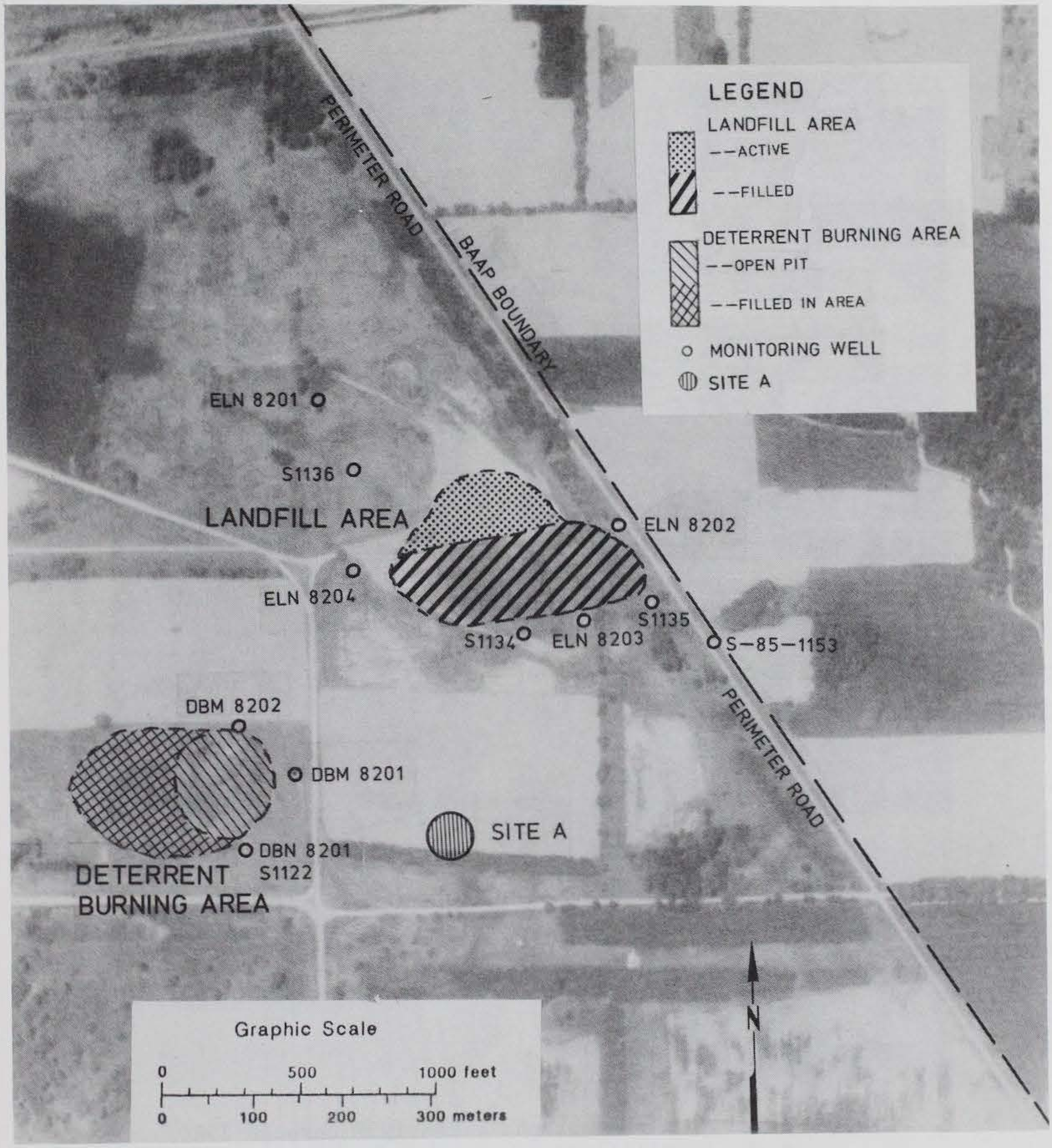

Figure 2. Site map showing the location of the landfill, deterrent burning area, and the ground-water monitoring wells

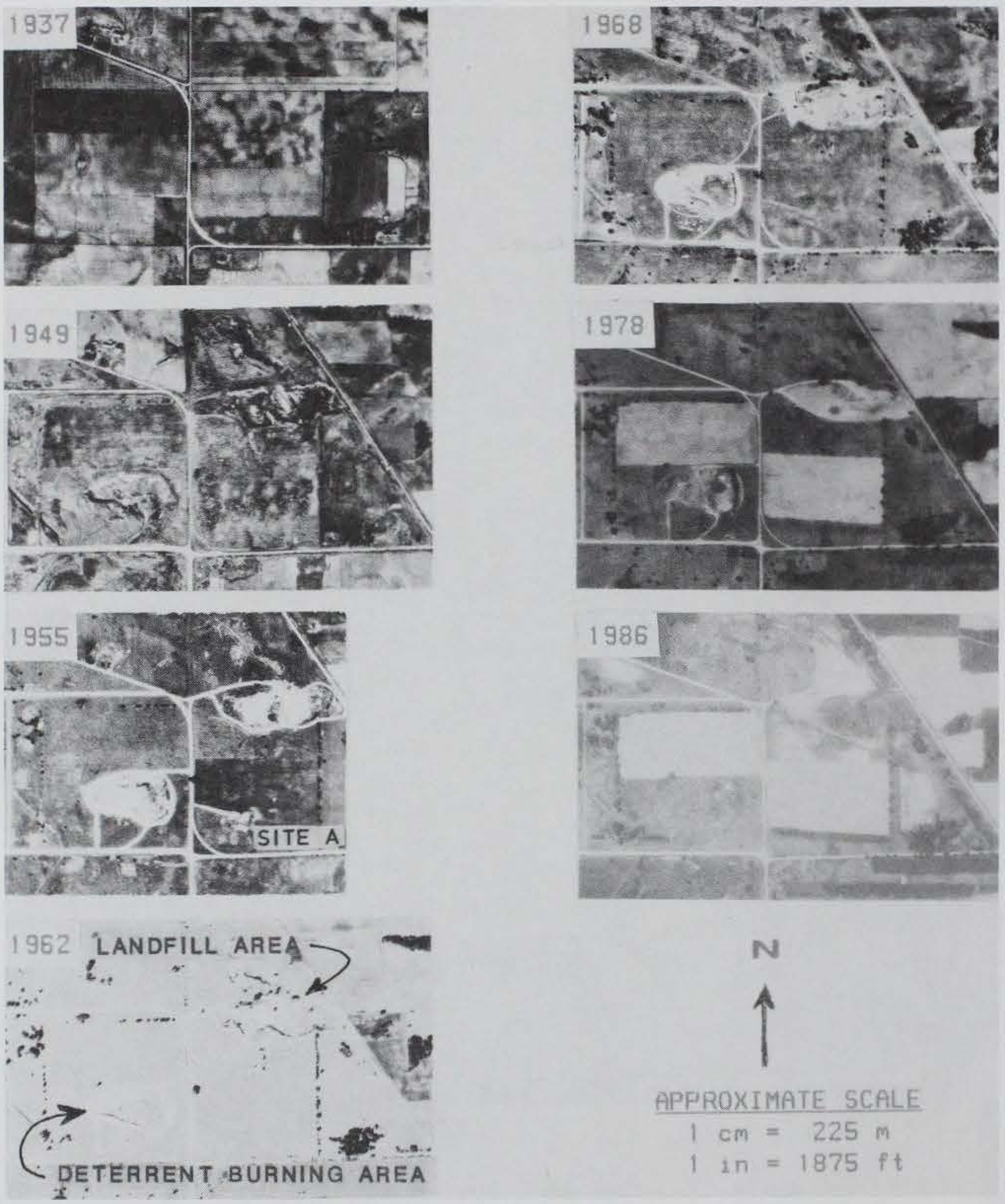

Figure 3. Aerial photographs dated 1937 through 1986
of the landfill and deterrent burning area

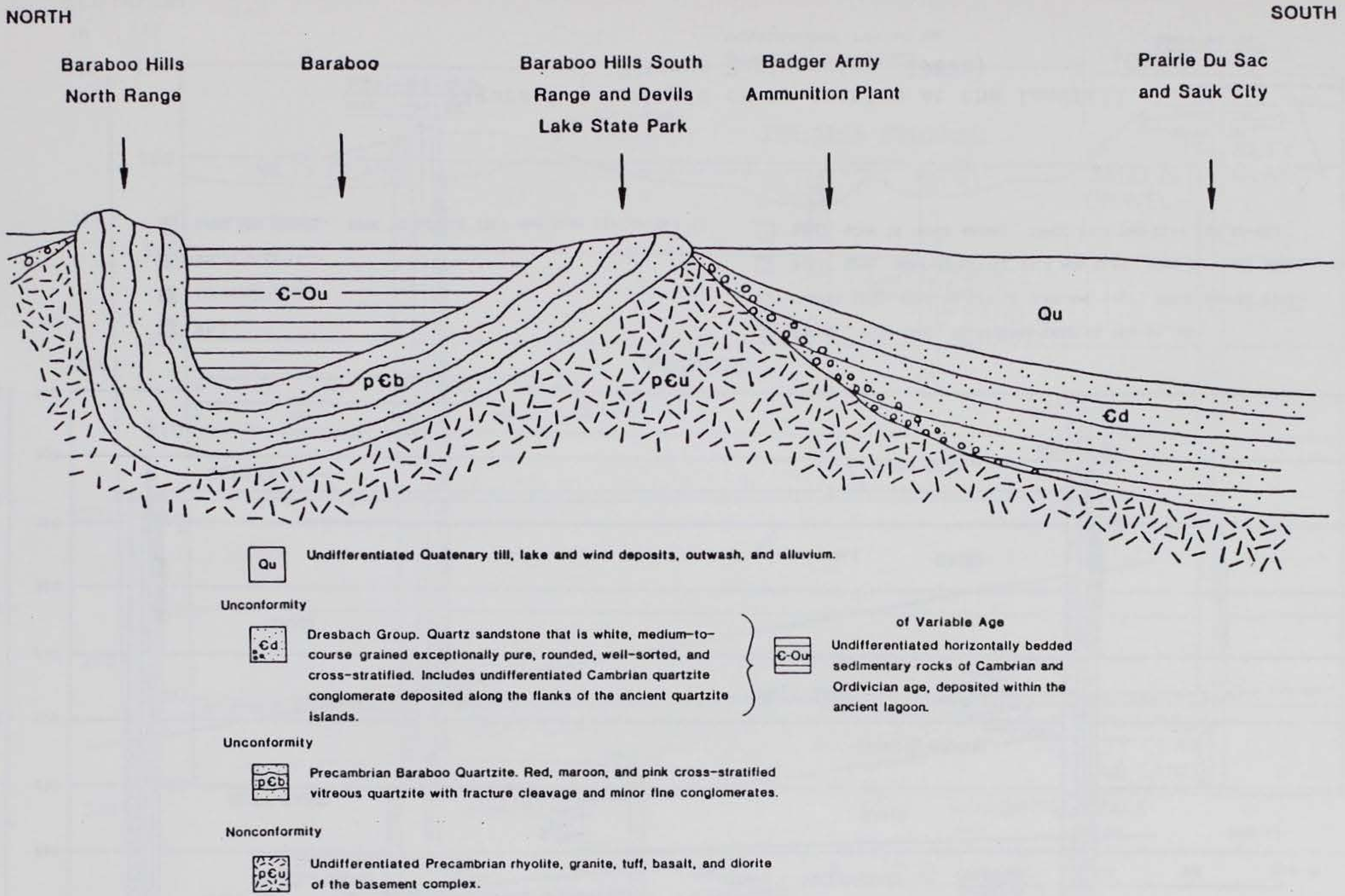

Figure 4. Bedrock geology of the BAAP area (Tsai et al. 1987)

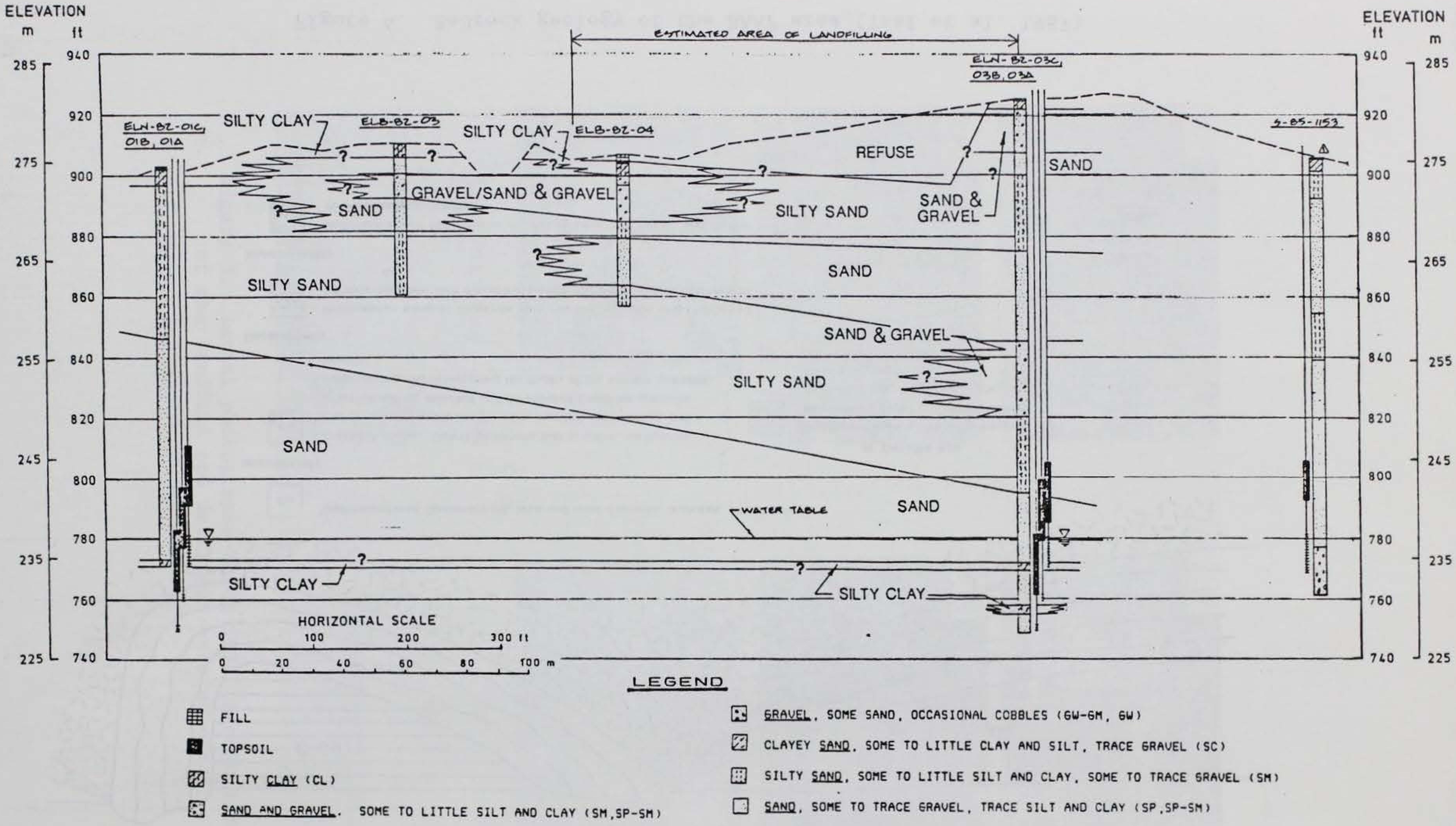

Figure 5. Geologic cross section at the landfill
(Warzyn Engineering 1982e)

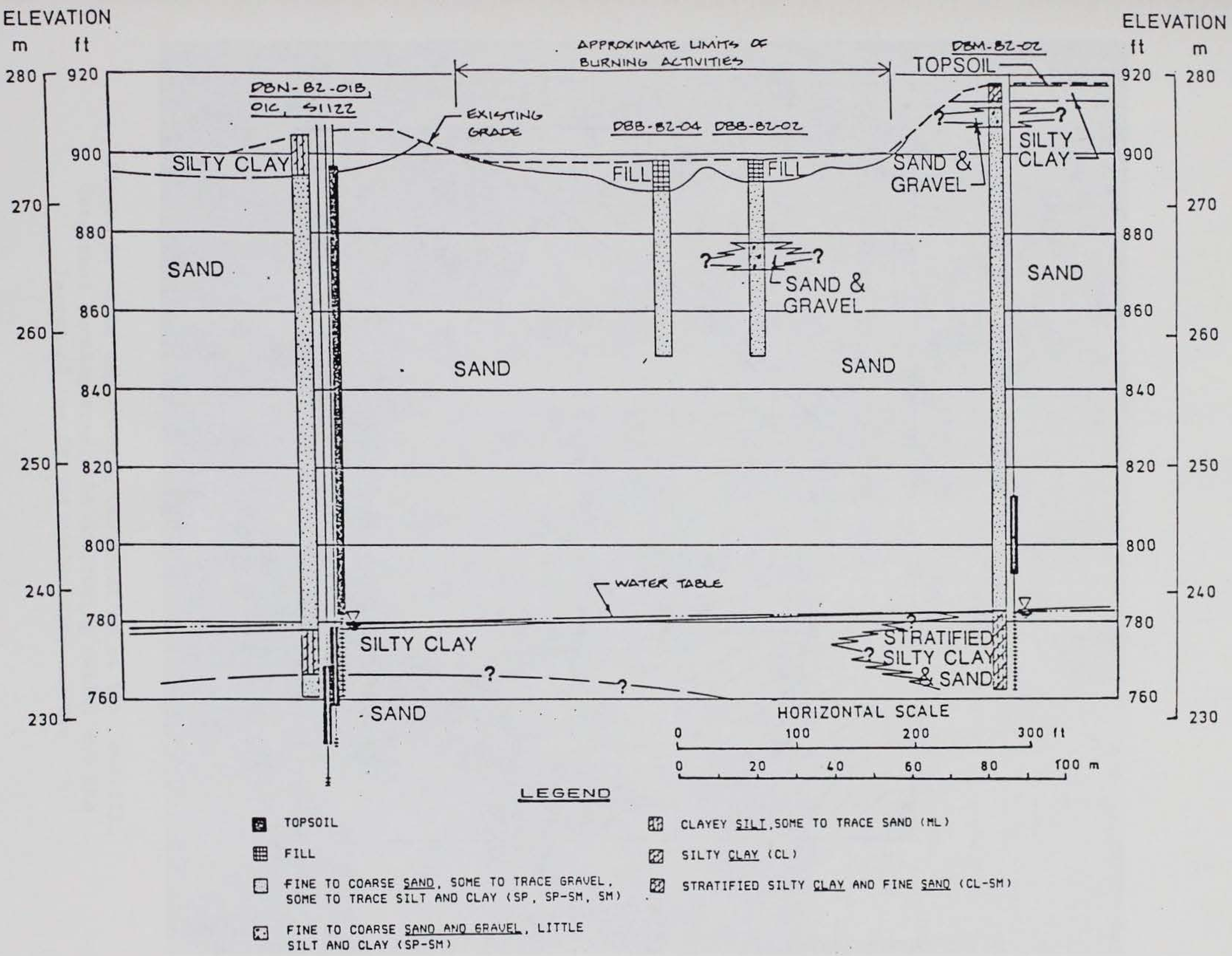

Figure 6. Geologic cross section at the deterrent burning area (Warzyn Engineering 1982f)

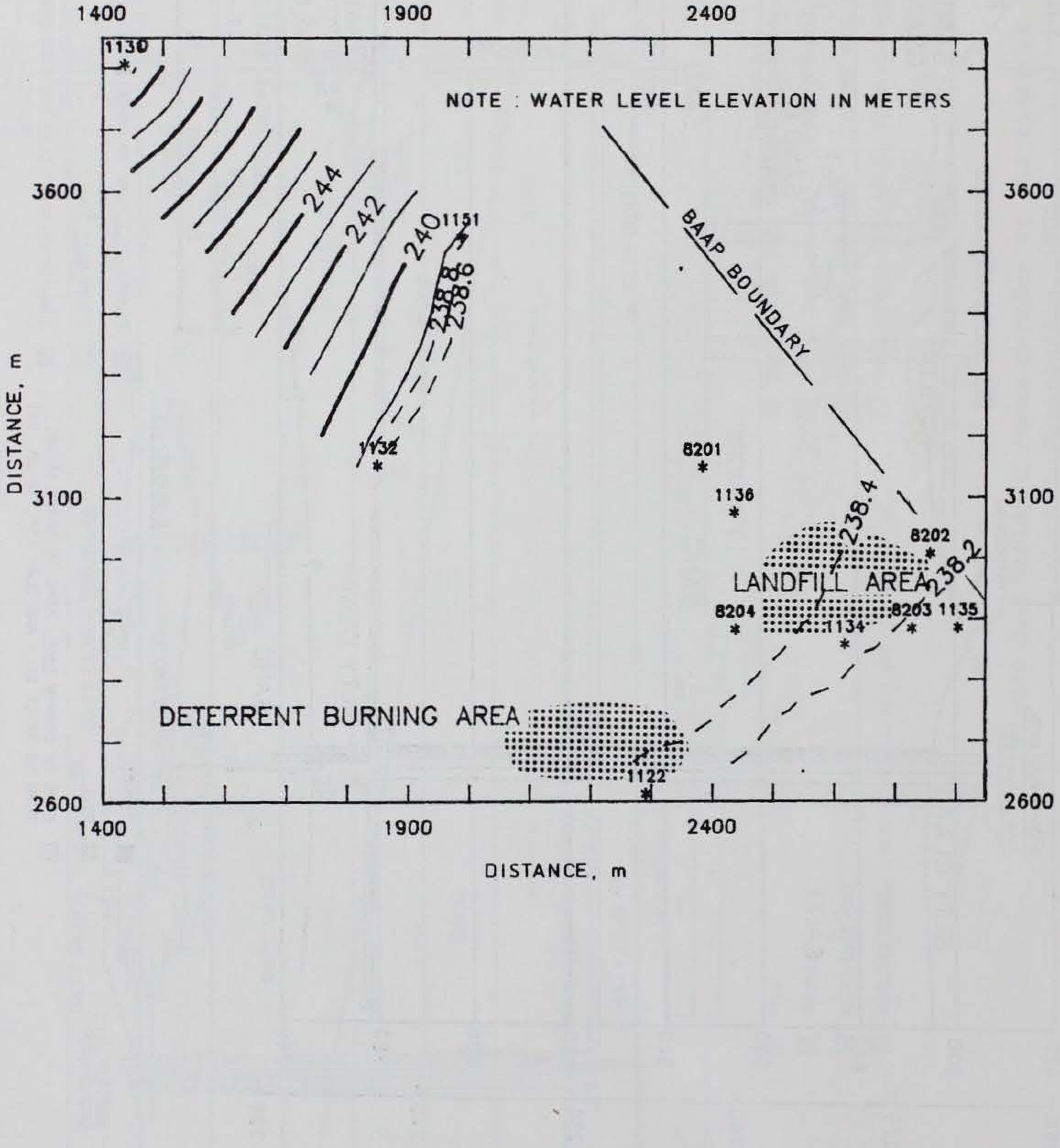

Figure 7. Ground-water elevations below the northwest section of the BAAP on 22 September 1987

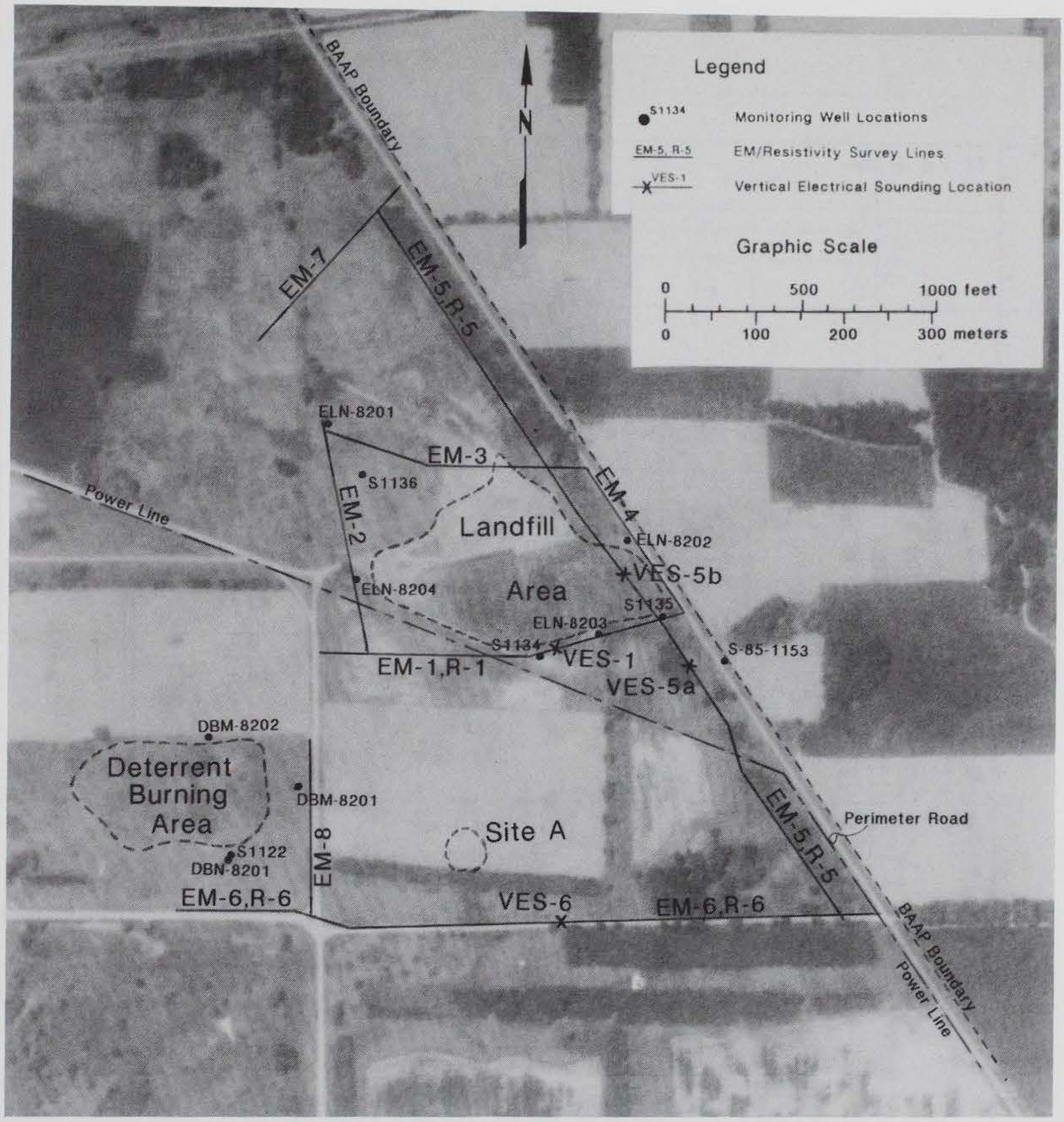

Figure 8. Site map showing the location of the landfill, deterrent burning area, the monitoring wells, and the layout of the EM and resistivity surveys

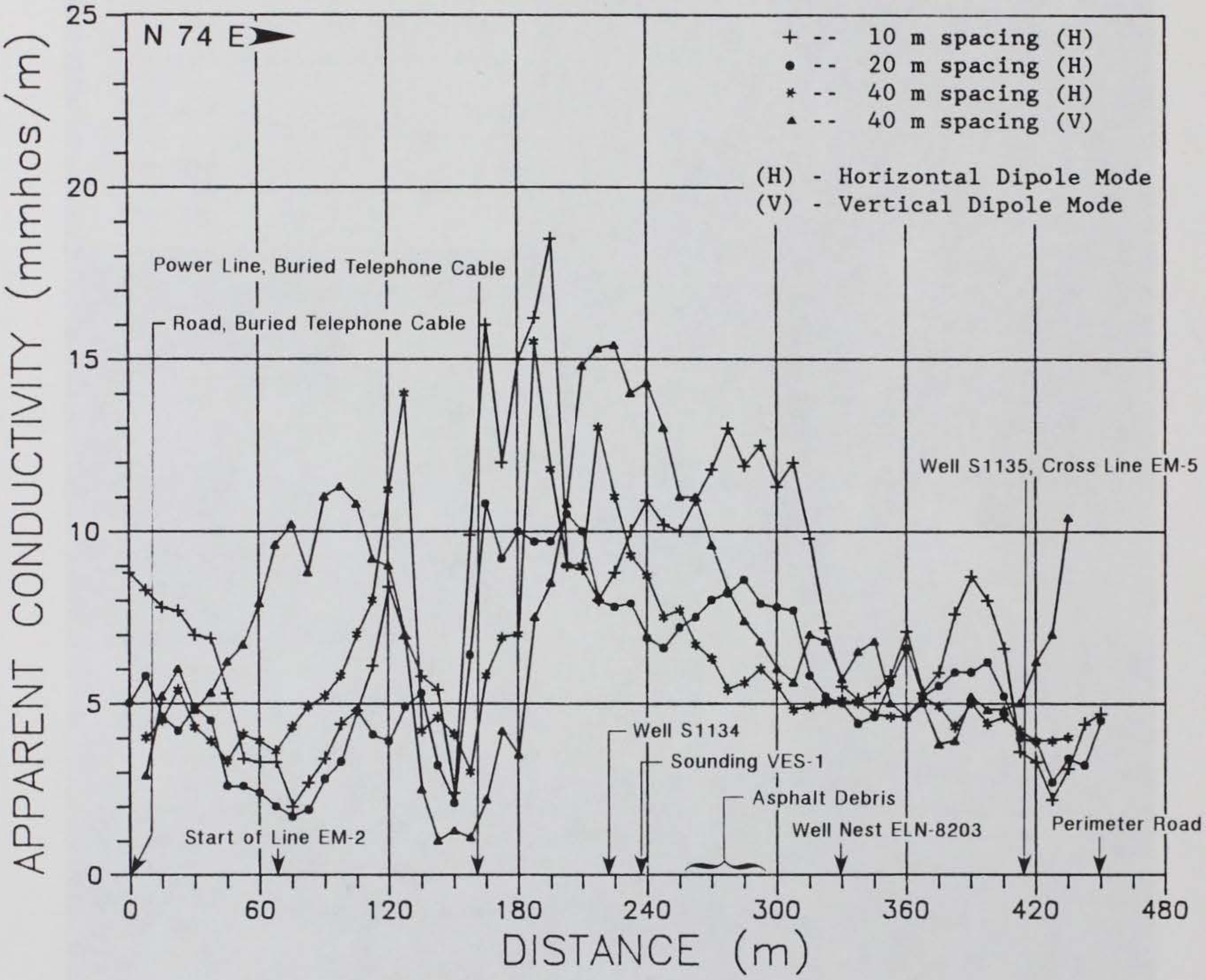

Figure 9. Results of EM survey line EM-1

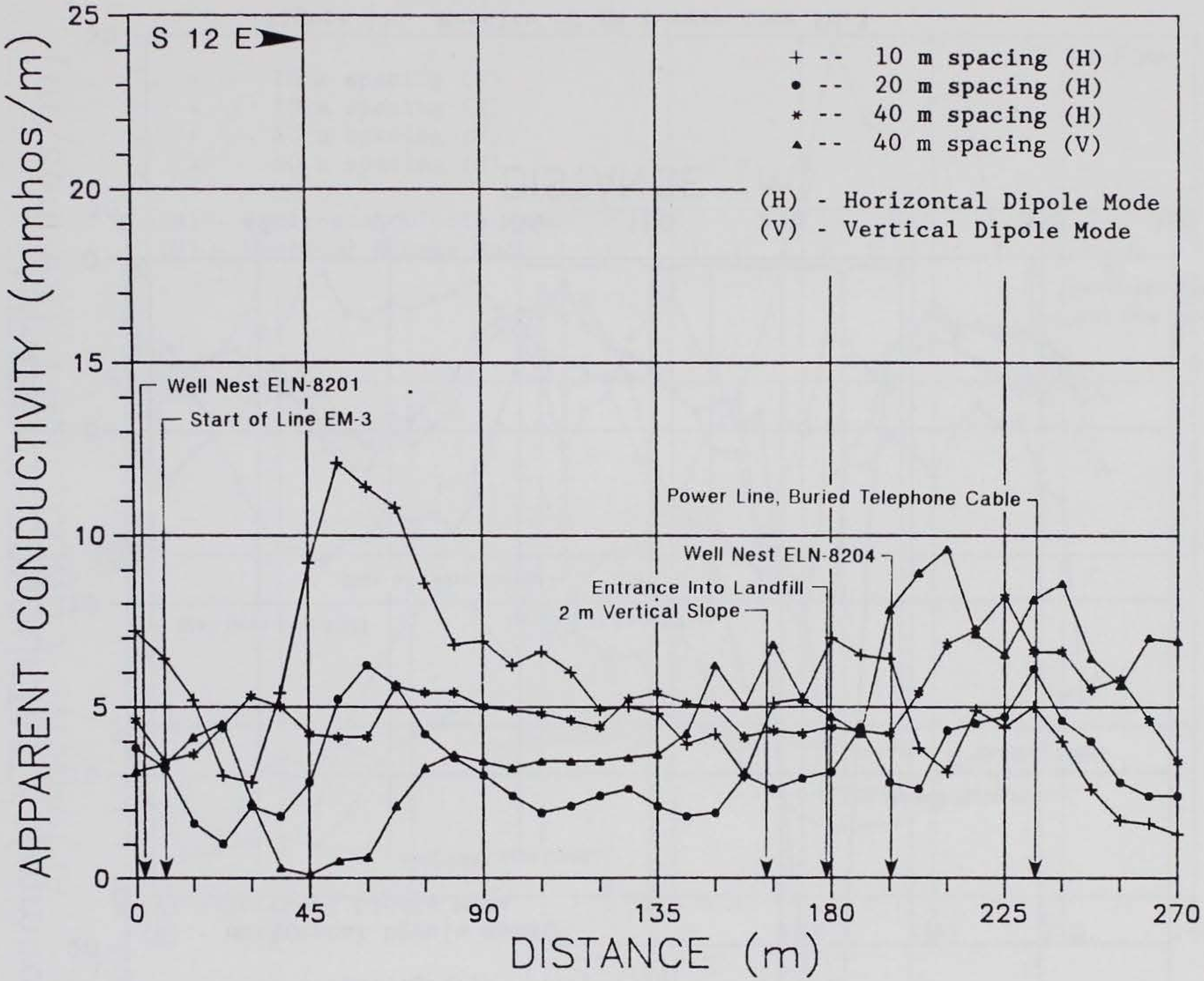

Figure 10. Results of EM survey line EM-2

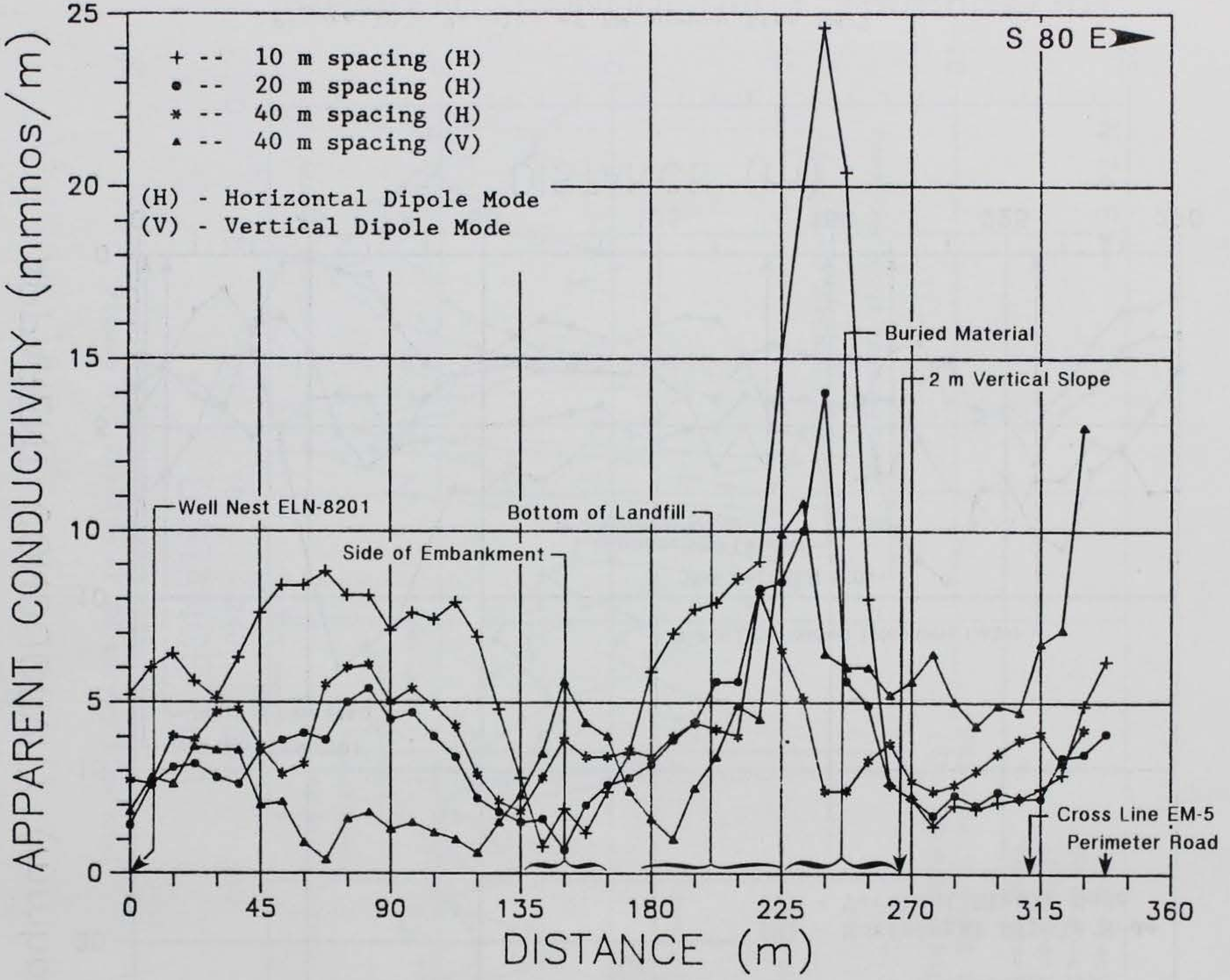

Figure 11. Results of EM survey line EM-3

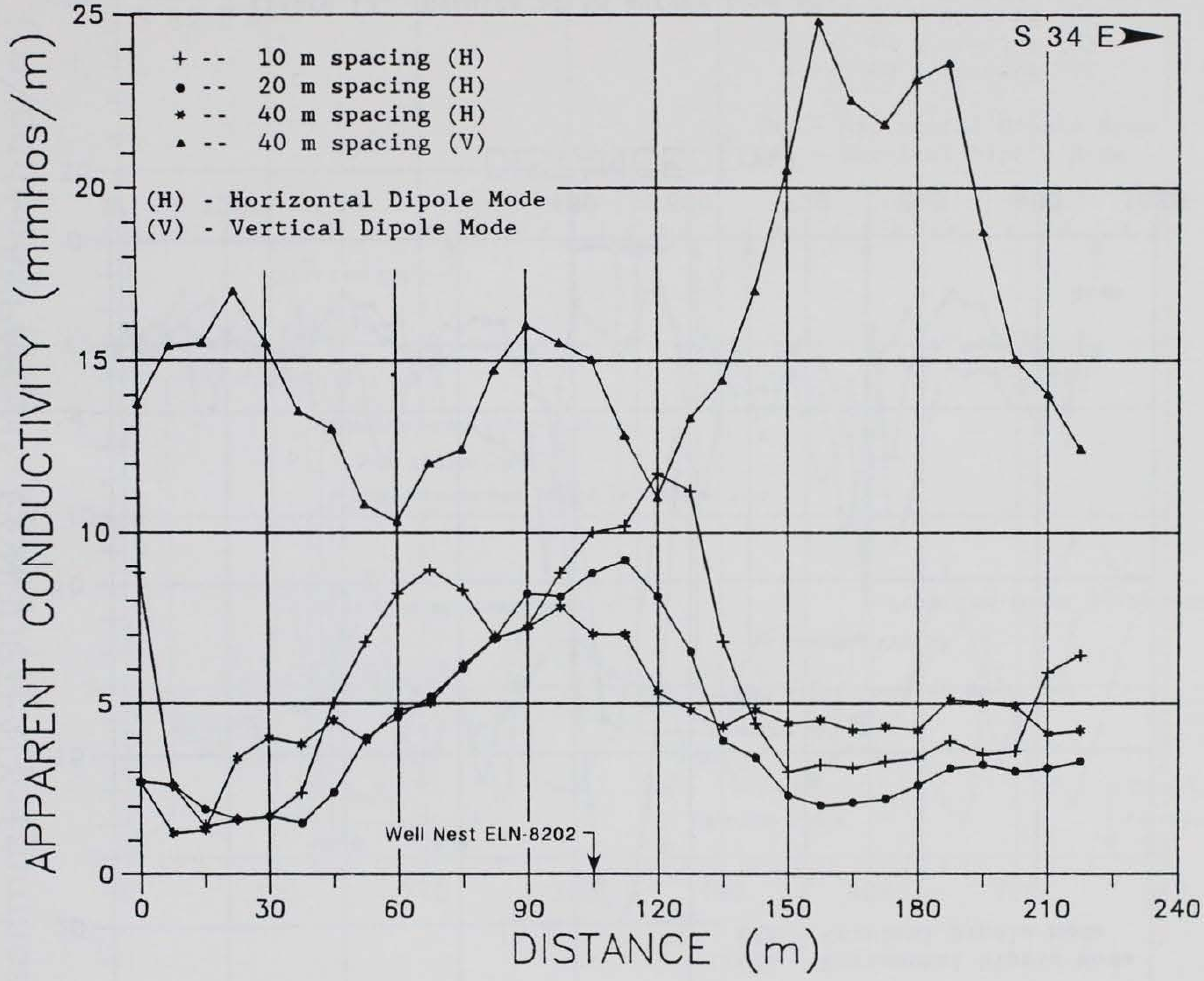

Figure 12. Results of EM survey line EM-4

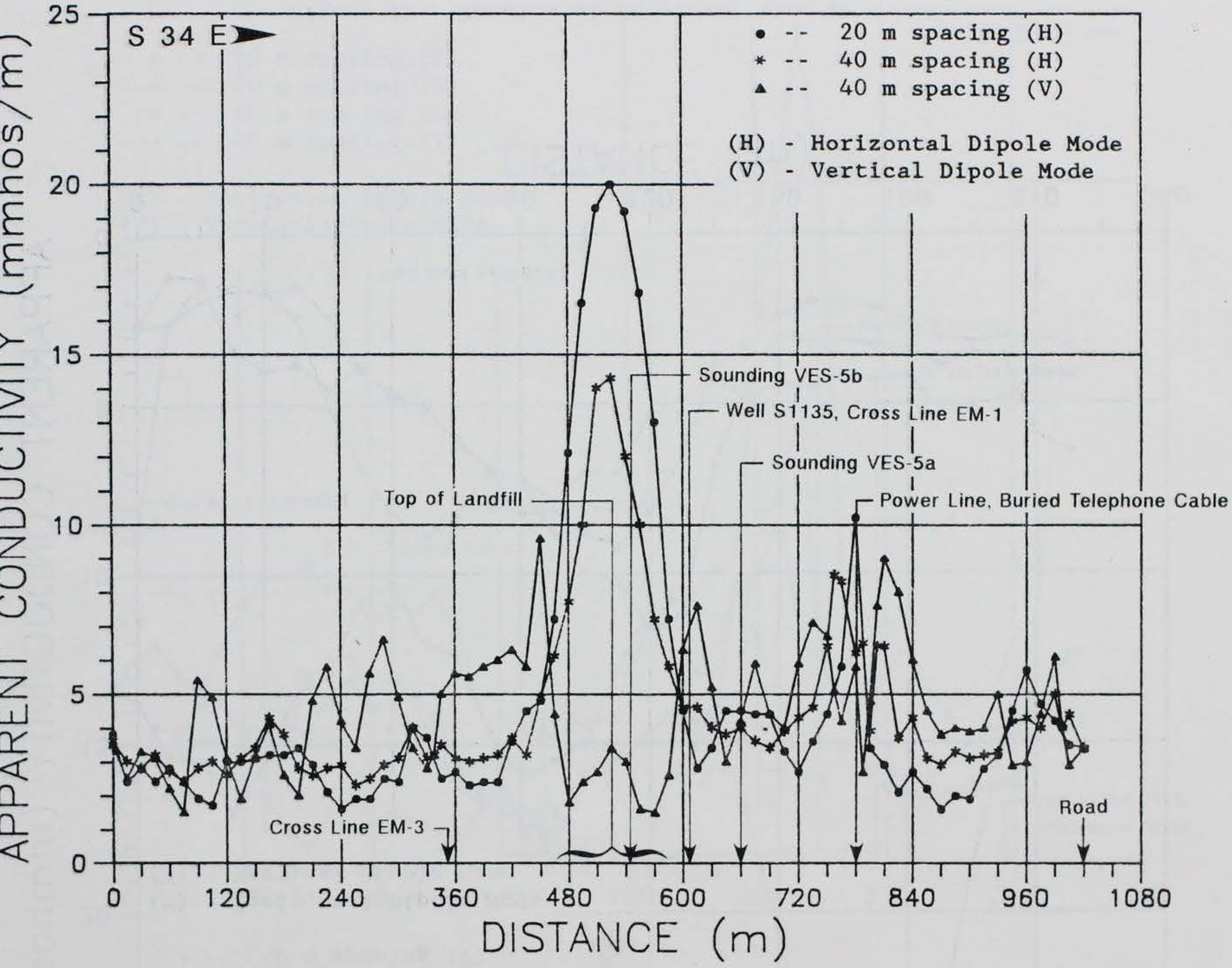

Figure 13. Results of EM survey line EM-5

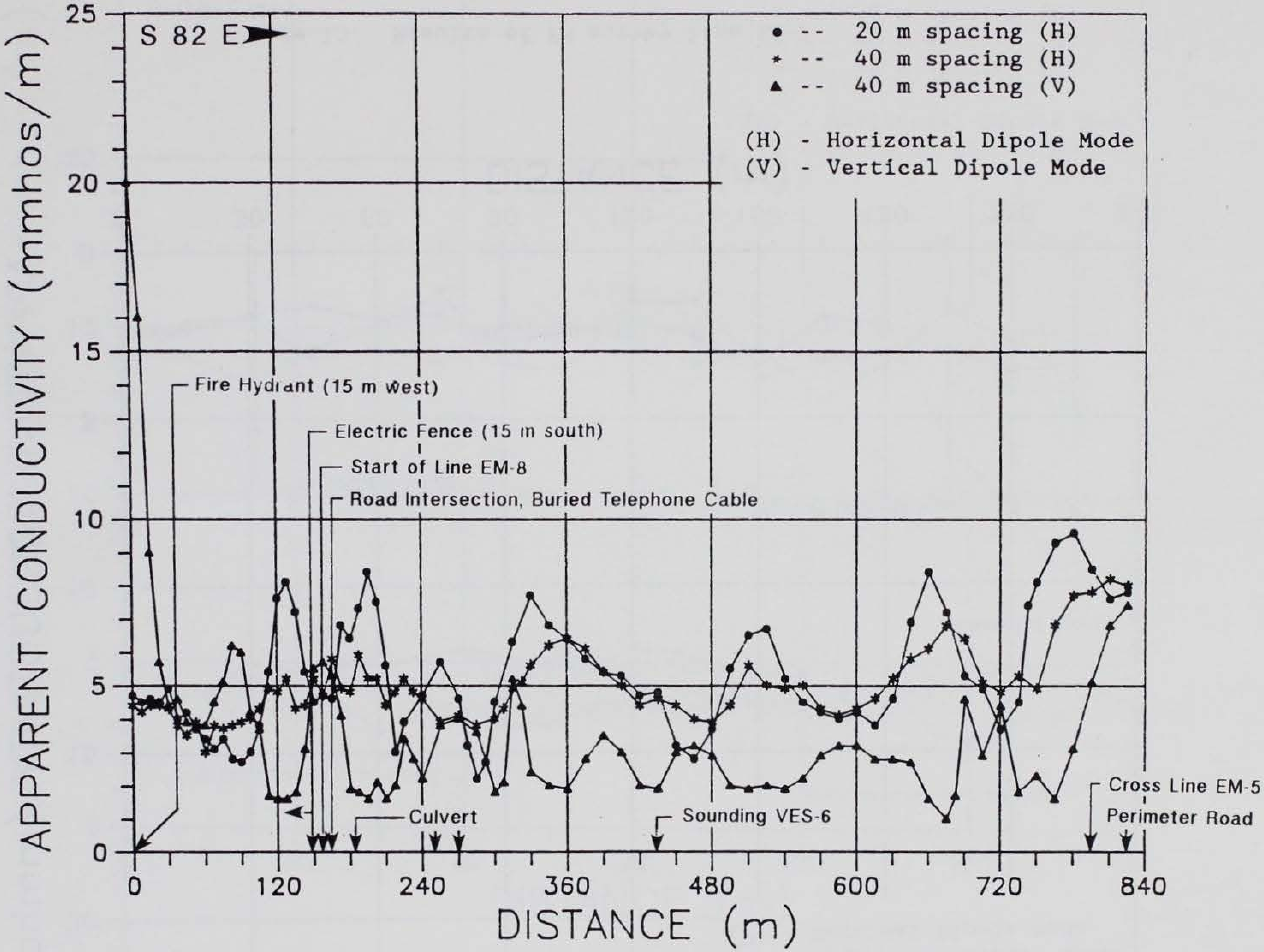

Figure 14. Results of EM survey line EM-6

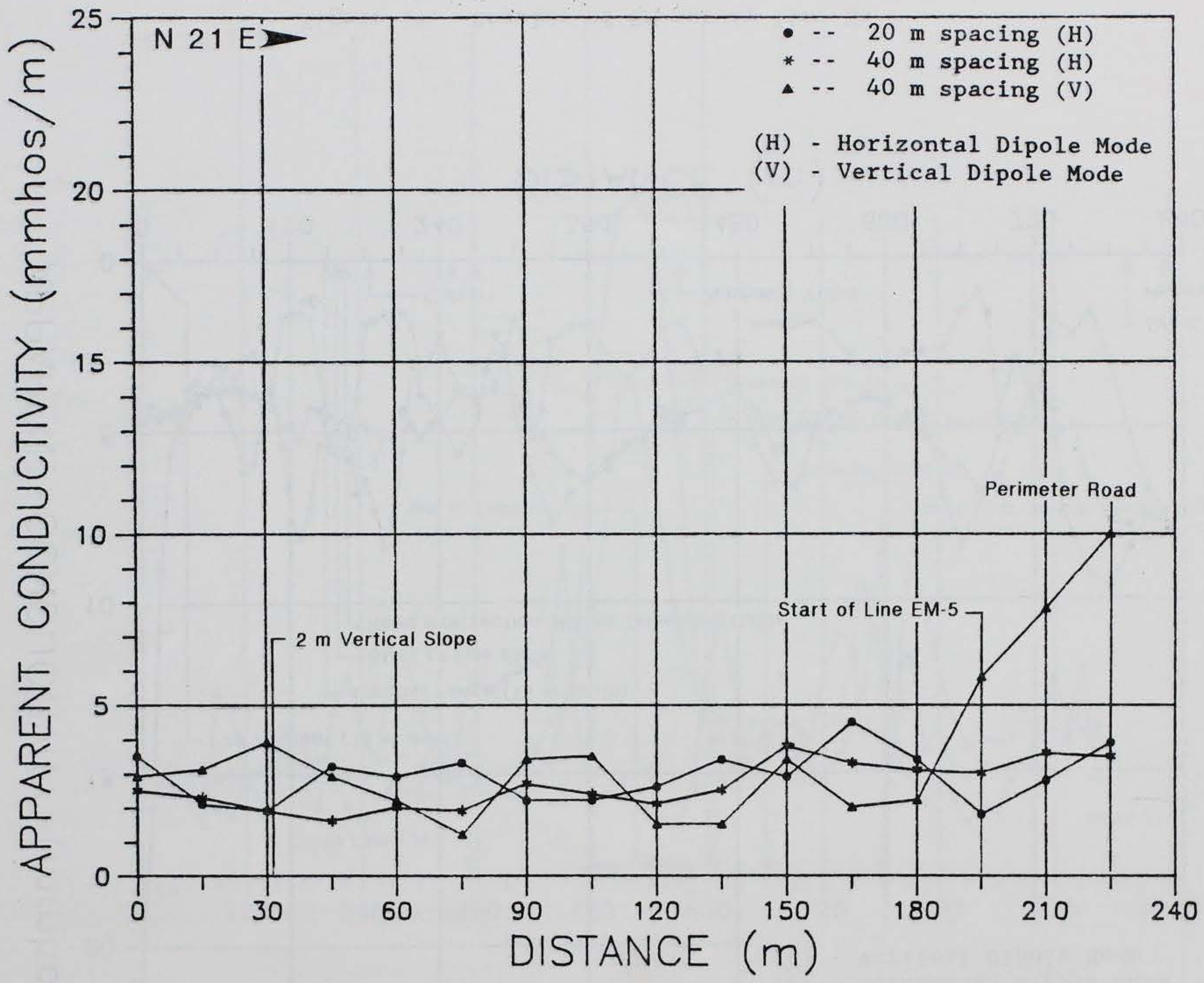

Figure 15. Results of EM survey line EM-7

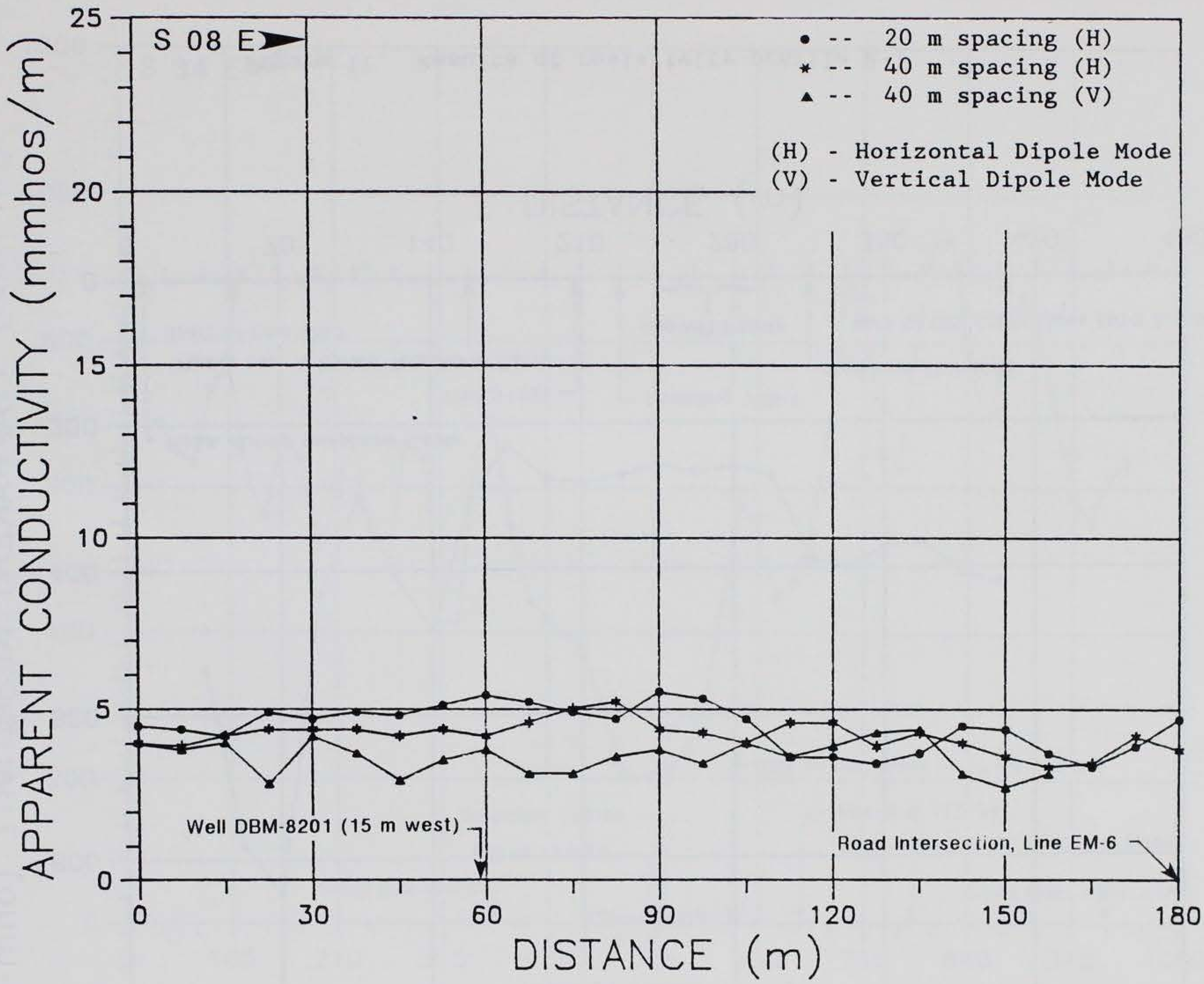

Figure 16. Results of EM survey line EM-8

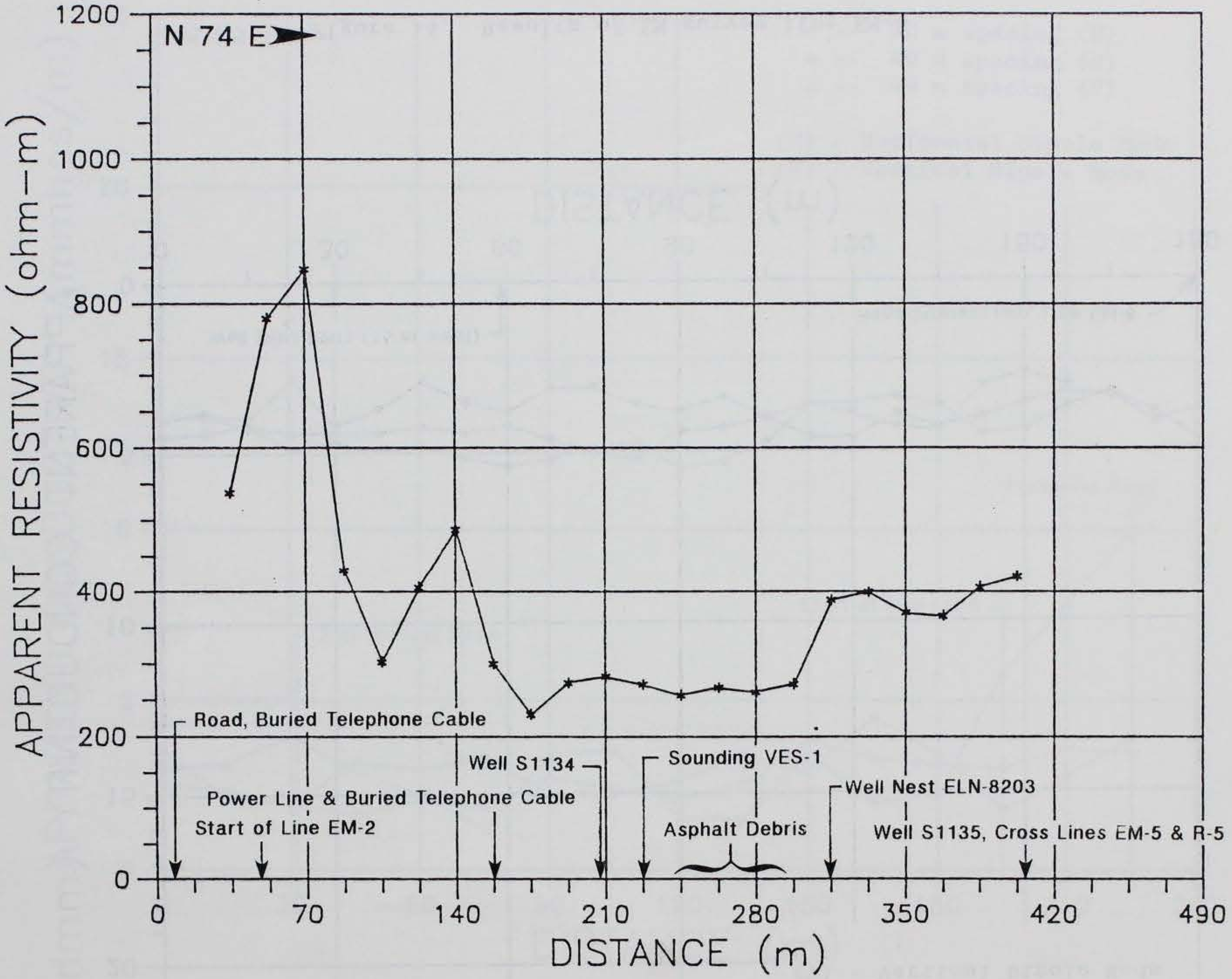

Figure 17. Results of resistivity profile R-1

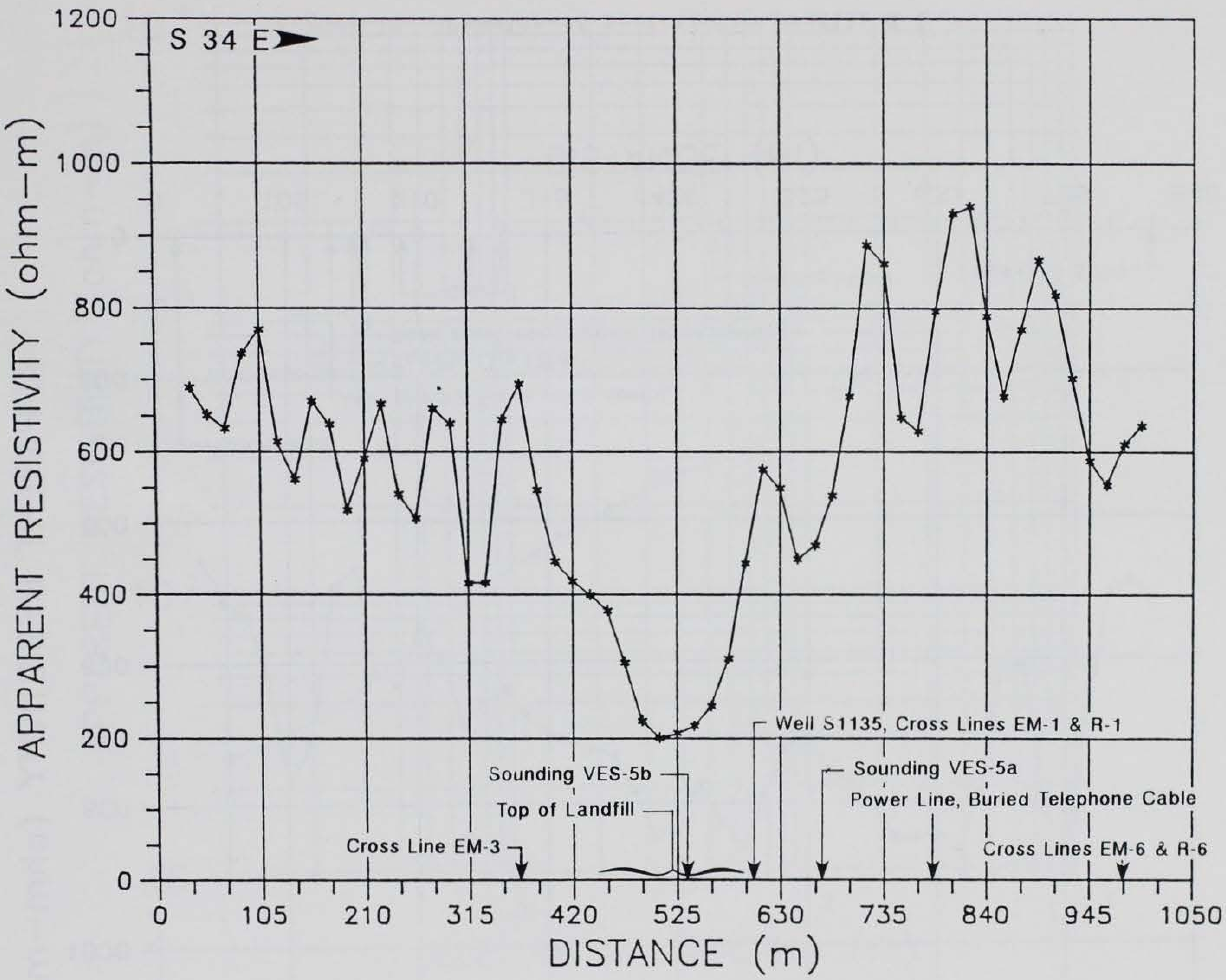

Figure 18. Results of resistivity profile R-5

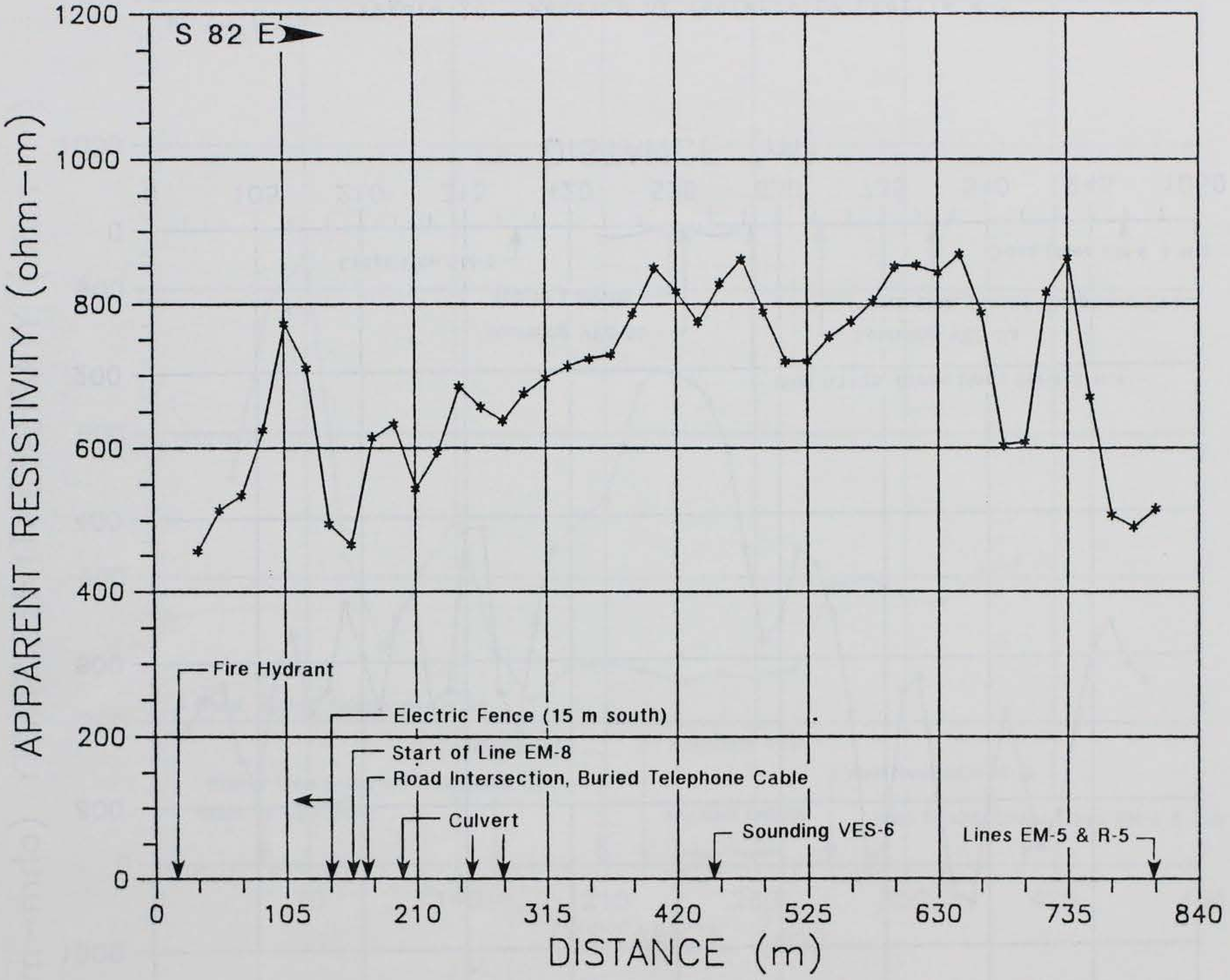

Figure 19. Results of resistivity profile R-6

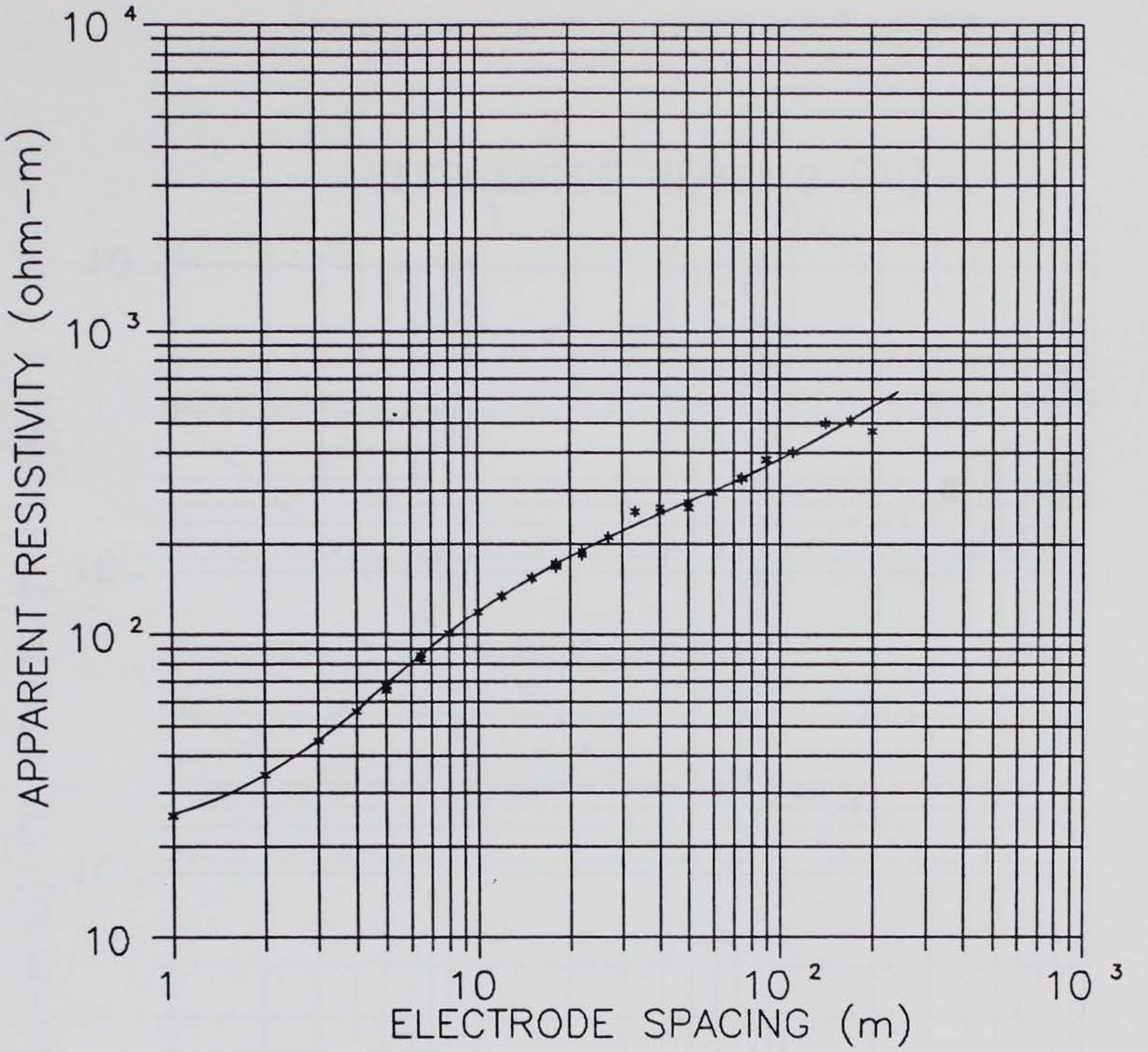

Figure 20. Data acquired from sounding VES-1

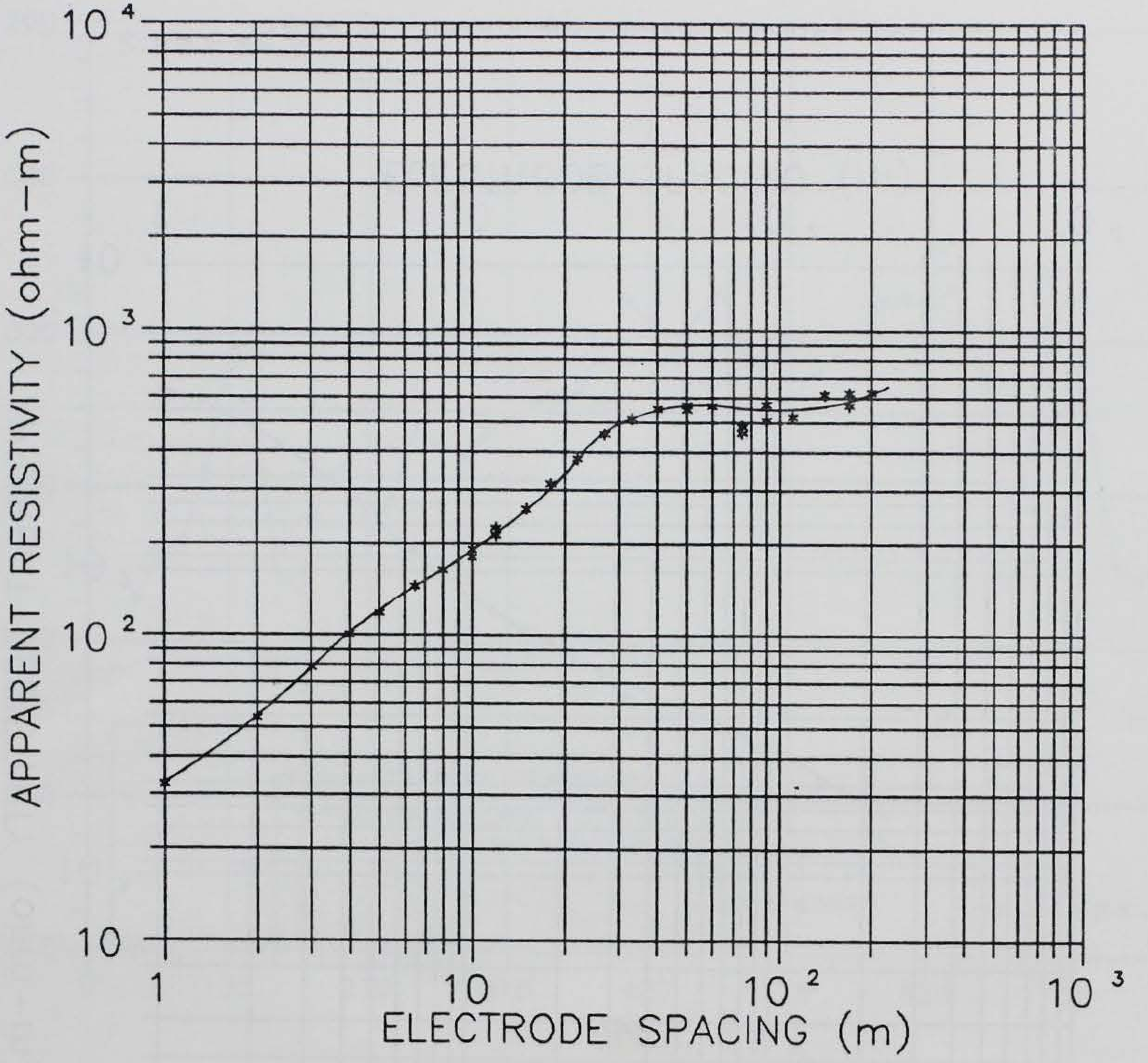

Figure 21. Data acquired from sounding VES-5a

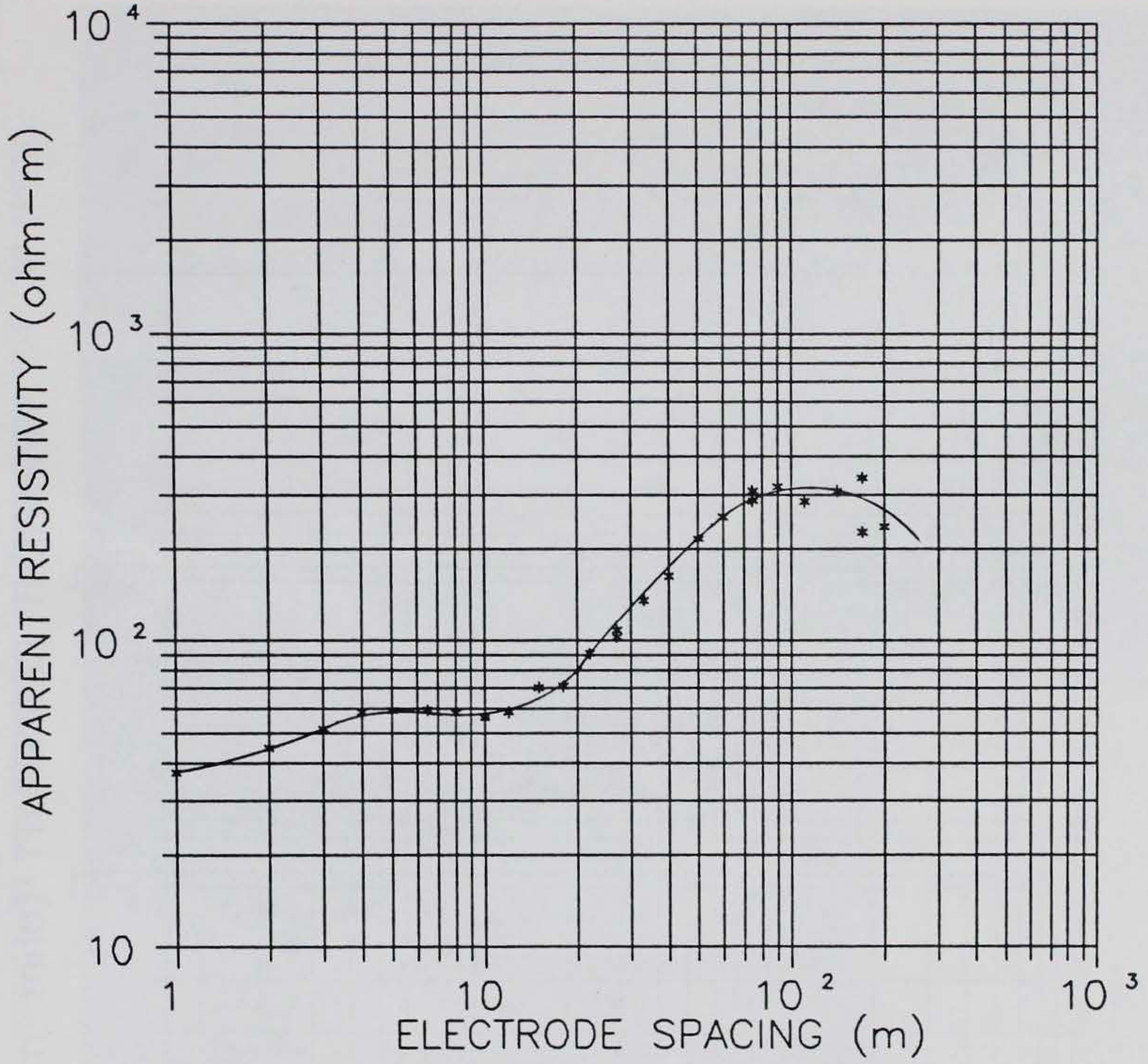

Figure 22. Data acquired from sounding VES-5b

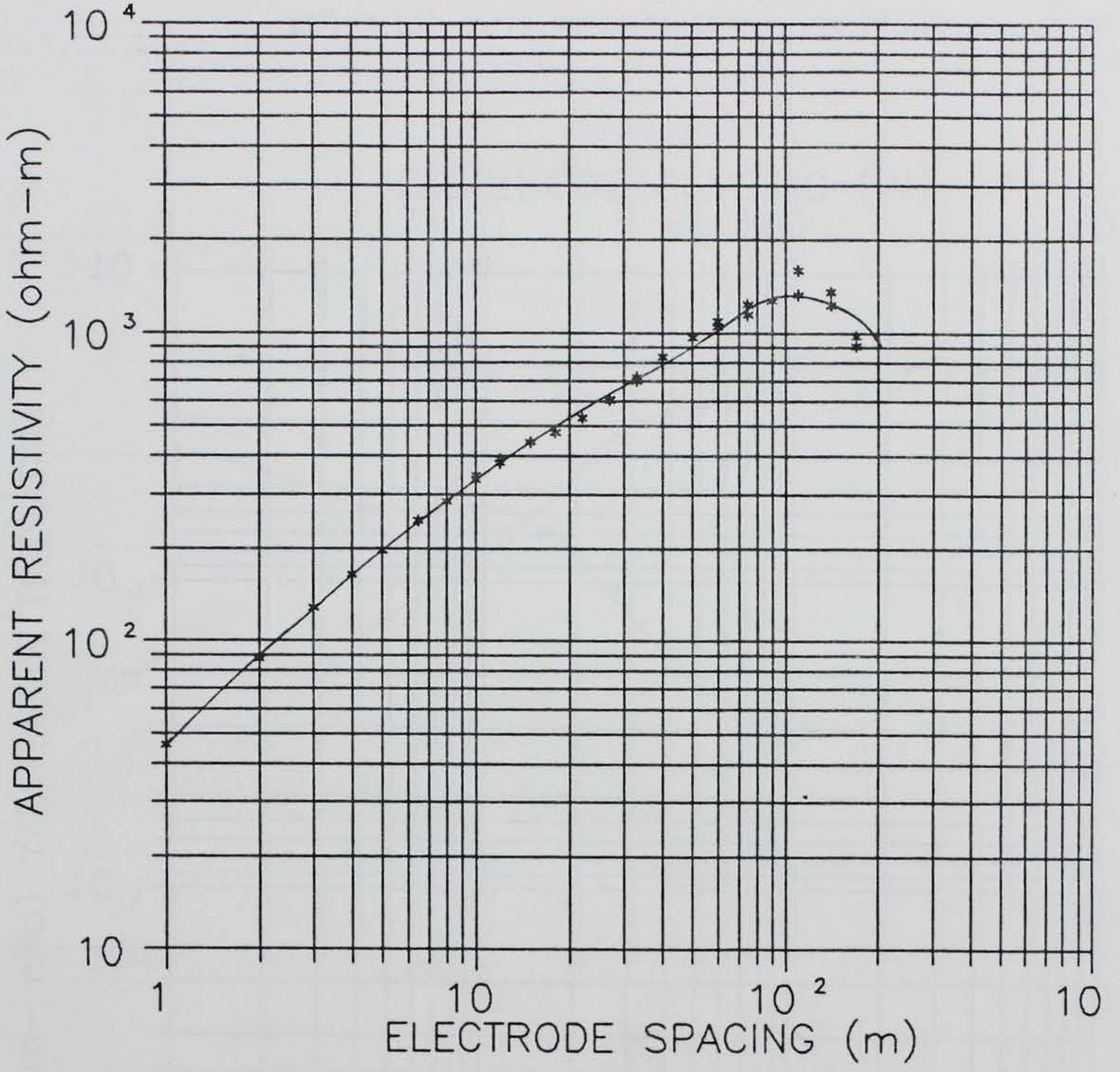

Figure 23. Data acquired from sounding VES-6

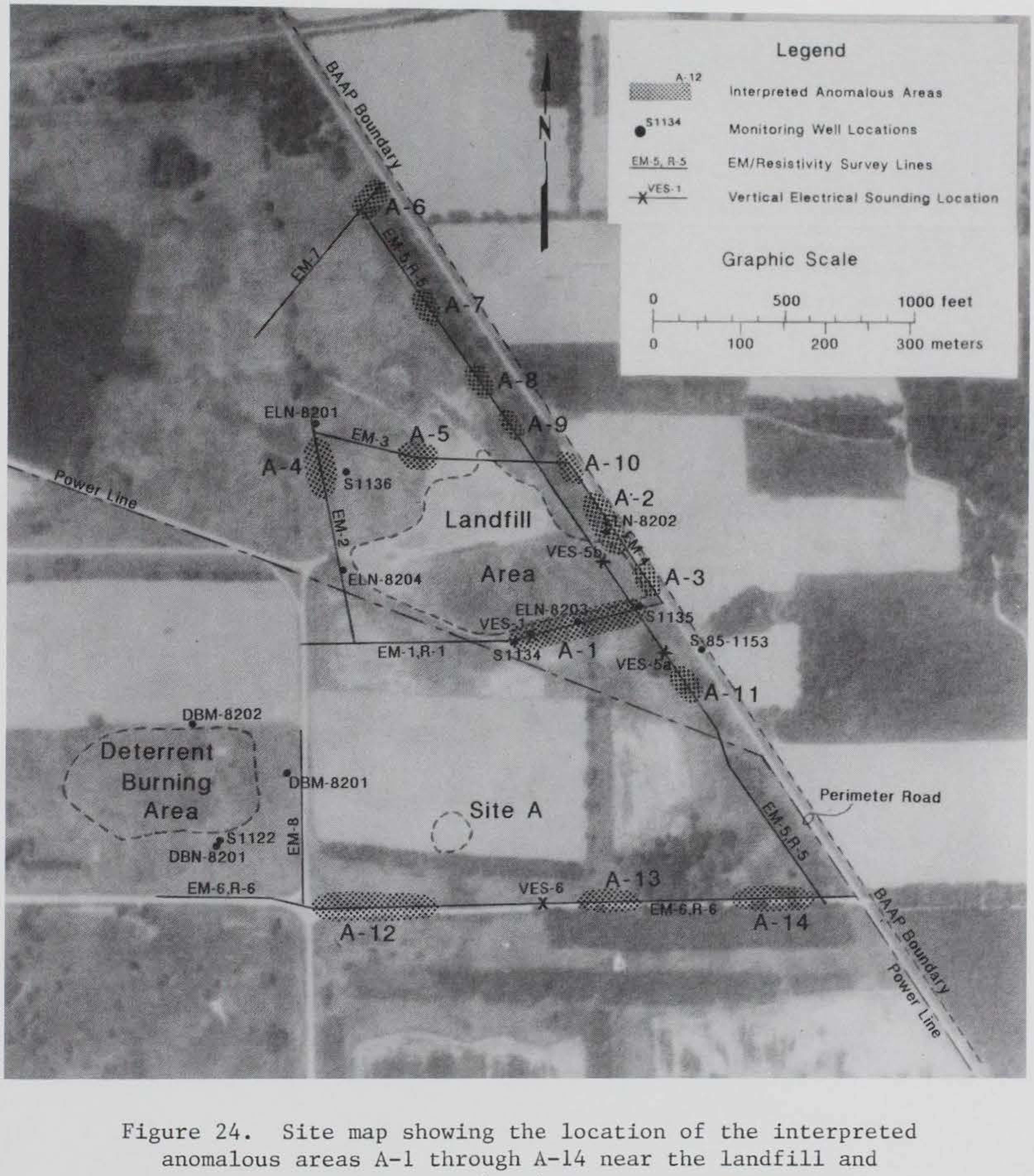

Figure 24. Site map showing the location of the interpreted anomalous areas A-1 through A-14 near the landfill and deterrent burning area