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Geophysical surveys of groundwater contamination at three sanitary landfills in Essex County, Ontario.

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GEOPHYSICAL SURVEYS OF GROUNDWATER CONTAMINATION AT THREE SANITARY LANDFILLS IN ESSEX COUNTY, ONTARIO

by
Ja'Afar W. Ali

A Thesis
submitted to the Faculty of Graduate Studies through
the Department of Geology in partial fulfillment
of the requirements for the degree of
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The University of Windsor

Windsor, Ontario, Canada
1983

DEDICATION

To my parents, brothers and friends. May peace be with you.

ABSTRACT

Surface electrical resistivity surveys were used to assess the extent of the contaminated groundwater plumes caused by leachate from three sanitary landfill sites in Essex County, Ontario: 1) Essex County Landfill No. 1; 2) Essex County Landfill No. 2; and 3) Windsor West End Landfill. The electrical resistivity surveys used the Wenner electrical profiling and sounding techniques. Seismic refraction surveys and electrical conductivity measurements of near-surface water were also used in this study to augment the electrical resistivity survey data.

The above listed landfill sites are situated in silty clay, sand and gravel, and sand surficial deposits, respectively.

Electrical sounding and seismic refraction surveys revealed resistivity and velocity layers which were generally comparable in definition with those indicated by borehole logs. Water table depths were accurately determined by seismic refraction. Apparent resistivity values, measured in the profiling surveys, appeared to be controlled by the character of the earth material and the quality of groundwater. Electrical conductivity measurements indicated deterioration in groundwater quality caused by the landfill sites.

The analysis of the resistivity data indicated that,

at Landfill No. 1, the main body of the contaminant plume extended approximately 300 to 350 m towards the south and southwest at depths of both 4.6 and 12.2 m. At Landfill No. 2, the extent of the contaminant plume was approximately 700, 750, and 650 m towards the east at depths of 1.8, 3.0, and 6.1 m, respectively. Toward the northeast, the extent of the plume was approximately 500 m at depths of both 3.0 and 6.1 m. At Windsor's landfill, the extent of the plume, at depths of both 3.0 and 4.6 m, was approximately 1.8 km toward the south.

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LIST OF ABBREVIATIONS

a	electrode spacing for Wenner array in m
C	coarse sand
°C	Celsius temperature in degrees
d	depth to an interface in m (seismic)
F	fine sand
h	thickness of a resistivity layer in m
i	angle of incidence of a seismic wave
i_c	critical angle for refraction
I	electrical current in mA
L	length in m
M	medium sand
m	metre
m/s	metre/second
mA	milliamperes
mg/l	milligram/litre
mV	millivolts
μS/cm	microsiemens/centimeter
Ωm	ohm-metre
ρ	electrical resistivity in Ωm
ρ_a	apparent resistivity in Ωm
r'	angle of refraction
r	interelectrode distance
R	resistance in Ω

σ	electrical conductivity in μS/cm
s	second
SP	spontaneous potential in mV
T	arrival time of a seismic wave
T_i	intercept time of a seismic wave
V	seismic velocity in m/s
V	voltage in mV
x	shot point - geophone distance in m
x_{cross}	crossover distance in m
Z	thickness of a seismic layer in m

1.0 INTRODUCTION

1.1 Purpose and Scope

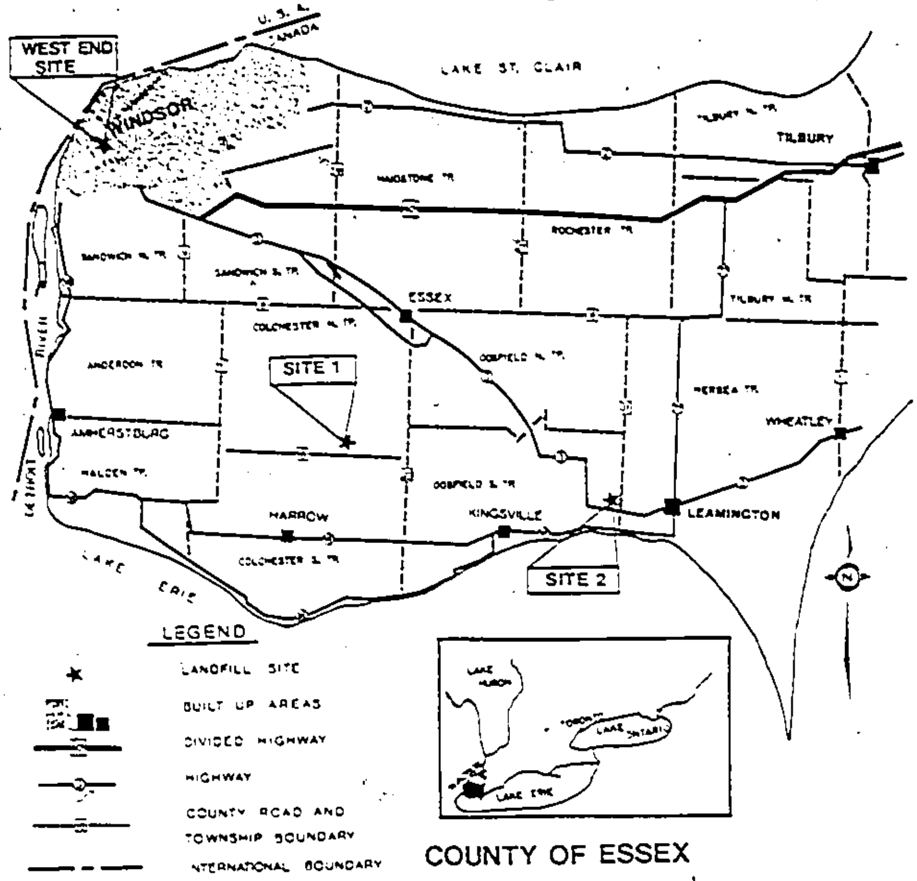
Landfill sites have been long recognized as potential sources of groundwater contamination (Todd and McNulty, 1976). Leachate, a highly mineralized water, is generated by the percolation of water through the refuse and subsequently, the contamination of groundwater is likely to happen as the leachate moves downward and enters the body of the groundwater (Miller 1980).

Surface electrical resistivity methods have been used routinely to detect and trace contaminated groundwater plumes caused by waste disposal sites (Rogers and Kean, 1980; Kelly, 1976; Klefstand, Sendlein and Palmquist, 1975; Stollar and Roux, 1975; and others). Surface electrical resistivity methods are based on the observed inverse relationship between groundwater quality and the electrical resistivity of groundwater. The degree of success achieved with this method depends on several conditions, the most important of which are: good electrical contrast between contaminated and native groundwater, a shallow water table, and homogeneous and uniform subsurface geology (Kelly, 1976).

The purpose of this study is to assess the extent of the contaminated groundwater body produced by leachate from three landfills in Essex County, Ontario: Essex County Landfill No. 1; Essex County Landfill No. 2; and Windsor West End Landfill (Fig. 1). Surface electrical resistivity surveys combined with electrical conductivity measurements of near-surface water and seismic refraction surveys were employed in the vicinity of the three landfill sites.

These landfills may be, or have been shown to be sources of groundwater contamination because of the generation of leachate caused by water percolating through the refuse (Miller, 1980). In the area near the town of Leamington, where Essex County Landfill No. 2 is located, several residents who depend on groundwater for their domestic supply have complained about groundwater quality and some health problems, possibly related to contaminated groundwater, have occurred (local residents, personal communication). A study conducted by Essop and Brown (1980) concludes that the groundwater in the area of this landfill has been seriously degraded by leachate from the landfill.

Surface electrical resistivity methods were used in lieu of the normal method of installing observation wells and sampling the groundwater. The resistivity technique



COUNTY OF ESSEX
GENERAL LOCATION MAP

FIG. 1

0 1 2 3 4 5 KILOMETRES
Scale

is less expensive and more flexible than the observation wells approach. Also, it can be used as a guide in locating subsequent water quality monitoring wells.

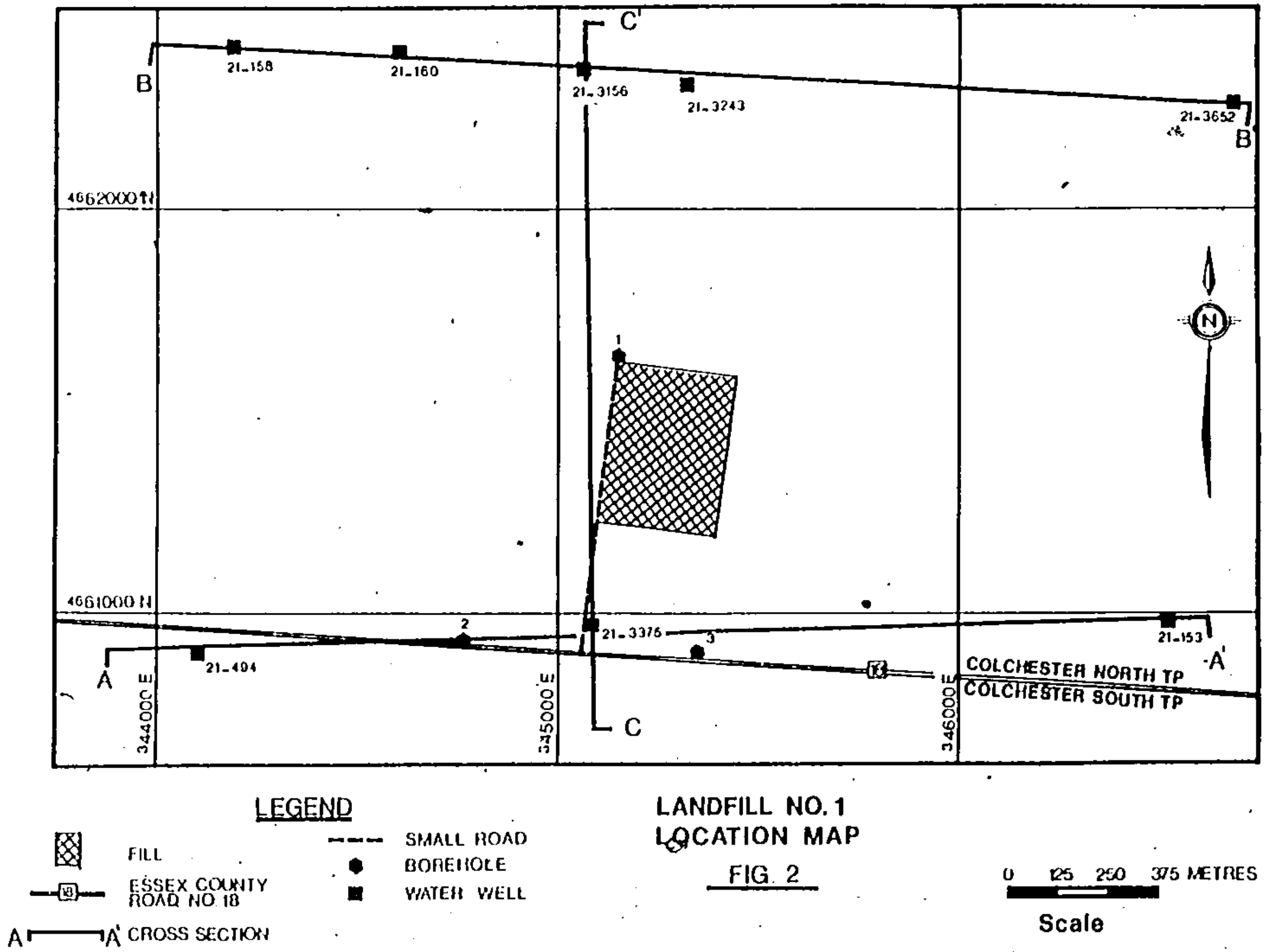
1.2 Location of the Study Areas

This study has been conducted at three landfill sites in Essex County, Ontario, Canada (Fig. 1) which lies between latitudes 40°00' N and 42°20'N, and longitudes 82°30'W and 83°08'W.

Essex County Landfill No. 1 is located on the north side of the Essex County Road No. 18 within Colchester North Township (Fig. 1). This landfill site lies between grid lines 345075 E and 345500 E, and 466175 N and 4661625 N of the Universal Transverse Mercator Grid System (Fig. 2). The National Topographic System (NTS) maps Nos. 40J/2c and 40G/15f cover the area at a scale of 1:25,000.

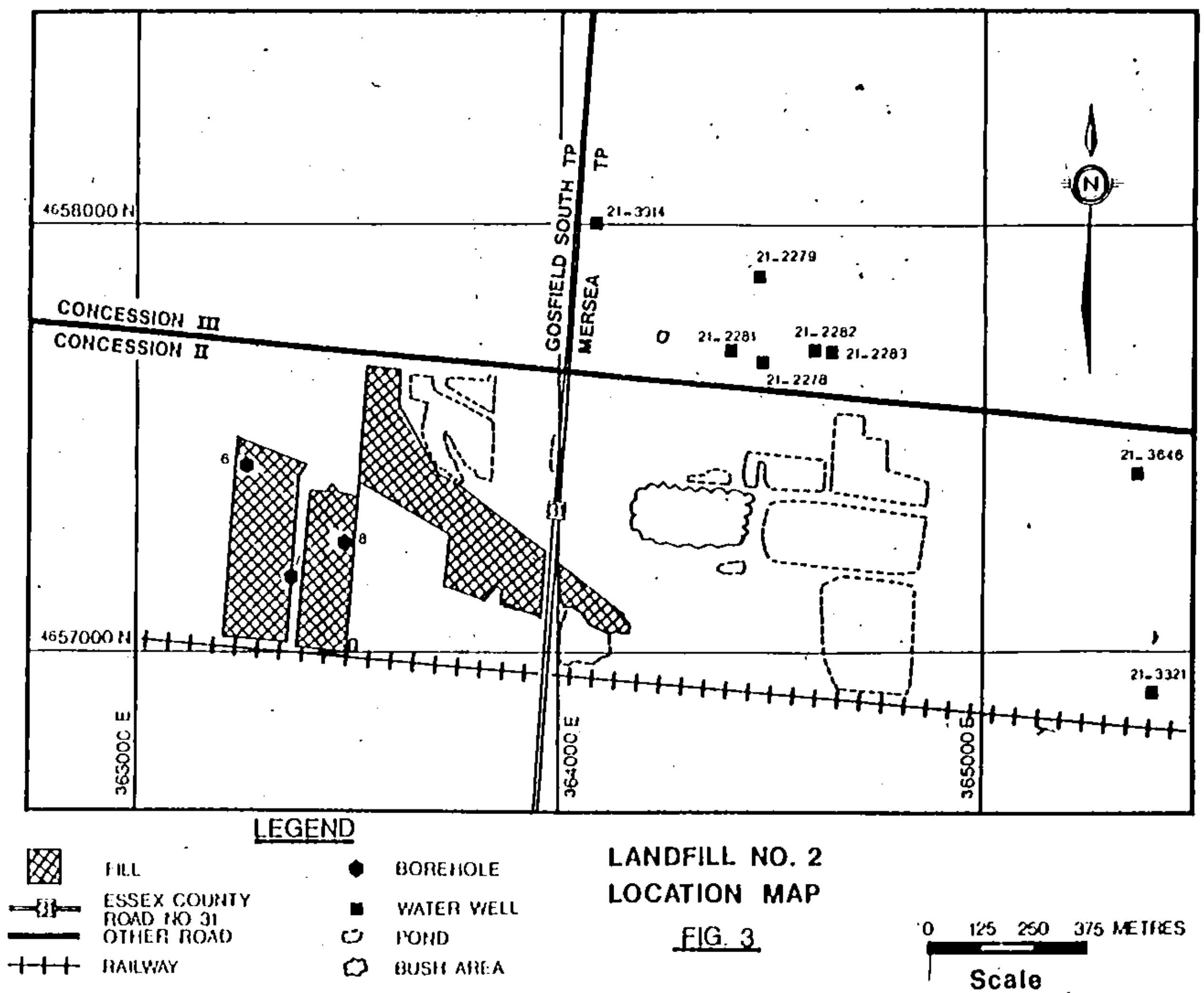
Essex County Landfill No. 2 is located on the west side of the Essex County Road No. 31 in the Gosfield South Township. A small abandoned landfill is found on the east side of that road within Mersea Township (Fig. 1). These landfill sites lie between grid lines 363200 E and 364200 E, and 4657000 N and 4657700 N of the Universal Transverse Mercator Grid System (Fig. 3). NTS map No. 40J/2b covers the area at a scale of 1:25,000.

The Windsor West End Landfill is located between Malden



LANDFILL NO. 1
LOCATION MAP

FIG. 2



LANDFILL NO. 2
LOCATION MAP
FIG. 3

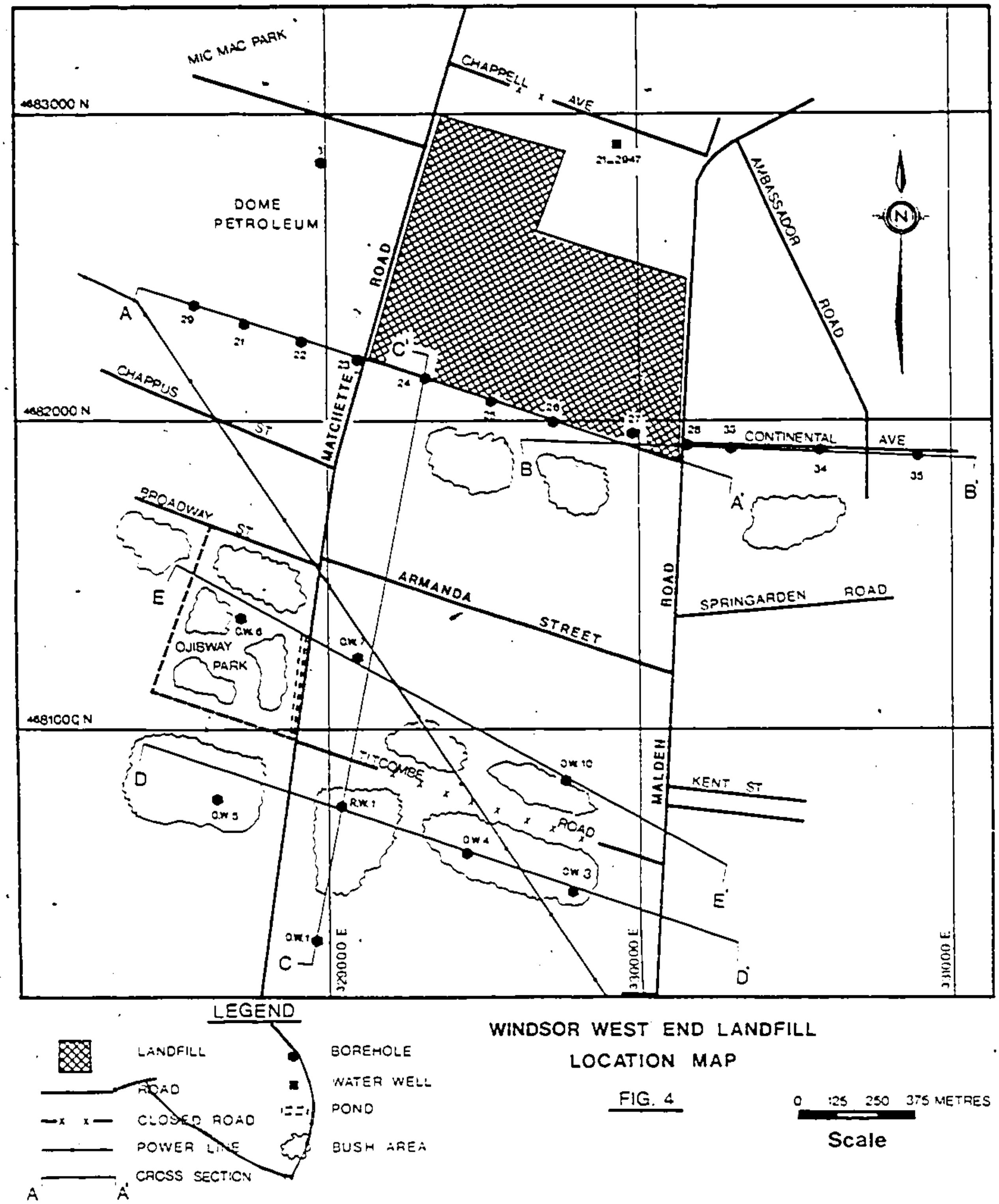
and Matchette Roads at the west end of the City of Windsor (Fig. 1). This landfill site lies between grid lines 329125 E and 330150 E, and 4681875 N and 4683000 N of the Universal Transverse Mercator Grid System (Fig. 4). NTS map No. 40J/6a covers the area at a scale of 1:25,000.

1.2.1 History of the Landfill Sites

Essex County Landfill No. 1 has been in operation since 1970. This landfill receives only domestic and municipal waste. Neither sewage sludge nor industrial sludge are accepted. The average received waste for the last three years was about 30,244 tonnes/year (Corporation of the County of Essex, 1983).

Essex County Landfill No. 2 has been in operation since 1970. The landfill receives both domestic and commercial waste. The average annual usage of the landfill for the last three years was about 49,986 tonnes/year. About 10% of the total accepted waste is industrial non-hazardous solid waste. Sewage sludge is accepted in this landfill, and it forms about 3% of the total waste (Sklash, Pers. comm.).

Windsor West End Landfill was opened in 1956 and closed in 1973. The landfill used to receive all categories of waste, mostly from the City of Windsor (Sklash, Pers. Comm.



WINDSOR WEST END LANDFILL

LOCATION MAP

FIG. 4

1.3 Geology of Essex County

Essex County is underlain by nearly flat lying Middle Devonian limestone, dolomite, and shale (Sanford, 1969). The regional dip of these beds varies from 4 to 6 m/km toward the south and southwest (Sanford and Brady, 1955). Figure 5 shows the bedrock geology of Essex County.

The oldest of the Devonian rocks belongs to the Detroit River Group. This group consists of grey to dark brown limestone, dolomite and light tan dolomite (Sanford, 1969). These rocks subcrop in the southern part of the county and along the Detroit River from Amherstburg to Windsor (Vagners, 1972a,b).

The Detroit River Group is overlain by brown limestone of the Dundee Formation. The Dundee Formation subcrops throughout the northern part of the county with the exception of a small area between Windsor and Belle River (Vagners, 1972a,b). The Hamilton Formation, consisting of grey shale and grey argillaceous limestone, overlies the Dundee Formation. The Hamilton Formation subcrops in a small area between Windsor and Belle River (Vagners, 1972a,b).

Bedrock is found exposed only in quarries in the southwestern part of Essex County near Amherstburg and McGregor. Elsewhere in the county, the bedrock is covered by a thick layer of Quaternary sediments (Vagners, 1972a,b).

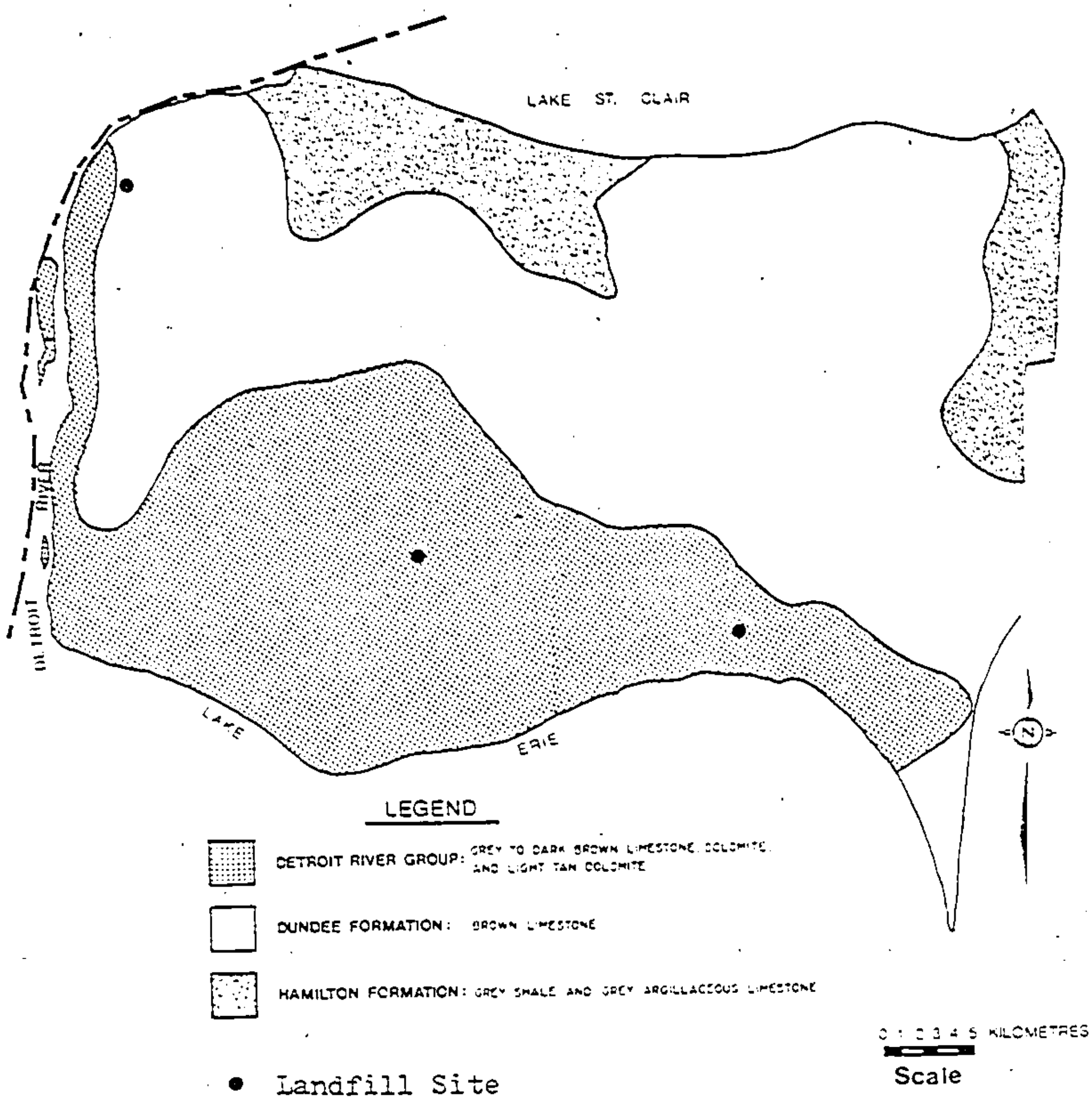


Figure 5. Bedrock Geology of Essex County(after Sanford, 1969).

The Quaternary deposits consist of nonstratified Pleistocene drift (i.e., till), stratified Pleistocene drift (i.e., sediments of glaciofluvial and glaciolacustine origin), and Recent sediments (Vagners, 1972a,b). Figure 6 shows the surficial geology of Essex County.

The oldest Quaternary deposits found in Essex County are glacial tills formed during the Wisconsinan (Vagners, 1972a,b). Clayey silt till was the major sediment that was deposited during the retreat of the Wisconsinan ice sheet. This sediment is found in almost all of the region. Some sandy silt tills were deposited directly onto bedrock in the southwestern part of the county and in the Windsor area. Sandy loam till is found overlying gravel in a small area about 5 km northwest of Leamington (Vagners, 1972a,b).

After the retreat of the Wisconsinan glaciers, Essex County and the surrounding area was submerged beneath several glacial lakes. Shorelines of old beaches, which were left behind by glacial Lakes Whittlesey, Warren, Grassmere and Lundy, have been identified in the area (Vagners, 1972a,b). Lake Wittlesey and Lake Warren, which covered the entire area, failed to leave deep stratified drift on the underlying clayey silt till (Chapman and Putnam, 1973).

The Essex Till Plain (Chapman and Putnam, 1973), which was deposited during the retreat of the Wisconsin ice sheet,

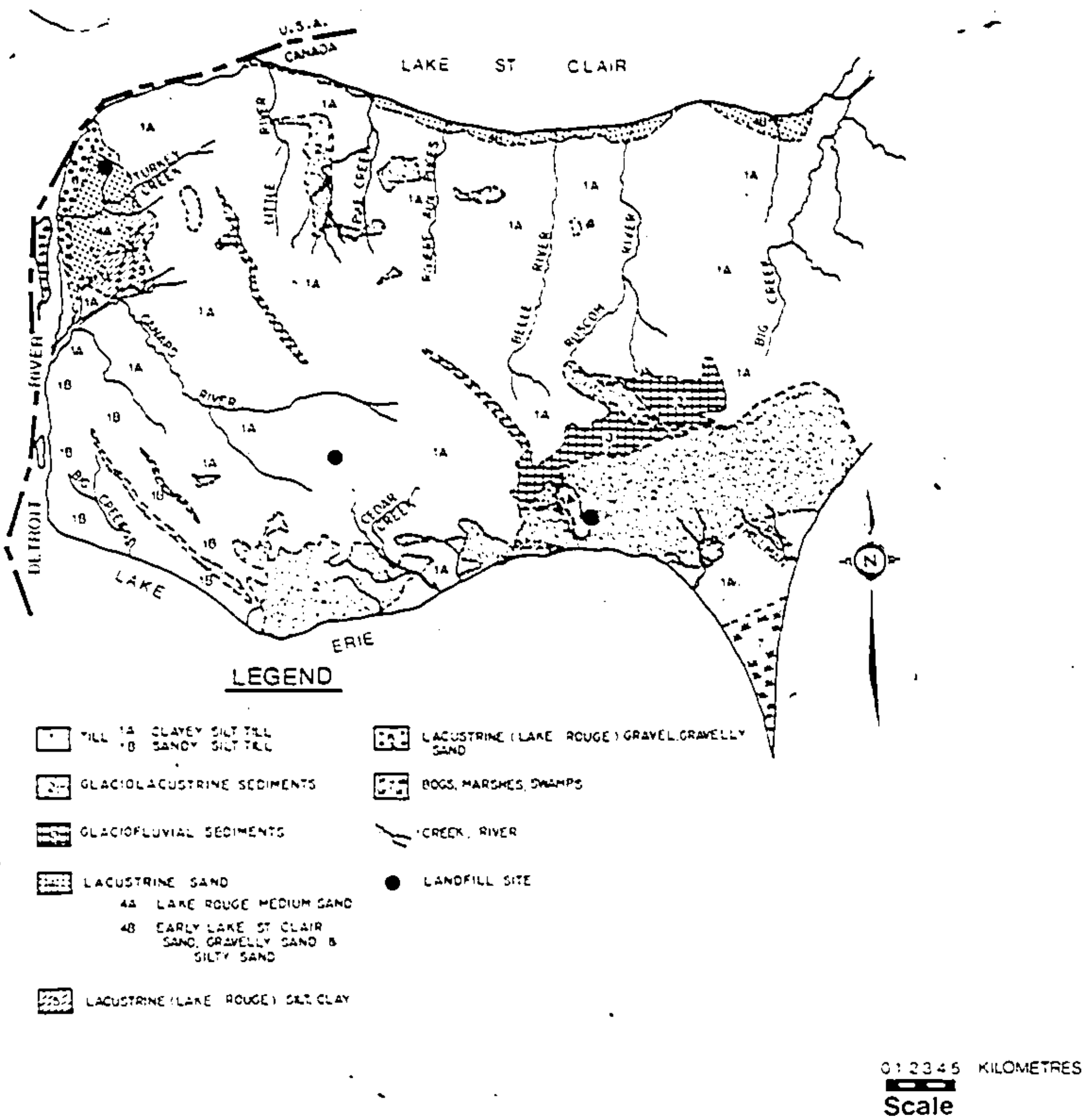


Figure 6. Surficial Geology of Essex County(after Guiton, 1978).

was smoothed by shallow deposits of lacustrine clay. These lacustrine sediments settled in the depressions while the knolls were being lowered by wave action (Chapman and Putnam, 1973). Some of the glaciofluvial sediments found in some areas in the county that have been modified by the lacustrine conditions, were deposited by melt water discharging from the retreating Wisconsinan ice sheet (Vagners, 1972a,b).

The glacial lakes were followed by the low-water level lakes, Early Lake St. Clair and the short-lived Lake Rouge (Vagners, 1972a,b). Sand, gravelly sand and silty sand deposits, which are found along the shore of the present Lake St. Clair, were left behind by Early Lake St. Clair. Lake Rouge deposits of gravel, gravelly sand, sand and silty clay are found in a small area southwest of the City of Windsor. Fluvial silty loam is found along Big Creek east of Amherstburg (Vagners, 1972a,b).

The Essex Moraine, a low broad hill of till, was left during the retreat of Wisconsinan glaciers (Chapman and Putnam, 1973). The Essex Moraine including the high knoll west of Leamington ("the Leamington moraine" (Chapman and Putnam, 1973)) was smoothed by the action of Lakes Whittlesey and Warren. Gravelly beach deposits were left around the sides and the shoulders of this moraine by Lakes Whittlesey and Warren, and the gravel bar along the crest of this moraine was left by a Lake Grassmere storm (Chapman and Putnam, 1973).

During the Recent Epoch, the action of waves and currents along the shorelines of Lakes Erie and St. Clair have been forming gravel and sand deposits. Wind activity has reworked some of the glaciolacustrine sediments, examples of which are the sand dunes east of Leamington and on Point Pelee. Organic materials have accumulated in swamps, bogs and marshes. One of the largest deposits of this type are the organic deposits at Point Pelee (Vagners, 1972a,b).

1.4 Topography of Essex County

Essex County occupies the extreme western part of the St. Lawrence physiographic region (Caley, 1946). Most of the surface is a glacial till plain characterized by a general lack of relief. The topography of the area is controlled by the surficial deposits and does not reflect the attitude of the bedrock (Caley, 1946).

The ground surface of Essex County rises gradually from an altitude of 175 m above sea level (a.s.l.) at Lake St. Clair to an average altitude of 190 m a.s.l. in the central part of the county. From this part of the county, the ground surface starts falling southward to an altitude of 175 m a.s.l. at Lake Erie.

In the area west of Leamington, the Essex Till plain is broken by a small morainic hill and series of old beaches and gravel bar deposits (Chapman and Putnam, 1973).

Maximum relief in Essex County is at this morainic hill with an elevation of about 220 m a.s.l.

Small rivers and creeks are found in Essex County flowing south, west, and north from the central part of the county into Lake Erie, the Detroit River, and Lake St. Clair, respectively (Fig. 6).

1.5 Groundwater in Essex County

Most of the water wells recorded by the Ontario Ministry of the Environment (1977) in Essex County terminate in bedrock. A great number of these wells obtain water from the uppermost part of the bedrock (Ontario Water Resources Commission, 1971). The groundwater flow system in this hydrogeologic unit is considered to be a regional flow system recharging in the upper Great Lakes and discharging toward Lake Erie (Guiton, 1978).

Wells penetrating deep into the bedrock are common in the Leamington-Harrow area. In that area, water obtained from the dolomite and limestone bedrock, which belong to the Detroit River Group, is generally fresh; however sulphurous water is found in some places (Ontario Water Resources Commission, 1971).

In the eastern, western, and northern parts of the county, many wells were reported to yield sulphurous and mineralized water from the limestone bedrock of the Dundee and Hamilton Formations.

Shallow dug wells are common in the Leamington-Harrow area. Fresh water is obtained from the glaciolacustrine sand deposits that are found in this area. Dug wells are also found in a 6 km wide strip in the northern part of the county along the Lake St. Clair shoreline. In that area, fresh and clear water is obtained from the lacustrine sediments (Ontario Water Resources Commission, 1971).

Generally, groundwater is the essential supply for most farmers and cottagers in Essex County. Groundwater can be found in sufficient quantities in most parts of the county; however poor chemical quality has been reported in many cases (Ontario Water Resources Commission, 1971).

1.6 Local Geology and Hydrogeology

1.6.1 Essex County Landfill No. 1

The Soil Map of Essex County (1947) indicates that the soil at Essex County Landfill No. 1 is Toledo Clay in the western part and Jeddo Clay in the eastern part. Toledo Clay consists of black clay over mottled clay and heavy plastic stratified blue-grey clay. Jeddo Clay consists of dark grey clay and clay loam over mottled clay and compact grey clay with few stones. The thickness of the top soil is less than 0.5 m (Ontario Ministry of the Environment, 1977).

Essex County Landfill No. 1 is situated in the Essex Clay Plain (Fig. 6). The area is generally flat and the slope of the ground surface is about 1 m/km towards the south and southwest. Clayey silt till, the most common Quarternary sediment in Essex Region (Vagners, 1972a), is found in this area. This till consists of: an upper layer of at least 3.5 m of very stiff light brown to grey brown silty clay with some sand and occasionally fine to medium gravel (Golder Associates, 1969a); and, a lower layer of 5 to 20 m of stiff to firm grey silty clay with some sand and occasionally fine to medium gravel (Ontario Ministry of the Environment, 1977). This till unit overlies deposits of grey to black, fine to medium sand and lenses of clay with occasional coarse sand and gravel. The thickness of the overburden in this area is between 20 and 30 m (Vagners et al. 1973a). Below the overburden is a Middle Devonian dolomite which belongs to the Detroit River Group (Sanford, 1969).

Geological cross-sections of the site based on the literature (A-A', B-B', and C-C' from Fig. 2) are illustrated in Fig. 7. Borehole data are listed in Appendix I-5.

There are three main hydrogeologic units which are partially recharged from this area: a silty clay till, a confined sand aquifer, and the bedrock aquifer (Ontario Ministry of the Environment, 1977).

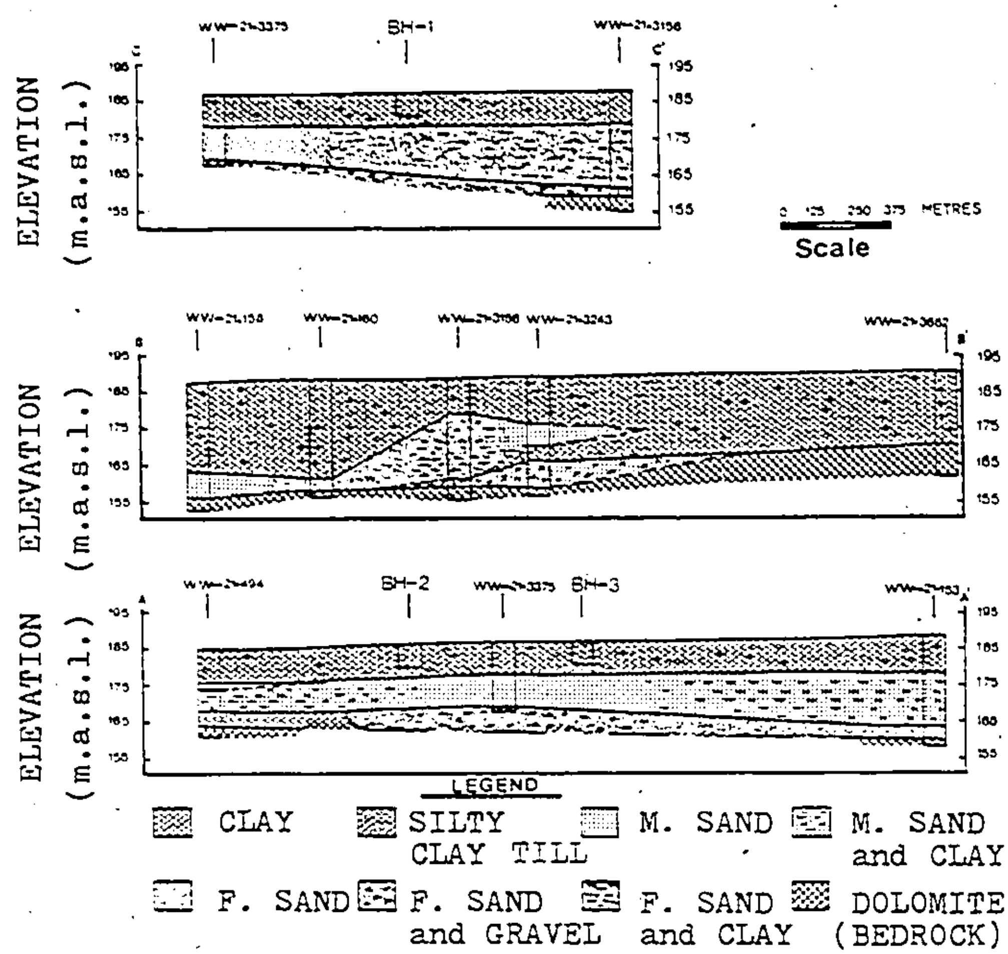


Figure 7. Geological Cross-Sections in the area of Essex County Landfill No. 1 (From Golder Associates, 1969a; Ontario Ministry of the Environment, 1977).

The silty clay till unit consists of a 9 to 24 m thick layer of silty clay till (Ontario Ministry of the Environment, 1977). The groundwater level normally lies within 5 m of the existing ground surface (Golder Associates, 1969a). This till unit behaves as an aquitard.

The presence of a landfill may cause the water table to rise as a goundwater mound on the local groundwater flow system. Based on the topography, the local groundwater movement is expected to be to the south and southwest..

The confined sand aquifer unit underlies the silty clay aquitard and consists of a 10 to 20 m thick layer of sand with some interbedded sandy clay and sandy gravel layers (Ontario Ministry of the Environment, 1977). Two wells near the landfill obtain fresh water from this aquifer, i.e., Well No. 21.3375 and Well No. 21-3243 (Ontario Ministry of the Environment, 1977).

The bedrock in this area is 20 to 30 m below the ground surface (Vagners et al. 1973a). Groundwater obtained from this aquifer is generally sulphurous and used for domestic and stock purposes only (Ontario Ministry of the Environment, 1977).

1.6.2 Essex County Landfill No. 2

The soil in this area is classified as Burford Loam in the Gosfield South Township (western part of the area), and

Fox Sandy Loam in the Mersea Township (eastern part of the area). Burford Loam consists of brown gravelly loam over reddish brown clay loam then grey stratified sand and gravel with many cobblestones. Fox Sandy Loam consists of light brown and yellow sandy loam over reddish brown loam then stratified sand and gravel (Soil Map of Essex County, 1947). The thickness of the top soil varies from 0 to 1 m (Ontario Ministry of the Environment 1977).

The continuity of Essex Till Plain is interrupted near Leamington by a small morainic hill, standing about 40 m above the surrounding sand plain (Chapman and Putnam, 1973). The landfill site is located on an old beach shoreline oriented north-west to south-east adjacent to this hill.

Vagners (1972b) shows that the area at and around the landfill site consists of glaciolacustrine deposits of sand and some gravel except for a small area immediately west of the landfill site which consists of clayey silt till (Fig. 6). The thickness of the glasiolacustrine sand varies from a trace to 5 m in the vicinity of the landfill, and reaches a maximum of about 12 m in the area north-east of the landfill (M. M. Dillon, 1981).

Underlying the glaciolacustrine deposits is a clayey silt till. This glacial till contains a large layer of sand and gravel estimated to be 6 to 8 m thick beneath and east of the landfill. Random and discontinuous sand seams are also found within this glacial till (M. M. Dillon, 1981). The thickness of the overburden in this area is between 45 and 60 m (Vagners et al. 1973b).

Below the overburden is a Middle Devonian dolomite which belongs to the Detroit River Group (Sanford, 1969).

The topography of the area is uneven with maximum elevation of about 220 m a.s.l at the location of the landfill site. From this height of land, the ground surface slopes north-east and south-west toward the surrounding sand plain. The geomorphology of the area has been severely altered by the mining and excavation of sand which has left many abandoned pits. Ponds have developed in the floor of these sand pits for aggregate washing. Figure 8 shows a schematic section in the area of landfill No. 2 (after M. M. Dillon, 1981). Appendix II-5 lists the available bore hole logs.

There are three aquifers which are partially recharged from this area: a shallow unconfined sand aquifer, a confined sand aquifer, and the bedrock aquifer (M. M. Dillon, 1981).

The shallow unconfined sand aquifer consists of a 4 to 12 m thick layer of sand (M. M. Dillon, 1981) in which the water table lies within 1 to 7 m of the existing ground surface. The ponds that are found in the area are a reflection of this groundwater level.

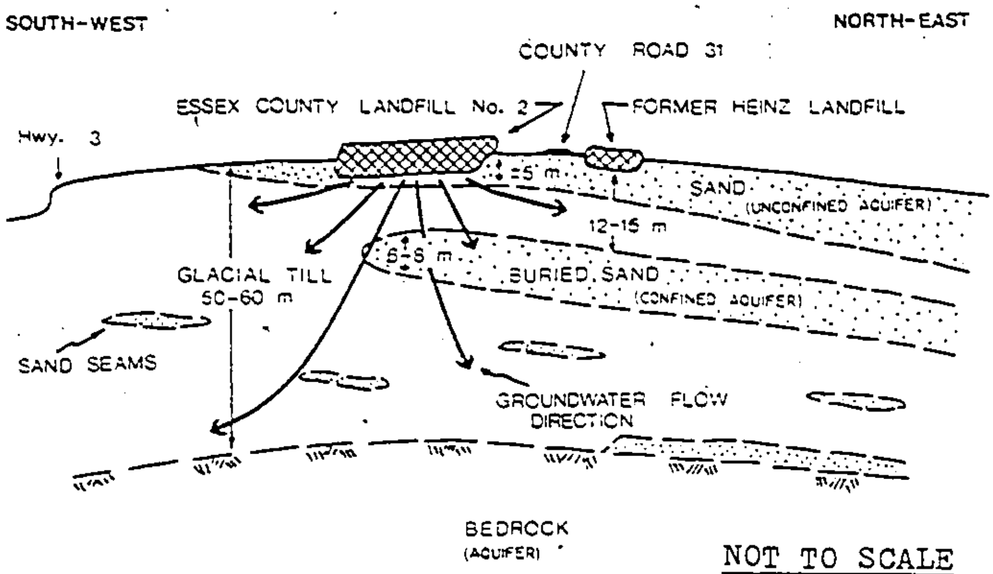


Figure 8. Schematic Section in the area of Essex County Landfill No. 2(after M.M. Dillon,1981).

The presence of the landfill, which may cause a mounding effect on the groundwater table, and the mining operations in the area, which may increase the hydraulic gradient towards the sand pits, have complicated and modified the local groundwater flow system. Local groundwater movement is generally to the northeast, east, and southeast (M. M. Dillon, 1981).

There are numerous shallow wells in the area which obtain water from this unconfined aquifer. This water is generally used for domestic purposes. A study carried out by Essop and Brown in 1980 indicated that the groundwater in a number of these shallow wells was seriously degraded by leachate from Landfill No. 2.

Buried within the clayey silt till which underlies the unconfined sand aquifer, there is a 6 to 8 m thick confined sand and gravel aquifer (M. M. Dillon, 1981). This confined aquifer is 12 to 15 m below the ground surface and yields variable quantities of water.

Most of the recorded water wells in this area terminate in the bedrock. The majority of these wells penetrate deep into the dolomite bedrock (Ontario Ministry of the Environment, 1977), 45 to 60 m below the ground surface (Vagners et al. 1973b). Groundwater obtained from this aquifer is generally fresh and is used for irrigation (Ontario Ministry of the Environment, 1977).

1.6.3 Windsor West End Landfill

The Soil Map of Essex County (1947) indicates that the soil in this area is Granby Sand in the western part and Berrien Sand in the eastern part. Granby Sand consists of dark grey sandy loam over grey or mottled sand with clay at depths of about 1 m. Berrien Sand consists of brown sand over yellow sand then mottled sand with clay at depths of about 1 to 2 m.

This area is located within the Lake Rouge Lacustrine deposits (Fig. 6). It is generally flat and the slope of the ground surface is about 1 m/km towards the south and southwest.

Below the top soil, a thin surficial layer of sand or fill covers the entire area (Vagners, 1972a). This surficial layer, with thicknesses from 0.5 to 2 m, consists of medium to coarse brown sand in the northern part of the area (Golder Associates, 1969c), and fine medium brown sand in the southern part of the area (Guiton, 1978). The fill material at and around the property of the landfill was found to be organic in nature (Golder Associates, 1969c).

Beneath the sand deposits is the extensive and thick clayey silt till. This glacial till consists of 1 to 1.5 m of dessicated grey brown silty clay which contains many thin sand seams, and a 10 m thick layer of soft to stiff grey silty clay; and a firm to stiff grey silty clay. Underlying the clayey silt-till, a thin layer of basal sandy till is found in the area (Golder Associates, 1969c). The thickness of the overburden in this area is about 30 m (Vagners et al. 1973a).

Figures 9a and 9b illustrate geological cross-sections along A-A', B-B', C-C', D-D', and E-E' from Fig. 4, based on data from the literature. Borehole logs are listed in Appendix III-5.

Below the overburden is a Middle Devonian brown limestone of Dundee Formation (Sanford, 1969).

There are three aquifers which are partially recharged from this area. These are a shallow unconfined sand aquifer, a deep confined basal till, and the bedrock aquifer (Guiton, 1978).

The shallow unconfined sand aquifer consists of 0.5 to 2 m of sand with a water table lying within 0 to 2.5 m of the existing ground surface (Golder Associates, 1969c). The groundwater flow system may be modified by the mounding effect due to the presence of the landfill in this area. The local groundwater flow system is drained to the south by the Canard River and to the west by the Detroit River (Guiton, 1978).

A thin layer of basal sandy till was found confined between the extensive and thick overlying clayey silt till

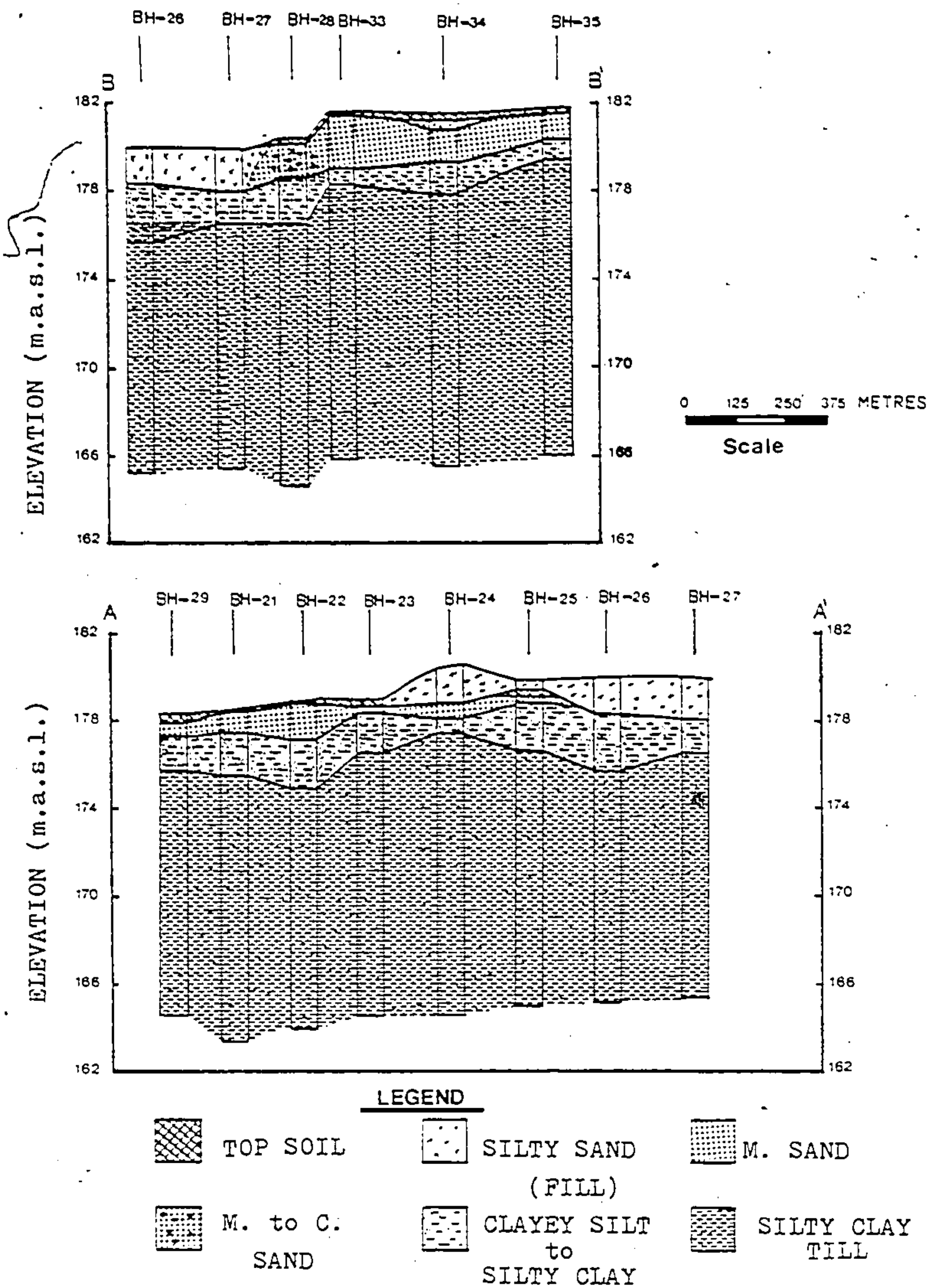


Figure 9a. Geological cross-sections in the area of Windsor West End Landfill (From Golder Associates, 1969c).

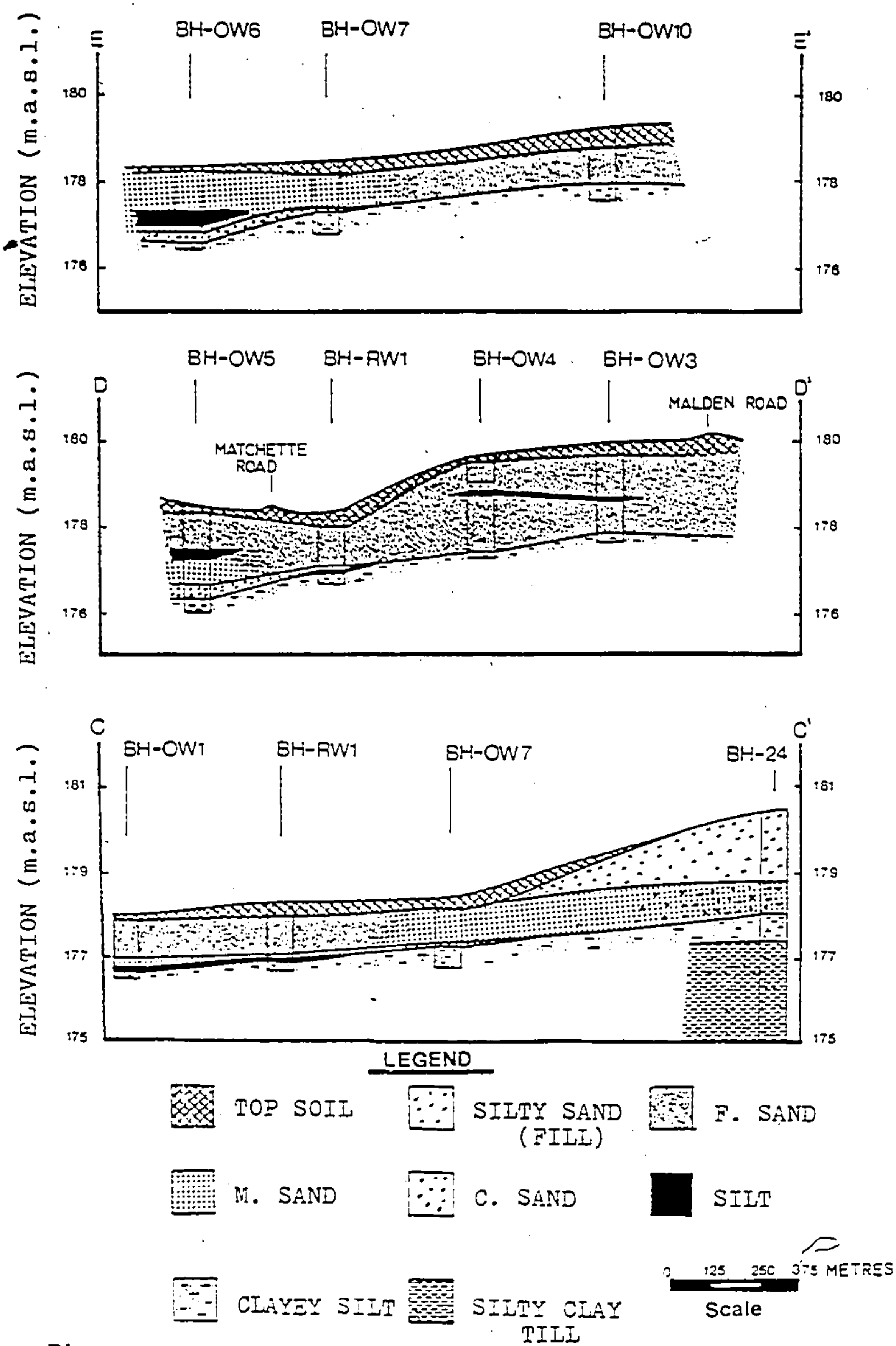


Figure 9b. Geological cross-sections in the area of Windsor West End Landfill (From Guiton, 1978; Golder Associates, 1969c).

and the underlying limestone bedrock (Golder Associates, 1969c). This confined aquifer consists of less than 3 m of coarse sand and gravel.

There are few water wells recorded in this area. Of these wells, most obtain water from the uppermost part of the limestone bedrock (Ontario Ministry of the Environment, 1977) which is about 30 m below the ground surface (Vagners et al. 1973a). Groundwater obtained from this aquifer is generally sulphurous (Ontario Water Resources Commission, 1971).

1.7 Previous Studies of Electrical Resistivity Surveys of Groundwater Contamination

Several successful studies have been reported on the use of surface electrical resistivity methods in groundwater contamination problems associated with landfill sites. A number of typical studies are summarized below.

Cartwright and McComas (1968) conducted four groundwater contamination studies in northeastern Illinois to determine whether electrical resistivity techniques could be used to detect groundwater contaminated by leachates from buried refuse. They found that the method was successful in delineating contaminated zones in the areas where the resistivity values were mostly controlled by water quality;

however, they achieved poor results at one site because of the variability in thickness of unsaturated deposits.

Warner (1969) used surface electrical resistivity profiling to detect contaminated zones near five septic tank and cesspools areas on Long Island, New York, and three oil field brine disposal pits in Western Texas. Warner was successful at four of the sites but he was not successful at the others because of large lateral variations in the surficial deposits and the presence of buried conductors.

Stollar and Roux (1975) applied Wenner resistivity sounding and profiling techniques at four industrial and landfill sites to delineate near surface contaminated groundwater. In three cases, the results of the resistivity survey successfully defined the lateral extent of the groundwater contamination. In the fourth case, the resistivity method was totally unsuccessful in defining either the lateral or vertical extents of the groundwater contamination plume. This failure was due to the relatively deep water table, the relatively small differences in specific conductance between the contaminated and native groundwater, the lateral variations in geology, and extensive man-made obstructions.

Klefstad et al. (1975) have conducted a detailed study on the limitations of the electrical resistivity method at a landfill site in Ames, Iowa. Their study investigated the interrelationships between electrical resistivity, material variation, and water quality. The study suggested that for any site, the threshold value must be known before the resistivity method can be applied successfully. This threshold value represents the minimum level of contamination that can be detected over the natural scatter in resistivity caused by lateral variations in material.

Kelly (1976) used the surface resistivity sounding method for estimating specific conductance of groundwater in the vicinity of the West Kingston landfill site on Rhode Island. In his study, all of the conditions were considered to be favorable and the differences in resistivity values were assumed to be due only to differences in groundwater quality. In this case, Kelly developed a relationship between the observed resistivity and the specific conductance of the groundwater for converting resistivity values to specific conductances.

More recently, Rogers and Kean (1980) used surface resistivity sounding and profiling to monitor groundwater contamination at the Saukville landfill site in Wisconsin. In their study, they observed resistivity changes as a function of saturation, temperature, and conductivity of the pore fluid.

2.0 GEOPHYSICAL METHODS

2.1 Seismic Refraction

2.1.1 Introduction

The seismic method of prospecting utilizes the elastic properties of rocks as an aid in subsurface exploration. These properties govern the propagation of seismic waves through the earth. Refraction at discontinuities is one of the seismic wave propagation characteristics in earth materials (Dobrin, 1976).

When a seismic wave strikes an abrupt change in the elastic properties, such as at a geological boundary, part of the seismic energy will be reflected in the same medium while the balance of the energy will be refracted into the other medium with an abrupt change in the direction of wave propagation at the interface (Telford et al. 1976)

Since different kinds of rock have different elastic properties, seismic waves propagate at different velocities through different materials (Grant and West, 1965). Therefore, seismic velocities can be used as an aid in the identification of subsurface deposits.

The seismic refraction method is used to find discontinuities in the elastic properties of subsurface material. Essentially, the method begins by artificially producing a shock wave in the earth. This is done by various methods ranging from a sharp hammer blow to powerful blasting caps. The shock wave propagates through the subsurface and a refracted wave is picked up by a detector "geophone" at the ground surface. The time for the seismic wave to travel from the shot point to the geophone is recorded by a seismograph. This indicates the seismic velocity of the subsurface material.

Seismic refraction surveys have been employed in this study to locate the water table and to identify subsurface deposits and their depths.

2.1.2 Seismic Refraction Theory

When a pressure is suddenly applied at a point inside a homogeneous elastic medium of infinite size, seismic waves will be generated at that point and regions of compression and rarefaction will move outward from the disturbance as an expanding spherical shells or "fronts" (Dobrin, 1976). According to Huygens' principle (Telford et al. 1976) every point on a wavefront can be regarded as a source of a new wave which also propagates in spherical shells. Once the radius of the front becomes large enough, then the front can be treated as a plane. Seismic wave propagation is often described by lines perpendicular to the wavefronts called wave "paths" or "rays" (Dobrin, 1976).

Let us consider the case of a subsurface consisting of two media having "different" uniform elastic properties and separated by a horizontal interface at depth Z (Fig. 10). The velocities of the seismic waves are V_1 in the upper layer and V_2 in the lower layer with $V_2 > V_1$ (Dobrin, 1976). Wavefronts are represented by paths. Suppose that a seismic wave is generated at point A on the surface. This wave will travel through the first layer with velocity V_1 and strike the interface at point B with an incident angle i. Part of the seismic energy will be reflected back to the ground surface. The balance of the energy will be refracted into the lower layer (Dobrin, 1976), according to Snell's law:

$$\frac{\text{Sin } i}{\text{Sin } r'} = \frac{V_1}{V_2} \qquad (2.1)$$

where, r' is the angle of refraction.

When r' = 90°, then

$$i_c = \text{Sin}^{-1} \ (V_1/V_2) \qquad (2.2)$$

The angle (i_c) is known as the critical angle for refraction (Dobrin, 1976). As the wave strikes the interface at the critical angle (i_c), it will be refracted along the interface and travel with velocity V_2. According to Huygen's principle (Telford _et al_. 1976), every point on the interface will be the source of a new wave that travels out from it, therefore, at any point C on the interface, a seismic wave will be

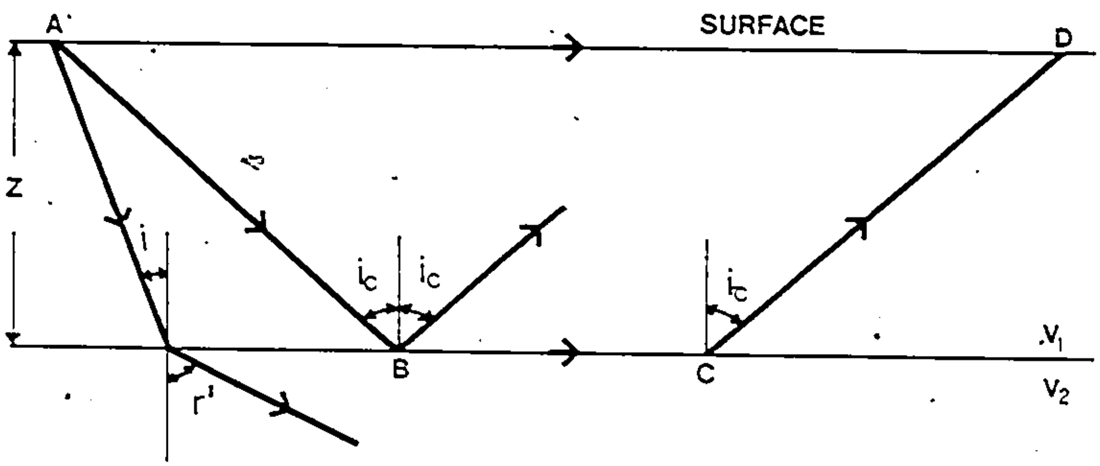


Figure 10. Refraction of seismic wave across an interface (after Dobrin, 1976).

refracted back upwards into the upper layer at the angle i_c having the velocity V_1. This wave can then be detected at point D.

The first wave to be detected at the surface between Point A and D is the one which travels directly through the upper layer. This is because the path AD is shorter than the path ABCD. At point D, the travel time for the direct wave travelling in the upper layer and the refracted wave travelling along the path ABCD, are equal. Beyond point D the refracted wave will be detected first on the surface since time is gained in travelling through the high-speed layer (Dobrin, 1976). The distance AD is called the 'cross-over distance" (x_{cross}) (Telford et al. 1976).

2.1.3 Interpretation of Seismic Refraction Data

Data collected in a seismic refraction survey includes the first-arrival times and the shotpoint-geophone distances. The simplest way to represent these data is to plot the first-arrival time T versus the shotpoint-geophone distance x (Fig. 11). This plot will consist of linear segments in the case of a subsurface consisting of discontinuous homogeneous layers (Dobrin, 1976).

Let us consider the case represented in Fig. 11. The velocities of these layers can be determined directly from the time-distance curve. The velocity of a layer is the

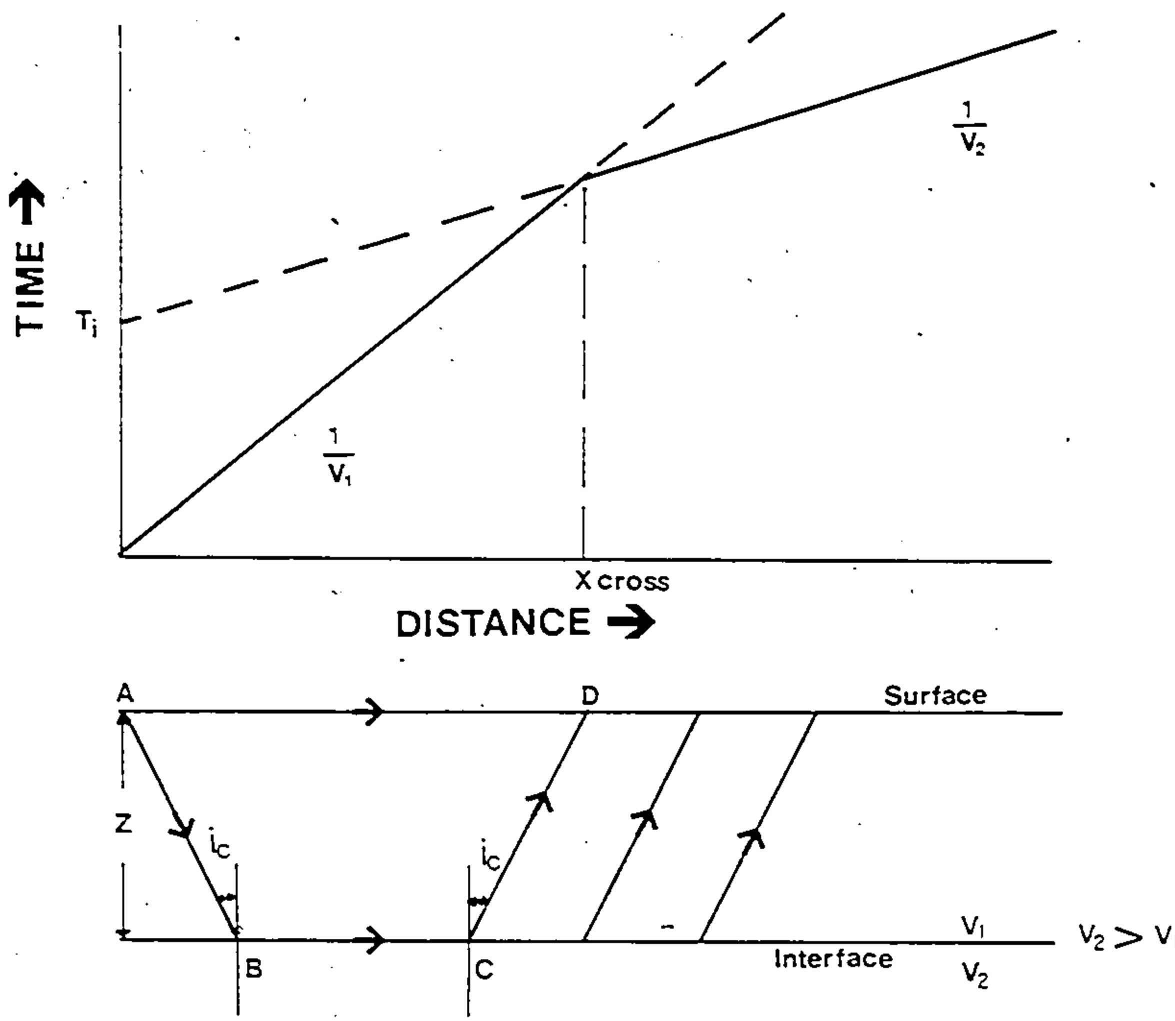


Figure 11. Ray paths of least time and time-distance curve for two layers separated by a horizontal interface at depth Z (after Dobrin, 1976).

reciprocal of the slope of the linear segment for that layer on the time-distance curve (Grant and West, 1965). The depth to the interface (Z) can be determined by using the formula:

$$Z = \frac{T_i}{2} \frac{V_2 V_1}{\sqrt{V_2^2 - V_1^2}} \qquad (2.3a)$$

where T_i is the intercept time which can be determined graphically as shown in Fig. 11.

For more than two layer cases, the time-depth relationship can be generalized as follows:

$$Z_{n-1} = \frac{1}{2} \left(T_{i_n} - 2Z_1 \frac{V_n^2 - V_1^2}{V_n V_1}\right) \frac{V_n V_{n-1}}{\sqrt{V_n^2 - V_{n-1}^2}} \qquad (2.3b)$$

where:

n is the number of various layers

Z_{n-1} is the thickness of a (n-1) layer

T_{i_n} is the intercept time of a (n) layer

V_n is the seismic velocity of a (n) layer

V_1 is the seismic velocity of the upper layer, and,

Z_1 is the thickness of the upper layer.

The derivation of the equations (2.3a and 2.3b) can be found in Dobrin (1976).

The main failure of most refraction interpretation techniques is in the assumption that the velocity of any layer is constant (Telford et al. 1976). Most methods assume straight line raypaths from the interface to the ground surface even though the velocity of the overburden is normally not constant. Another problem in interpretation results from a "hidden" or "low speed layer" (Dobrin, 1976) or "hidden zone" (Telford et al. 1976). A hidden layer is defined as a layer whose velocity is lower than the one above it. It is undetectable by the refraction technique and its arrival time will not show up on the time-distance curve. The theoretical explanation for the hidden layer lies in the fact that when $V_1 > V_2$, Snell's law gives $r' < 90°$. This means that all seismic energy will be deflected into the downward direction in the lower layer and the interface will not be shown on the time-distance curve. Another problem is referred to as a "blind zone" which is a layer whose velocity is greater than the above one but yet it does not show on the time-distance curve (Telford et al. 1976). This situation occurs when a layer is too thin to produce a first-arrival without being masked by refracted waves from deeper interfaces (Soske, 1959; Hawkins and Maggs, 1961; and Green, 1962).

2.2 Electrical Resistivity

2.2.1 Introduction

The electrical method of prospecting utilizes the electrical properties of rocks as an aid in subsurface exploration. It makes use of three fundamental properties of rocks: 1) electrical resistivity (or the inverse, conductivity), 2) natural electrical potentials, and 3) the dielectric constant. Of these properties, electrical resistivity is the most important (Telford et al. 1976).

Of all the electrical techniques, the electrical resistivity method is probably the simplest to operate and to understand (Grant and West, 1965). Essentially, the method involves the introduction of an artificial source of current into the ground through point electrodes. The procedure then is to measure the potential difference at other electrodes. The electrical resistivity of the subsurface then can be determined from these measurements (Telford et al. 1976).

The deployment of the current and potential electrodes is related to the type of problem in question. In general, there are two kinds of problems: vertical and horizontal (Grant and West, 1965). The electrical resistivity sounding technique is applied to vertical problems while the electrical resistivity profiling technique is applied to horizontal problems.

Within each of these techniques, several electrode arrays can be used. The Wenner array is one of the most common and convenient electrode configurations for electrical sounding and profiling (Dobrin, 1976), and it was used in this study.

2.2.2 Electrical Resistivity Theory

2.2.2.1 Electrical Resistivity

The electrical resistivity of any material is defined as the resistance R between the end faces of a cylinder of unit length L and a unit cross-sectional area A (Telford et al. 1976). The electrical resistivity ρ is expressed by the formula:

$$\rho = \frac{RA}{L} \qquad (2.4)$$

If L is in metres, A in metres^2 and R in ohms, the electrical resistivity unit is the ohm-metre.

By Ohm's Law, the resistance of the cylinder is:

$$R = \frac{V}{I} \qquad (2.5)$$

where V is the voltage (in volts) across the ends of the cylinder and I is the current (in amperes) flowing through it.

The electrical resistivity of porous materials depends on the resistivity of the pore fluid as well as the properties

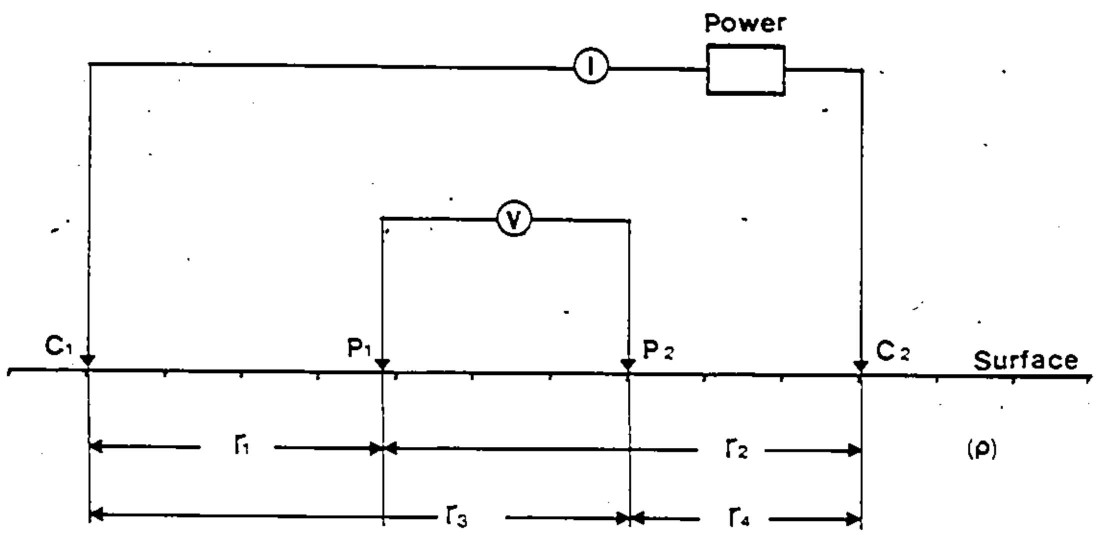


Figure 12a. Two current and two potential electrodes on the surface of homogeneous isotropic layer of resistivity P (after Telford <u>et al</u>, 1976).

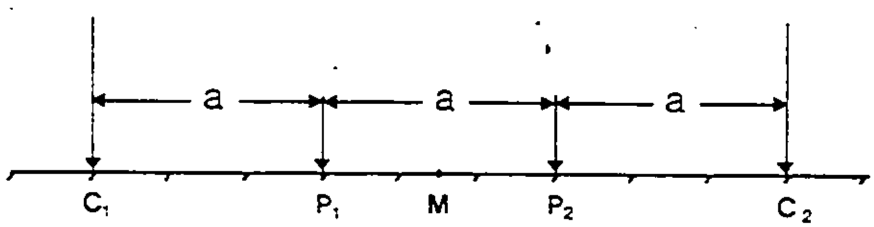


Figure 12b. Wenner electrode configuration (after Telford <u>et al</u>, 1976).

of the porous medium. In most rock materials the porosity and the chemical composition of the contained fluid is more important in governing formation resistivity than the resistivity of the material itself (Dobrin, 1976).

Let us now consider a homogeneous isotropic layer of geologic material having an electrical resistivity ρ. The electrical resistivity of this layer can be measured by introducing a controlled source of current I into the ground through two current electrodes, C_1 and C_2. The procedure then is to measure the potential difference ΔV between two points in the vicinity of the current flow using two potential electrodes P_1 and P_2 (Fig. 12.a). It is then possible to determine the electrical resistivity of the layer using the formula given below (Telford _et al_. 1976):

$$\rho = 2\pi \; \Delta V/I \; [(\frac{1}{r_1} - \frac{1}{r_2}) - (\frac{1}{r_3} - \frac{1}{r_4})] \qquad (2.6)$$

where r_1, r_2, r_3 and r_4 are inter-electrode distances. The derivation of the equation (2.6) can be found in Telford _et al_ (1976).

2.2.2.2 Apparent Resistivity

If the ground were uniform "electrically" as it was considered in the preceding section, a single measurement of the current and potential difference would determine its electrical resistivity using the Equation (2.6) (Grant and West, 1965). In this case the electrical resistivity will be constant for any current and electrode arrangement (Telford et al, 1976). If, however, the ground is not homogeneous, the same equation can be used to define an apparent resistivity (ρ_a) which is: "the resistivity which the ground would have if it were homogeneous" (Grant and West, 1965). In this case, if the electrode spacing is changed, or if the spacing is kept constant while the whole array is moved, then the measured quantity will change for each measurement (Telford et al, 1976). The measured "apparent" resistivity usually falls within the range of the true resistivity but it does not represent the true resistivity of the ground. The apparent resistivity will either rise above or fall below the true resistivity of the materials (Van Nostrand and Cook, 1966).

2.2.3 Electrical Resistivity Methods

2.2.3.1 Electrode Configuration

The geometric arrangement of the current and potential electrodes is referred to as "electrode configuration." The Wenner configuration was used in this study in both the electrical sounding and profiling surveys.

In the Wenner configuration (Fig. 12.b), the two outer electrodes are the current electrodes and are designated

C_1 and C_2. The two inner electrodes are the potential electrodes and are designated P_1 and P_2. M is the midpoint between P_1 and P_2. These electrodes are always uniformly spaced in a line. Equation (2.6) solved for the Wenner configuration gives:

$$\rho_a = 2\pi \ a \ \Delta V/I \qquad (2.7)$$

where "a" is the inter-electrode spacings such that $C_1 P_1$, $P_1 P_2$, and $P_2 C_2$ are always equal. When the Wenner configuration is used, the depth of penetration is assumed to be roughly equal to "a" (Dobrin, 1976).

2.2.3.2 Electrical Sounding Method

The change of the apparent resistivity with electrode spacing makes it possible to determine the variation of resistivity with depth (Dobrin, 1976). The field procedure is to use an electrode array with a fixed centre and an expanding spread. In the Wenner configuration, the three distances between consecutive electrodes are equal. Consequently, the four electrodes are moved outward simultaneously to increase the depth of the penetration of the measurements. This method may be used to detect horizontal beds of different resistivities and to determine the depth to the water table.

In this study, although the main interest was in lateral exploration, electrical sounding was used to detect the vertical extent of contaminant plumes. More importantly, sounding was used as an aid in establishing proper spacings for electrical profiling surveys.

For each sounding station and for each electrode spacing, an apparent resistivity value is calculated using Equation (2.7). For Wenner soundings, the field data are interpreted by curve matching with theoretical master curves for the Wenner array prepared by Lazreg (1972). To prepare the field data for analysis, the apparent resistivity values (ρ_a) are plotted against the electrode spacings (a) on transparent double logarithmic graph paper of modulus 62.5 mm and a smooth curve is drawn for each of the sounding.

The theoretical basis behind the construction of the master curves for the Wenner array has been described by Telford *et al.* (1976). The equation relating the apparent resistivity (ρ_a) and the true resistivity (ρ_1) is given below:

$$\rho_a = \rho_1 (1 + 4D_w) \tag{2.8}$$

where

$$D_w = \sum_{m=1}^{\infty} k^m \left[\frac{1}{\sqrt{[1+(2mh/a)^2]}} - \frac{1}{\sqrt{[4+(2mh/a)^2]}} \right]$$

$$k = \frac{\rho_2 - \rho_1}{\rho_2 + \rho_1}$$

and

ρ_1 = the resistivity of the first layer

ρ_2 = the resistivity of the second layer

h = the depth to the second layer

a = electrode spacing

m = 1, 2, ... ∞

The master curves are prepared with dimensionless coordinates by dividing the ρ_a by ρ_1 (Telford et al. 1976). The ratios ρ_a/ρ_1 are plotted against a/h on a double logarithmic paper of modulus 62.5 mm. This makes the size and shape of the curves independent of the measurement units. The master curves for the Wenner array prepared by Lazreg (1972) include three groups of curve sets: one set of curves for the two-layer earth models; seventy-six sets of curves for the three-layer earth models (which are grouped into four types of curves); and thirty sets of curves for the four-layer earth models (which are grouped into eight types of curves derived from the combination of various types of three-layer models). A detailed description of these curves can be found in Lazreg (1972).

The field curve is superimposed on various master curves until a suitable match with one of the master curves is found with the respective coordinate axes kept parallel. The point where ρ_a/ρ_1 = a/h = 1 on the master sheet then determines the values of ρ_1 and h on the field curve (Telford *et al*. 1976). ρ_2 is then found from the value of k which is appropriate to the matching master curve (Grant and West, 1965). In principle, the method of curve matching can be extended to the three-layer and four-layer earth models.

2.2.3.3 Electrical Profiling Method

This method is used to detect areally isolated bodies of anomalous resistivity (Telford *et al*. 1976). The field procedure is to use a fixed electrode spacing while the whole array of electrodes is moved to different stations. In the Wenner configuration, the three distances between consecutive electrodes are always kept equal and constant throughout the survey. The apparent resistivity is calculated using equation (2.7) and plotted at the midpoint (M).

The selection of "a" for each profiling survey is done by the aid of the sounding, seismic and borehole data. Any body which has anomalous resistivity which is shallower than "a" should show up as an anomaly on the resulting resistivity map (Dobrin, 1976).

Electrical profiling method may be used to detect and trace groundwater contamination from waste disposal sites. The method is successful when favourable subsurface conditions exist, such as: a good electrical contrast between the contaminated and native groundwater, a shallow water table, and homogeneous and uniform subsurface geology (Kelly, 1976). However electrical contrast cannot be detected if the electrical conductivity of the contaminant itself is not significantly greater than that of the native groundwater, or if the native groundwater is originally highly conductive. Interpretation may be difficult where the water table is deep as a great thickness of unsaturated deposits may mask any contrast between the contaminated and native groundwater. Heterogeneous and complex geology make it difficult to relate variations in electrical resistivity to anomalies in groundwater quality since the formation resistivity depends on the electrical conductivity of both the pore fluid and porous medium (Klefstad et al. 1975; Stollar and Roux, 1975; and Kelly, 1976).

In general, for a successful electrical profiling survey, a relatively simple, uniform geological environment is required so that the resistivity values can be compared with each other.

2.3 Electrical Conductivity Measurement

2.3.1 Introduction

Specific conductance or "electrical conductivity" yields a measure of the capacity of the water to transmit an electric current (Standard Methods, 1971). It is related to the total concentration of the charged ionic species in the water and to the temperature of that water.

Freshly distilled water has a specific conductance of 0.5 to 2 microseimens/cm (μS/cm). Surface and ground waters generally have a specific conductance range from about 50 to 500 μS/cm. For highly mineralized waters, specific conductance may range from 500 to 1000 μS/cm or even more (Standard Methods, 1971). The specific conductance of some waters (sea water) may be as high as 50,000 μS/cm (Hem, 1970).

The relationship between the specific conductance and the ionic concentration is simple in dilute solutions as the ion concentrations increase, the specific conductance increases (Hem, 1970). This relationship becomes more complicated for higher solute concentrations. Figure 13a shows the relationship between the specific conductance (at 25°C) of potassium chloride solutions and their concentration. The relationship is a straight line to a concentration of approximately 0.01 molar (745.6 mg/l). At higher concentrations, the slope decreases slightly (Hem, 1970).

The relationship between the specific conductance of a solution and its temperature is a simple straight line over limited range of temperature. Figure 13b shows this relationship for a solution containing 0.01 molar of KCl

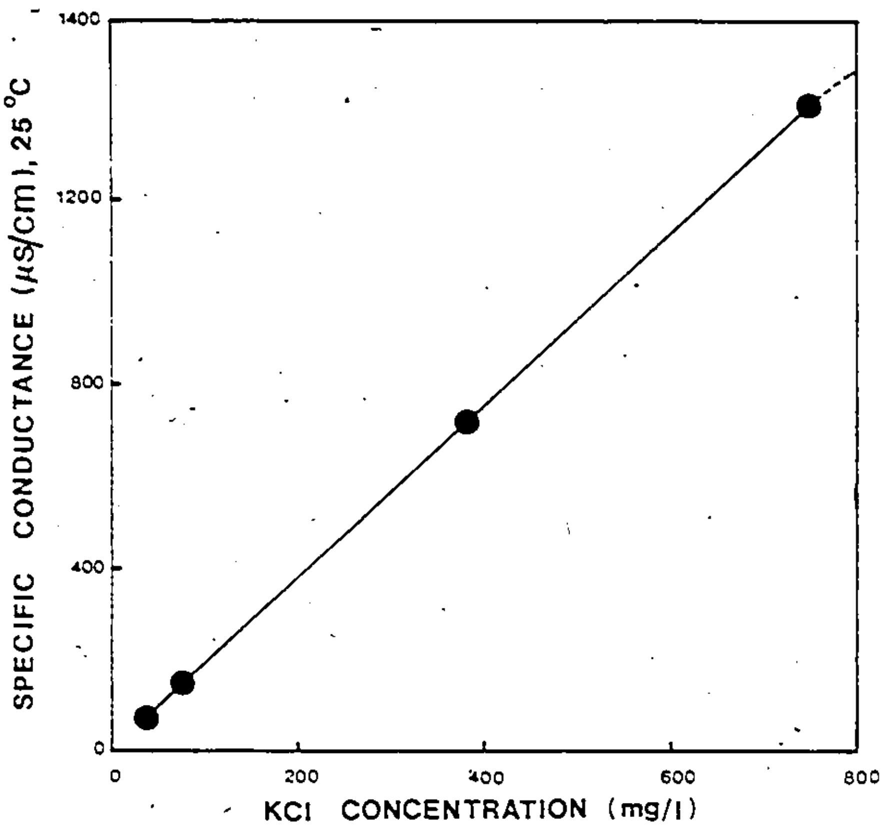


Figure 13a. The relationship between the specific conductance (at 25°C) of potassium chloride solutions and their concentration (after Hem, 1970).

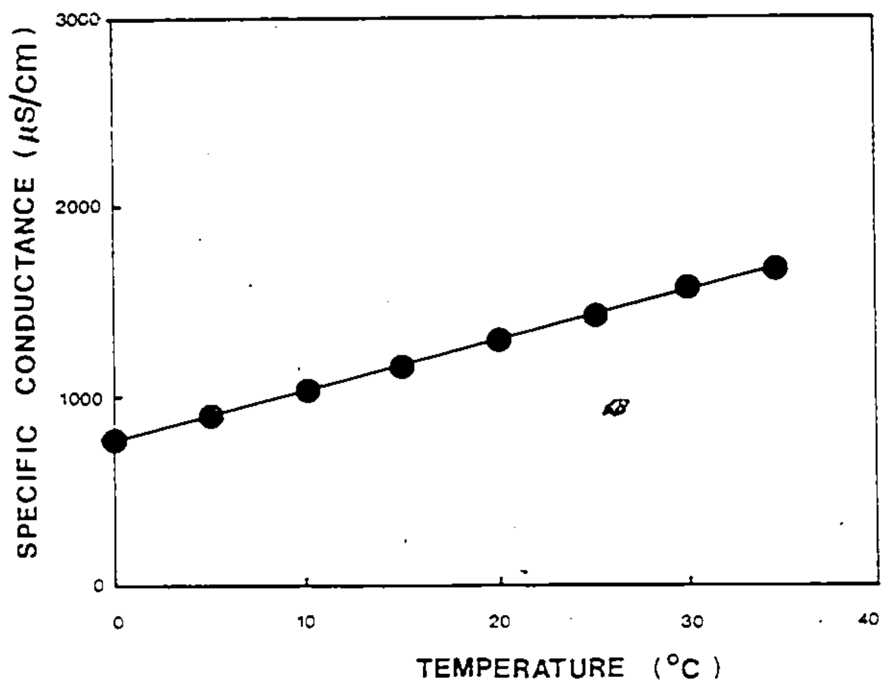


Figure 13b. The relationship between the specific conductance of a solution and its temperature (after Hem, 1970).

between 0° to 35°C (Hem, 1970).

2.3.2 Electrical Conductivity Theory

The resistance of electrolytic conductors resembles that of metallic conductors in its proportionality to the length of the conductors and inverse proportionality to the area of cross-section (Hammett, 1952). The electrical conductivity of a material is the reciprocal of its resistivity (Dobrin, 1976). From Equation 2.4, the electrical conductivity (σ):

$$\sigma = \frac{1}{\rho} = \frac{L}{RA} = \frac{C}{R} \tag{2.9}$$

where $C = \frac{L}{A}$ is the "cell constant".

Electrical conductivity has been defined by the American Society for Testing and Materials (Hem, 1970) as "the reciprocal of the resistance in ohms measured between opposite faces of a centimetre cube of an aqueous solution." The unit of the electrical conductivity is µS/cm and the standard temperature for measurement is 25°C.

2.3.3 Correction of Electrical Conductivity Measurements

2.3.3.1 Temperature Correction

Since the specific conductance of a solution varies with the temperature at which the measurement is made, temperature adjustment to the standard 25°C is important so that the variation in specific conductance can be related directly to variations in ion concentration. The specific conductance of a water sample is converted to equivalent specific conductance at standard temperature of 25°C. Figure 14 shows that the specific conductance varies by about 2% per degree centigrade (Standard Methods, 1971).

Specific conductance corrected to 25°C

$$= \sigma_{\text{water sample}} \times (25\text{-field temp}) \times 0.02 + \sigma_{\text{water sample}} \qquad (2.10)$$

2.3.3.2 Equipment Correction

The accuracy of specific conductance measurements depends on the type of equipment being used. A standard solution of known conductivity is used to correct equipment errors. A standard solution of KCl (0.01 molar) at 25°C has a specific conductance of 1413 μS/cm.

Corrected specific conductance

$$= \frac{1413\ \mu S/cm}{\sigma_{\text{St. KCl at 25°C}}} \times \sigma_{\text{water sample at 25°C}} \qquad (2.11)$$

An accurary of about ± 5% is possible when commercial equipment is used (Standard Methods, 1971).

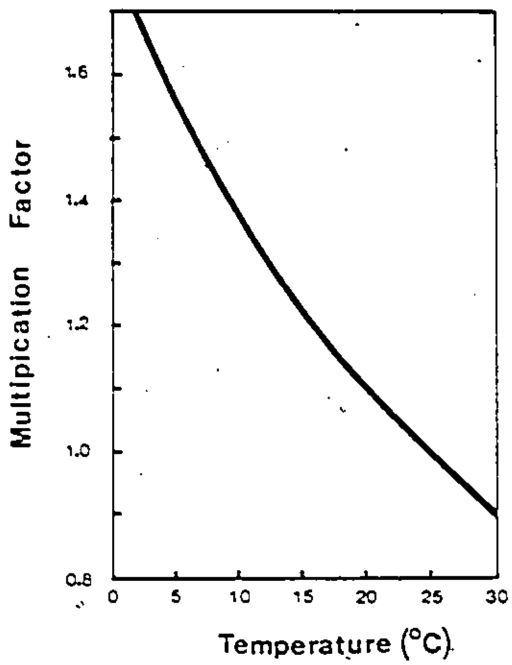


Figure 14. Factors for converting specific conductance of water to equivalent values at 25°C (after Standard Methods, 1971).

3.0 FIELD WORK

3.1 Instrumentation

Two seismic instruments were used in the seismic refraction surveys: the Bison Signal Enhancement Hammer Seismograph, Model 1570C, and the Huntec FS-3 Seismograph. Both instruments are self-powered, small, and portable. The Bison 1570C reads only the travel time for the first seismic signal (pulse) between a shotpoint "hammer" and a single geophone. The Huntec FS-3 automatically records the travel times for the seismic signals "pulses" between a shotpoint and two geophones. A sledge hammer striking a metallic plate was the source of the seismic energy for both instruments.

The Soiltest R-50 DC Resistivity Meter was utilized to conduct the electrical resistivity surveys. It consists of two units: the transmitting unit, and the receiving unit. A Simpson Model 360 Digital Volt-Ohm Milliammeter was used to measure the voltage instead of the receiving unit of the Soiltest equipment. Both the Soiltest and the milliammeter are self powered instruments. Four steel electrodes were used to connect these instruments to the ground.

A Barnstead Conductivity Bridge Model PM-70CB was used to analyze water samples for electrical conductivity. This instrument is small, portable, and self powered.

Photographs of all of the instruments are included in Appendix IV.

3.2 Field Work

3.2.1 Introduction

The single-profile shooting technique was used in the seismic refraction surveys. A single geophone (or two geophones) was placed at a selected point "station " while the hammer was moved progressively along the survey line away from the geophone (or geophones). When the Bison Model 1570C was used, a single geophone was placed on the survey line. When the Huntec FS-3 was used, two geophones were placed symmetrically about the survey line.

The starting geophone-hammer distance (d) was 0.9 m. The increment by which the geophone-hammer distance was increased differed for each seismograph. When the Bison 1570C was used, the distance (d) was increased by increments of 0.9 m up to a distance of 13.7 m, 1.5 m up to 30.5 m, 3.0 m up to 61.0 m, and by 6.1 m up to a maximum distance of 91.4 m. When the FS-3 was used, the increments were 0.9 m up to a distance of 13.7 m, 1.8 m up to 32 m, and by 2.7 m up to a maximum distance of 59.4 m.

The Wenner configuration was used for both the electrical sounding and profiling. In sounding, the starting electrode spacing "a" was 0.6 m. The "a" spacing was increased progressively by increments of 0.6 m up to 6.1 m, 1.2 m up to 12.2 m, 3.0 m up to 30.5 m, and by 6.1 m up to a maximum "a" spacing of 48.8 m. The "a" spacings used in the electrical profiling were selected for each site according to the geological and hydrogeological conditions of the area.

3.2.2 Essex County Landfill No. 1

Seismic refraction, electrical sounding, and electrical profiling surveys were carried out in this area during May and June 1982. Electrical conductivity measurements were made on November 5, 1982.

3.2.2.1 Seismic Refraction Survey

Five seismic refraction profiles were conducted in this area using the Bison Seismograph Model 1570C. The locations of these seismic refractions are shown in Fig. (15). Seismic profiles 1, 8, and 9 were oriented approximately north-south, while the orientation of profiles 2 and 6 was approximately east-west. The lengths of the refraction profiles were 67 m for seismic refraction 2, and 91.4 m for refractions 1, 6, 8, and 9.

In this study, elevation corrections were assumed to be negligible as the area was generally flat.

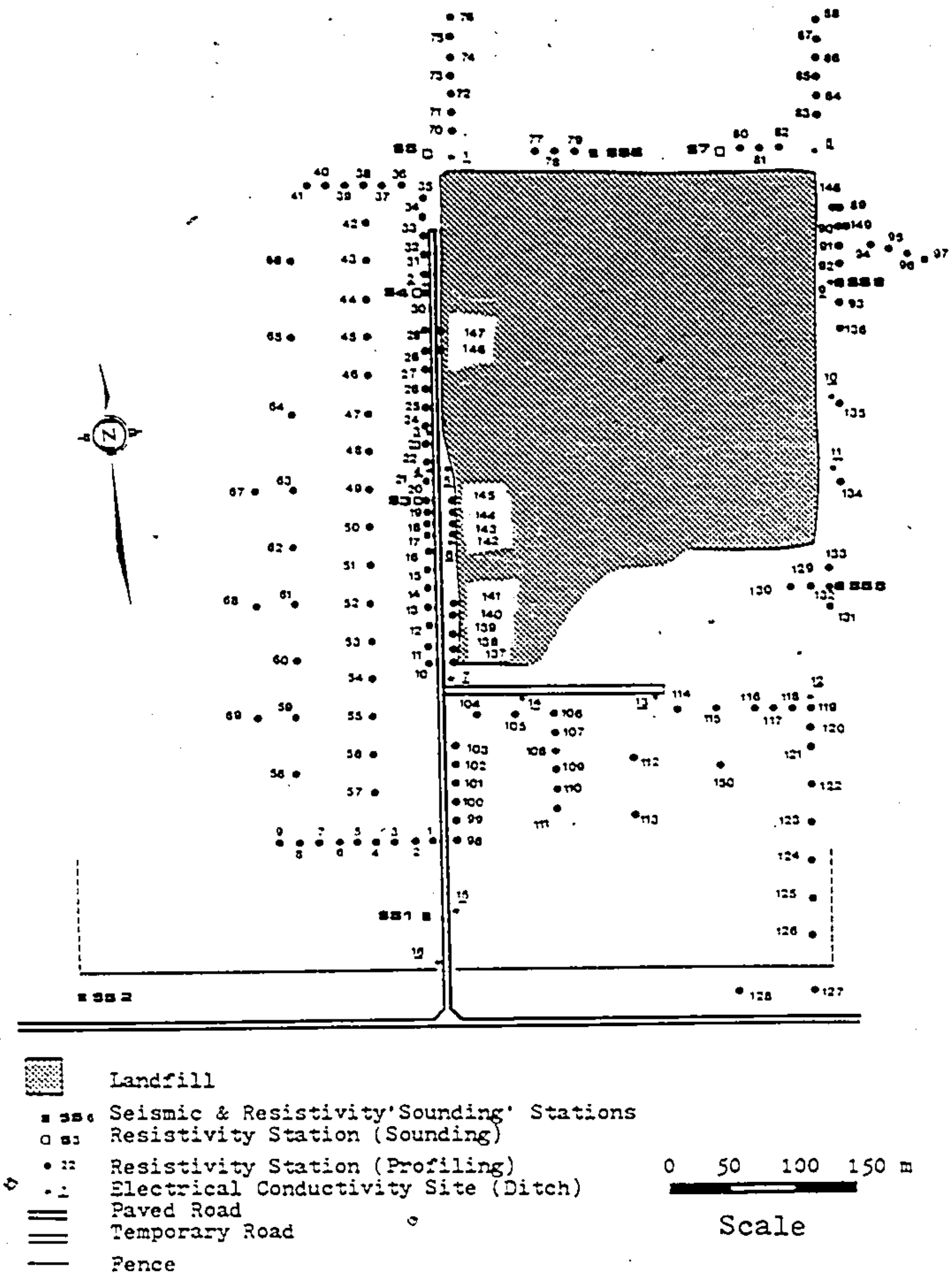


Figure 15. Station location map for the Essex County Landfill No. 1.

3.2.2.2 Electrical Sounding Survey

Ten electrical soundings using the Wenner configuration were made in this area. Nine of these soundings were located in the vicinity of the landfill (Fig. 15), while the tenth sounding (No. 10) was located about 1 km NW of the land fill and is not shown on the map. Sounding lines 1, 3, 4, 8, 9, and 10 were oriented approximately north-south, while sounding lines 2, 5, 6, and 7 were oriented approximately east-west.

The electrode spacing "a" ranged from 0.6 to 48.8 m for all soundings.

3.2.2.3 Electrical Profiling Survey

Two electrical profiling "mappings" using the Wenner configuration were made in this area. In the first profiling survey, the "a" spacing was 4.6 m, while the "a" spacing was 12.2 m in the second profiling survey. One hundred and fifty "resistivity" stations were established in the area for this purpose (Fig. 15). One hundred and fifty apparent resistivities were measured with "a" equal to 4.6 m and 144 were measured with "a" equal to 12.2 m.

The area around the landfill was farmland which was planted at the time of the survey thereby limiting the resistivity stations to the periphery of the landfill. Where it was possible to locate resistivity stations without harming the existing crops, stations were located north, west, and south of the fill.

3.2.2.4 Electrical Conductivity Measurement

The electrical conductivity was measured for 16 surface water samples taken from ditches around the fill. The conductivity measurements were done on site. The locations of the conductivity measurements are shown in Fig. (15).

3.2.3 Essex County Landfill No. 2

Seismic refraction, electrical sounding, and electrical profiling surveys were carried out during September and October 1982. Electrical conductivity measurements were performed on October 3 and November 5, 1982.

3.2.3.1 Seismic Refraction Survey

Four seismic refraction profiles were conducted in this area using the Bison Model 1570C and Huntec FS-3 seismographs. The locations of these seismic refractions are shown in Fig. 16. The Bison seismograph was utilized to conduct seismic profiles 1 and 4, which were oriented approximately north-south. The FS-3 seismograph was used to conduct seismic profiles 5 and 7 which were oriented approximately east-west. The lengths of seismic profiles 5 and 7 were about 59.5 m, while the lengths of profiles 1 and 4 were 30.5 and 48.8 m, respectively.

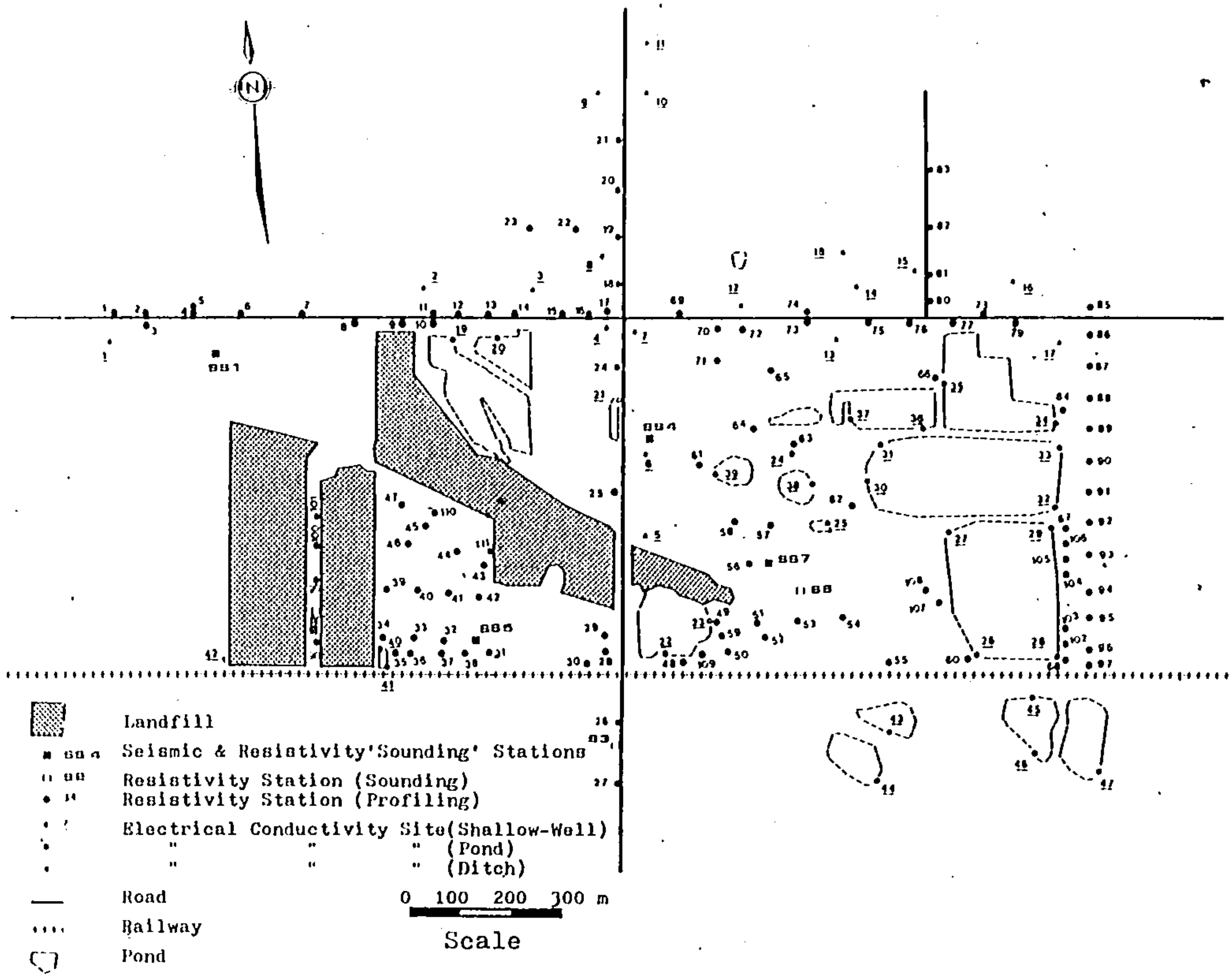


Figure 16. Station location map for the Essex County Landfill No. 2.

In this study, due to the topographic complexity of the area, seismic refractions were made in carefully chosen areas with relatively low relief in order to eliminate the need for elevation corrections.

As the background noise was at a high level due to the heavy traffic and the local machinery in the area, the Huntec FS-3 seismograph, which has better noise discrimination, was used to overcome the problem. The FS-3 seismograph gave results which were similar to the Bison, Model 1570C. To minimize the noise problem seismic profiles were kept short.

3.2.3.2 Electrical Sounding Survey

Seven Wenner electrical soundings were made in this area. The locations of these soundings are shown in Fig. 16. Soundings, 1, 2, 3, 4, and 6 were oriented approximately north-south while the orientation of sounding 5 and 7 was approximately east-west.

The electrode spacing "a" ranged from 0.6 to 48.8 m for soundings 1, 2, 3, 4, and 5, and from 0.6 m to 15.2 and 30.5 m for soundings 6 and 7, respectively.

3.2.3.3 Electrical Profiling Survey

Three Wenner electrical profilings "mappings" were made in this area. One hundred and eleven "resistivity" stations were established in the area for this purpose

(Fig. 16). Electrode spacings of 1.8, 3.0 and 6.1 m were used to conduct the first, second, and the third profiling surveys. Forty-three apparent resistivities were measured with "a" equal to 1.8 m, 101 with "a" equal to 3.0 m, and 61 with "a" equal 6.1 m.

Because of the uneven topography of the area, and because of the presence of large ponds and bushes, the electrical profiling survey was severely limited and restricted. Resistivity stations were located along the roads and on the sand pit floors. Some stations were also located on a high area just east of the eastern ponds (Fig. 16).

3.2.3.4 Electrical Conductivity Measurement

Electrical conductivity was measured for 67 water samples. Eighteen of these samples were taken from shallow wells, 48 samples were taken from the ponds at 28 locations, and one sample was taken from a ditch just west of the landfill site. The locations of the conductivity determination, are shown in Fig. (16). Conductivity measurements were done on site.

3.2.3.5 Topographical Survey

A standard levelling survey was carried out in some parts of the area to supplement the existing topographic map of the area.

3.2.4 Windsor West End Landfill

Seismic refraction, electrical sounding, and electrical profiling surveys were carried out during July and August 1982. Electrical conductivity measurements were made on November 8 and 9, 1982.

3.2.4.1 Seismic Refraction Survey

Five seismic refraction profiles were conducted in this area using the Bison Model 1570C. The location of these seismic refraction profiles are shown in Fig. 17. Seismic profiles 1, 2, 3, 4, and 5 were oriented approximately WE, SE-NW, NW-SE, SW-NE, and SN, respectively. The length of seismic profiles 1, 4, and 5 was 39.6, 30.5 and 48.8 m, respectively, while the lengths of profiles 2 and 3 were 61 m.

Because this landfill is located in an urban area, the background traffic and construction noise level was high. To minimize this problem, seismic profiles were kept short.

3.2.4.2 Electrical Sounding Survey

Five Wenner soundings were made in this area. The location of these soundings are shown in Fig. 17. Soundings 2 and 3 were oriented approximately SE-NW, while soundings 1, 4, and 5 were oriented approximately WE, SW-NE, and SN, respectively.

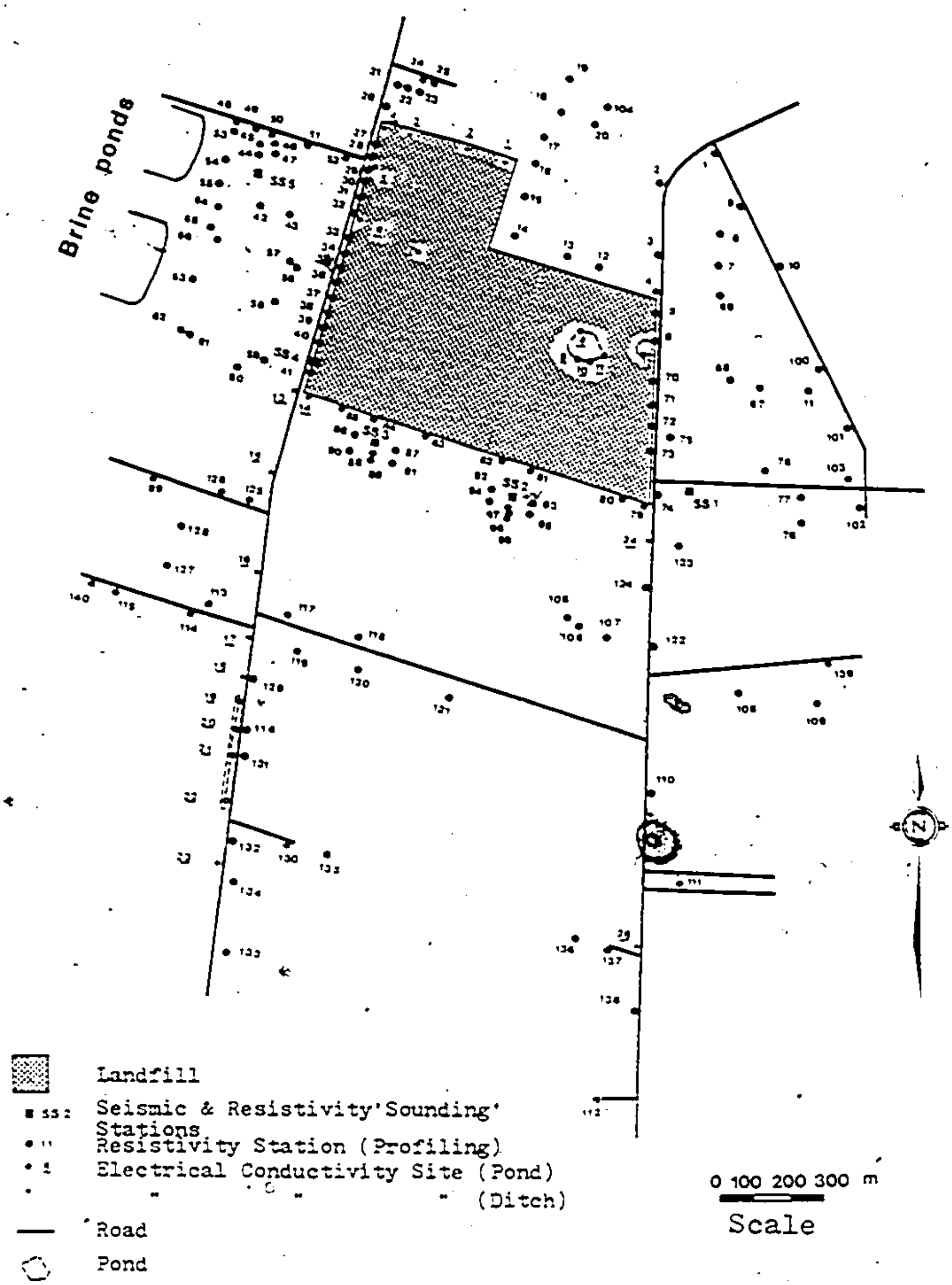


Figure 17. Station location map for the Windsor West End Landfill.

The electrode spacing "a" ranged from 0.6 to 48.8 m for soundings 1, 2, 3, and 5, while it ranged from 0.6 to 9.7 m for sounding 4.

3.2.4.3 Electrical Profiling Survey

Two Wenner electrical profiling "mappings" were made in this area. One hundred and forty "resistivity" stations were established for this purpose (Fig. 17). Electrode spacings of 3.0 and 4.6 m were used in the first and second profiling surveys, respectively. One hundred and seventeen apparent resistivities were measured with "a" equal 3.0 m and 140 were measured with "a" equal 4.6 m.

As this landfill is located in an urban area, the resistivity stations were limited mainly to the roads. Some stations were also located in the bush areas south and west of the landfill.

3.2.4.4 Electrical Conductivity Measurement

Electrical conductivity was measured for 26 water samples: 9 samples were taken from ponds and 17 samples were taken from ditches. The locations of the conductivity determinations are shown in Fig. 17. Conductivity measurements were measured on site.

4.0 RESULTS AND DISCUSSIONS

4.1 Essex County Landfill No. 1

4.1.1 Seismic Refraction Survey

The results of the seismic refraction survey for the Essex County Landfill No. 1 are plotted and listed in Appendix I-3. Table 1 summarizes the seismic velocities, intercept times, and interface depths determined for the five survey sites.

Four major seismic velocity layers were revealed in this area with the exception of the area near Essex County Road No. 18 where a thin low velocity layer was delineated. This layer has a seismic velocity range of approximately 208 to 277 m/s which probably represents the near-surface weathered layer.

The upper major layer has a seismic velocity range of approximately 320 to 645 m/s. The second, third, and fourth layers have seismic velocity ranges of approximately 1501 to 1592, 1806 to 2031, and 4389 to 4877 m/s, respectively. The four major layers probably represent, in descending order, the unsaturated silty clay, saturated silty clay, saturated clayey sand, and the underlying dolomite bedrock. Table 2 summarizes the seismic interpretations for the Essex County Landfill No. 1.

Table 1

Seismic Velocities, Intercept Times, and Interface Depths for the Essex County Landfill No. 1

Seismic Profile	Seismic Velocity* V(m/s)				Intercept Time** Ti(s x 10^{-3})			Depth to Interface*** d(m)		
	V_1	V_2	V_3	V_4	Ti_1	Ti_2	Ti_3	d_1	d_2	d_3
1	277	645	1648	4741	5.0	10.0	37.5	0.7	2.3	30.4
2	208	607	1548	1890	6.0	10.5	12.5	0.6	2.0	10.6
6	320	1670	2031	4877	13.6	17.7	40.0	2.2	8.1	37.2
8	330	1592	1868	4689	10.0	14.1	38.0	1.7	7.8	36.4
9	355	1501	1806	4389	7.5	11.2	37.5	1.4	6.3	35.8

*Obtained directly from the time-distance plots (Appendix I-3)

**Obtained directly from the time-distance plots (Appendix I-3)

***Calculated by using Equations 2.3a and 2.3b

Table 2

Summary of Seismic Interpretation for the Essex County Landfill No. 1

Layer	Calculated Seismic Velocity (m/s)	Probable Materials	Published Data	
			Seismic Velocity (m/s)	Reference
Upper	208-277	Top soil (weathered surface layer Pleistocene)	169-305	Heiland (1968)
2nd	320-645	Unsaturated glacial till (silty clay)	430-1040	Press (1966)
3rd	1501-1592	Saturated glacial till (silty clay)	1730	Press (1966)
4th	1806-2031	Sand (clayey)	1650-1950	Heiland (1968)
5th	4389-4877	Dolomite	3500-6900	Press (1966)

Seismic refraction interpretation was based on the calibration of seismic velocity layers with the available geologic data (Figs. 18, 19, and 20). The recorded velocities were also compared with the published data (Press, 1966; Heiland, 1968) to support the interpretation (Table 2).

It can be seen from Figs. 18, 19, and 20 that the silty clay layer correlates with the second and third velocity layers in Seismic Profiles 1 and 2, and the upper and second velocity layers in Seismic Profiles 6, 8, and 9. The significant increase in the seismic velocity that the silty clay exhibits across the second interface (d_2) in Seismic Profiles 1 and 2, and the first interface (d_1) in Seismic Profiles 6, 8, and 9, suggests that the velocity below these interfaces is the seismic velocity of the saturated silty clay, and the depths to the interfaces are the depths to the groundwater table. This velocity increase due to saturation is similar to that found by Duguid (1968). The seismically determined groundwater table varies from depths of 1.4 to 2.3 m in this area.

Figures 19 and 20 show that the clayey sand layer correlates with the third velocity layer (in Profiles 6, 8, and 9), and the fourth velocity layer in Seismic Profile 2. Thus, the second interface (d_2) (Profiles 6, 8, and 9), and the third interface (d_3) (Profile 2), are likely to be

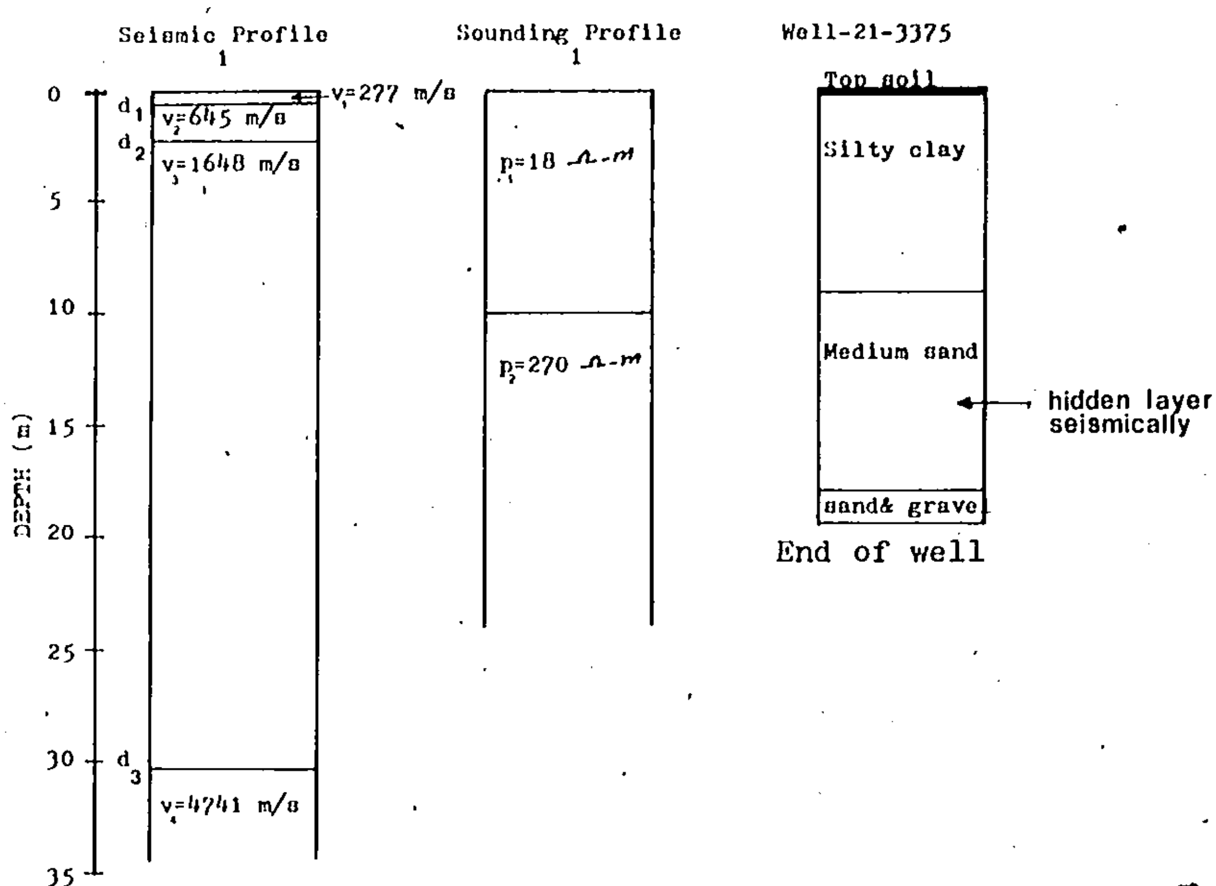


Figure 18. Comparison of Seismic and Sounding Profiles 1 with borehole log (Essex County Landfill No. 1).

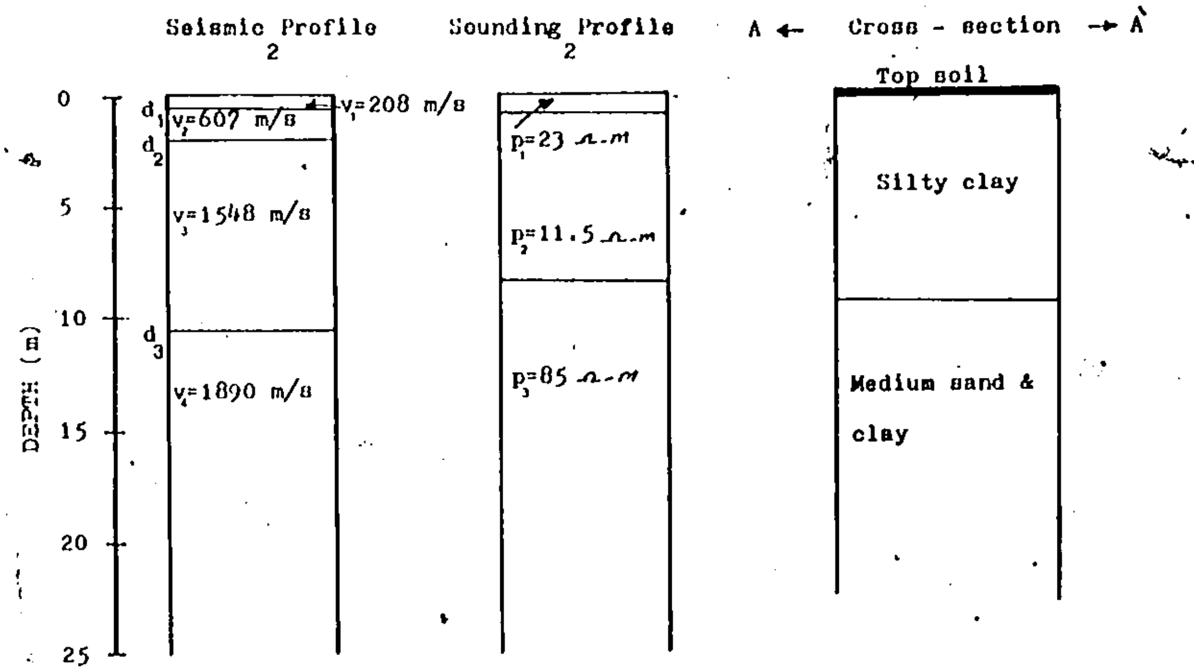


Figure 19. Comparison of Seismic and Sounding Profiles 2 with borehole log (Essex County Landfill No. 1).

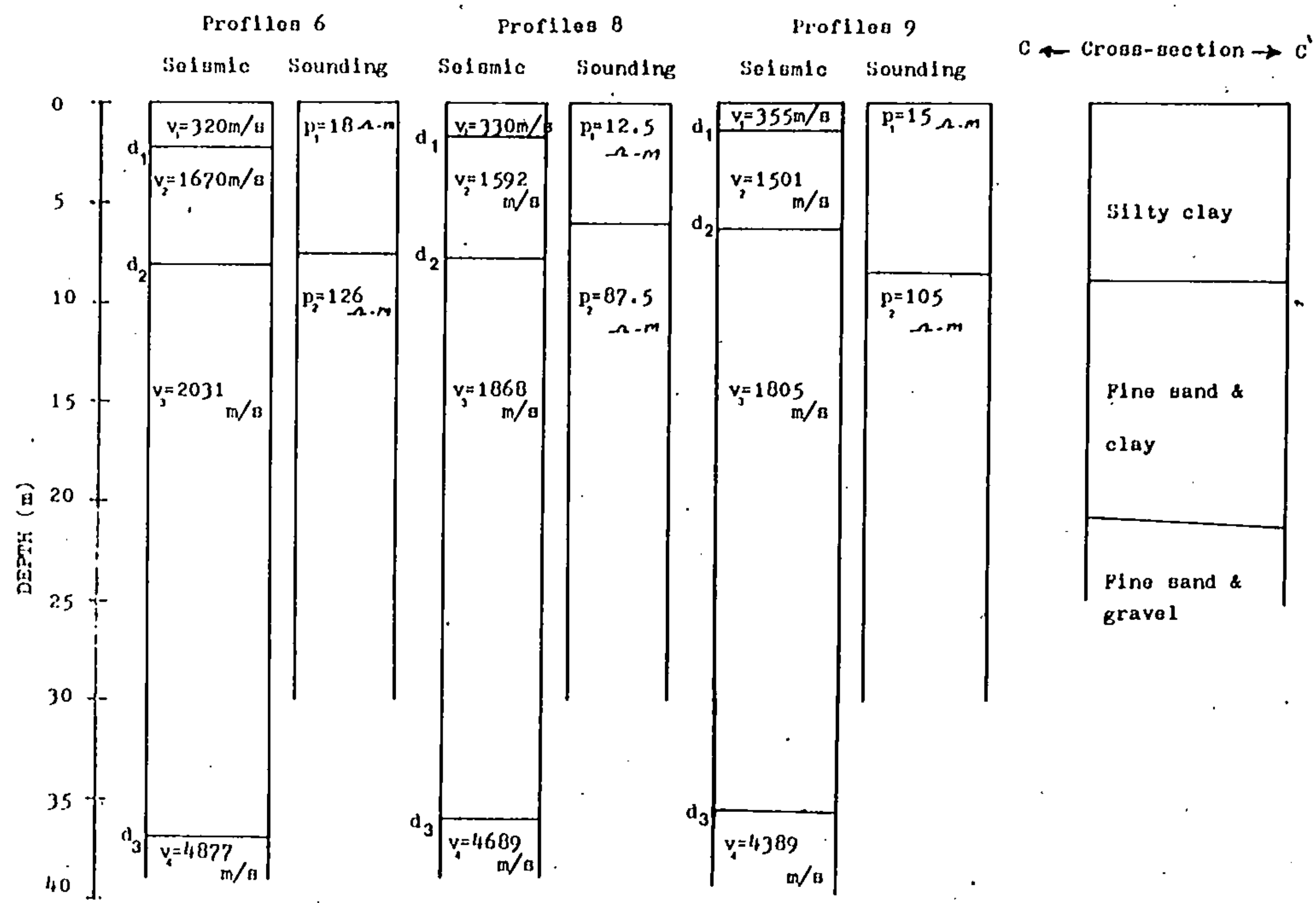


Figure 20. Comparison of Seismic and Sounding Profiles 6, 8, and 9 with borehole log (Essex County Landfill No. 1).

the contact of the silty clay with the clayey sand.

The calculated depths to the clayey sand layer were found to be in error by 11% for Seismic Profiles 2 and 6, and 14% for Seismic Profile 8. These errors are considered to be acceptable in seismic refraction work (Barker, 1981). In Seismic Profile 9, the calculated depth to the clayey sand was shallower than the depth obtained from the cross-section c-ć (Fig. 20) by 30%.

Zehner (1973) discussed this kind of error in seismic refraction work citing examples where the calculated depth to an interface was too shallow. He attributed this type of error to the presence of high velocity materials just above that interface, and/or to a 'blind zone' layer which might be present above a shallower interface.

In this study, since there are no boreholes close to the Seismic Profile 9, another geophysical means such as "electrical sounding" must be used to aid in the seismic interpretation.

The sand layer and the fine-grained sand and gravel layer (Fig. 18), and the fine-grained sand and gravel layer (Fig. 20) were not detected by seismic refraction. This may be attributed to the relatively low velocity of these layers compared to the layers above them. Dobrin (1976) refer to situations like this as a low-speed layer problem. The presence of such undetected low-speed layer (hidden layer) causes erroneous calculations of the depths to all interfaces below it (Dobrin, 1976).

The noticeably higher velocity (v_4) at depth in Seismic Profiles, 1, 6, 8, and 9, may represent the underlying dolomite bedrock (Press, 1966), and the (d_3) interface is most likely to be the top of the bedrock. Although the depth to the dolomite bedrock could not be determined exactly from the available geologic data, it is expected that the bedrock is between 25-28 m below the ground surface (Fig. 7). The calculated depths to the bedrock are therefore greater than the depths estimated from the well log data. The calculated depths were in error by 22% for Seismic Profile 1, and by 30-40% for Seismic Profiles 6, 8, and 9.

Zehner (1973) referred to situations such as this, and recorded an example where the seismically calculated depth to bedrock was greater than the depth obtained from a borehole log, with an error of ±43%. One of the causes for that error was attributed to the presence of the low-speed layer above the bedrock. In this study, the presence of the low-speed layers (sand, and fine-grained sand and gravel) may be partially responsible for error in the calculated depths to bedrock.

4.1.2. Electrical Resistivity Sounding Survey

Apparent resistivity values determined from the sounding survey are tabulated in Appendix I-1. The electrical soundings have been interpreted quantitatively by comparing the plots of "ρ_a" versus "a" with theoretical master curves (Larzeg, 1972). The "ρ_a" and "a" plots are given in Appendix I-1 and a summary interpretation of the data appears in Table 3.

Two major resistivity layers were revealed in all the soundings with the exception of Sounding 2 where a thin (0.9 m) near-surface layer covered the major layers. This layer probably represents the dry top soil (Fig. 19). The upper and lower layers were found to correlate with the silty clay and the sand (clayey) layers, respectively. Figures 18, 19, 20, and 21 compare the sounding and seismic results with the subsurface geology of the area. These figures show that the groundwater table which was previously determined by seismic refraction, was not detected by electrical sounding at all with the exception of Sounding 2. The low resistivity below the first interface (0.9 m) (Fig. 19), suggests that this interface is the groundwater table, however, since the Sounding 2 survey line crossed a 2 m wide ditch just about 1 m to the west of the sounding centre, it is possible that the first interface may not represent the groundwater table. This interface is shallower than the seismically determined depth to the groundwater table (2.0 m) which was assumed to be correct.

It is possible that the inability to detect the

Table 3

Summary Results of Sounding Interpretation (Curve Matching) for the Essex County Landfill No. 1

Sounding Station	Resistivity Layer 1		Resistivity Layer 2		Resistivity Layer 3	
	ρ_1	h_1	ρ_2	h_2	ρ_3	h_3
1	18	10.0	270	-	-	-
2	23	0.9	11.5	7.6	85	-
3	15	7.6	105	-	-	-
4	17	6.5	85	-	-	-
5	18	8.0	126	-	-	-
6	18	7.6	126	-	-	-
7	20	7.7	100	-	-	-
8	12.5	6.0	87.5	-	-	-
9	15	8.5	105	-	-	-
10	13.5	8.0	135	-	-	-

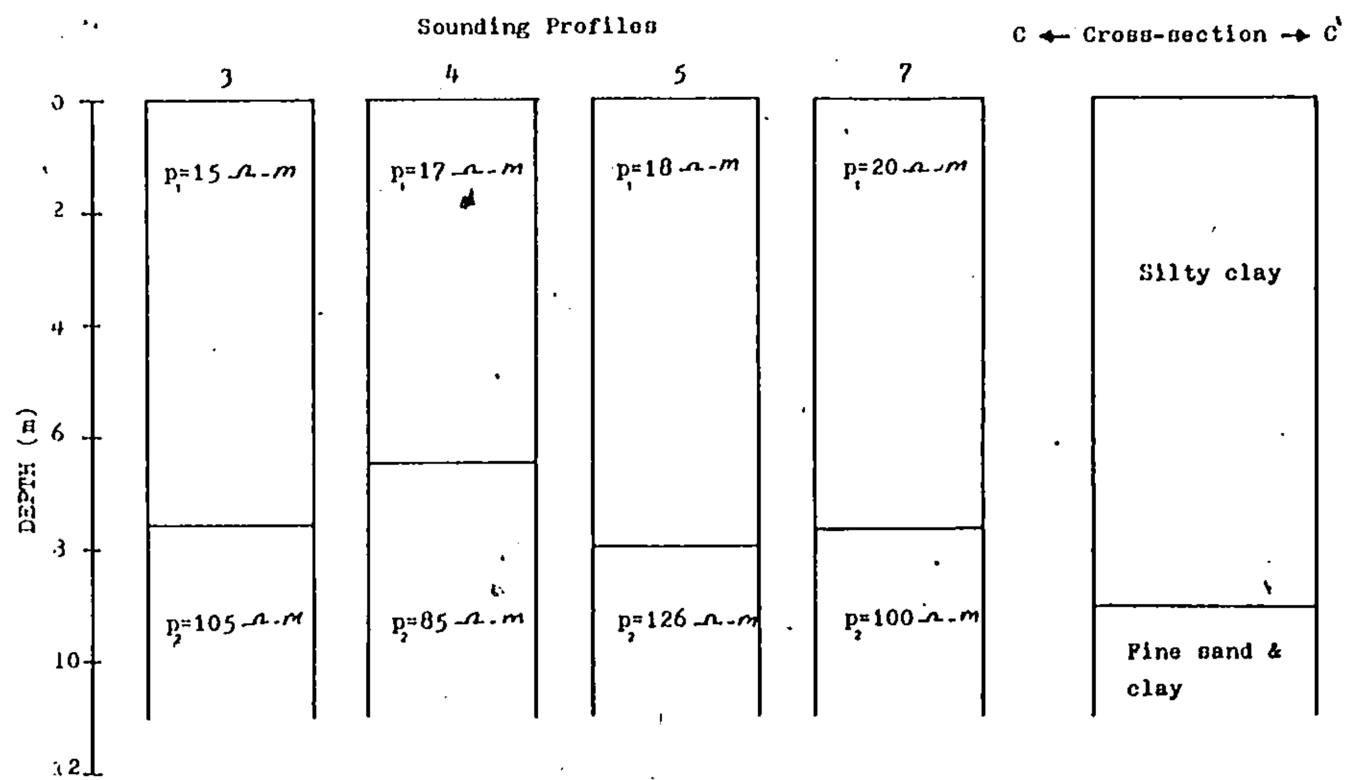


Figure 21. Comparison of Sounding Profiles 3, 4, 5, and 7 with borehole log (Essex County Landfill No. 1).

groundwater table by electrical sounding is related to the high content of clay minerals in the silty clay near the surface. Keller (1967) indicated that clay minerals have a great influence on the resistivity of soils. A large amount of clay minerals in a soil will result in a low resistivity for the soil because of the ion exchange capacity of the clay minerals.

In this study, the decrease in the resistivity of the silty clay due to saturation (at the water table) may have been less than that due to high content of the clay material in the silty clay near the surface (above the water table). The result would be that the electrical sounding could not detect the groundwater table.

The depths to the clayey sand layer were found to be shallower than the depths obtained from borehole log data. The depth to the clayey sand layer determined in Sounding 9, was found to be closer to the actual depth than the depth determined by Seismic Profile 9 (Fig. 20). Reference to Fig. 18 shows that Sounding 1 has successfully delineated the sand layer which is undetected by seismic refraction.

4.1.3 Electrical Resistivity Profiling Survey

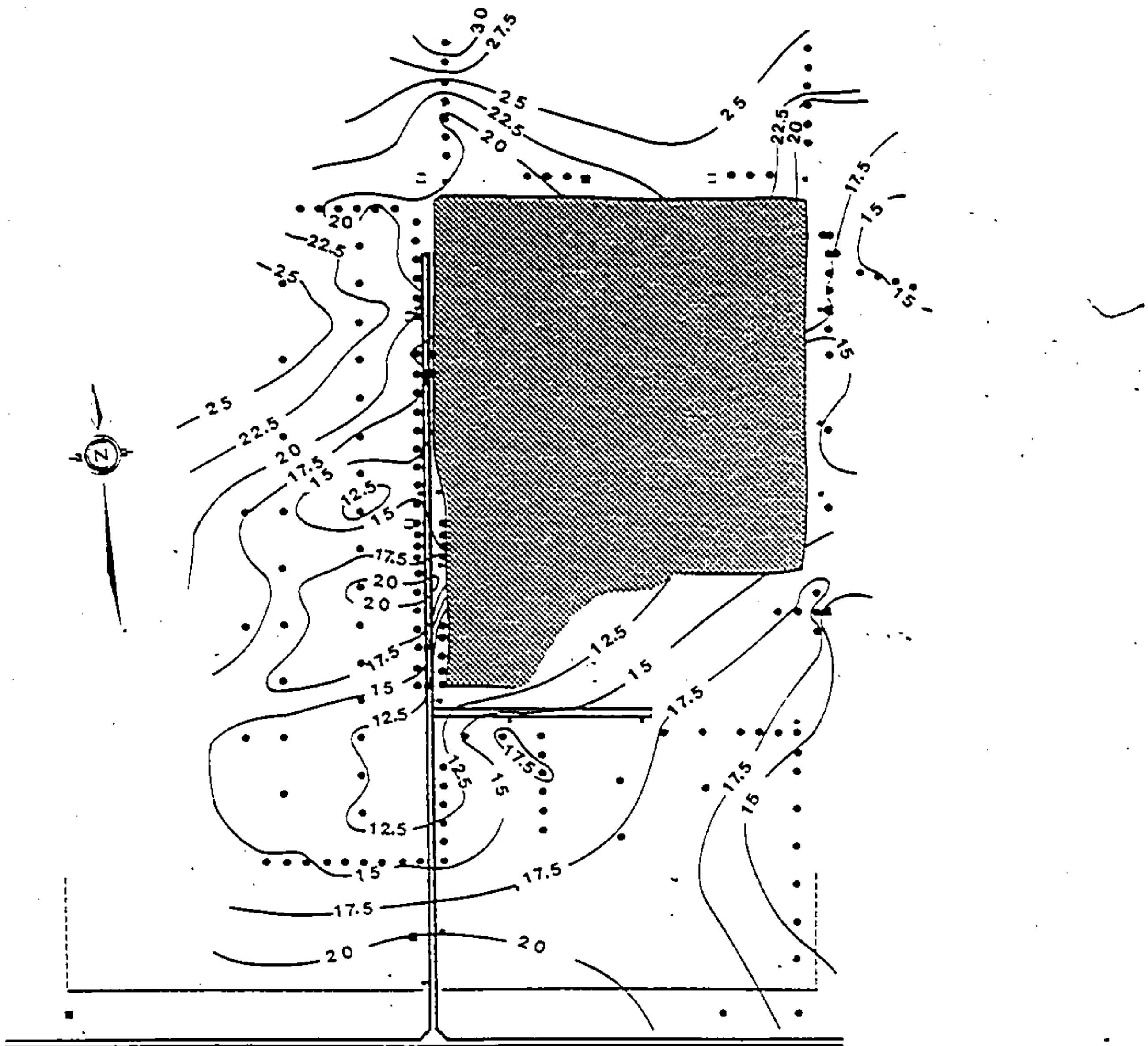
Two electrical profiling surveys using 'a' spacings of 4.6 and 12.2 m were carried out at Essex County Landfill No. 1. The 4.6 m spacing was chosen in order to determine the resistivity variations within the silty clay layer and to reach well below the groundwater table which was indicated by seismic refraction to be within 2.3 m below the ground surface. The electrode spacing of 12.2 m was chosen in order to determine whether the contaminant plume from the landfill may travel in the underlying sand layer.

The results of the electrical profiling surveys are tabulated in Appendix I-2. The measured apparent resistivities for each 'a' spacing were contoured and two isoresistivity maps were constructed (Figs. 22 and 23).

The isoresistivity map for the area at an 'a' spacing of 4.6 m (Fig. 22), shows a general decrease in apparent resistivity as the landfill is approached. Apparent resistivities range from a low value of about 6.3 Ωm at Resistivity Station #140, to a high value of about 32.5 Ωm at Resistivity Station #76 (Fig. 15).

The most prominent feature of the map is the wide area of low resistivity to the south and southwest of the landfill. This map also shows small areas with a relatively higher resistivity in the north of the landfill, and west of the southwestern corner of the landfill.

The isoresistivity map for the area at an 'a' spacing of 12.2 m (Fig. 23), shows similar contour patterns as the apparent resistivities decrease towards the landfill. Apparent resistivities range from a low value of about 11.9 Ωm at Resistivity Station #145, to a high value of



Landfill

- ■ Seismic & Resistivity 'Sounding' Stations
- ⁚ Resistivity Station (Sounding)
- • Resistivity Station (Profiling)
- . Electrical Conductivity Site(Ditch)
- ═ Paved Road
- ═ Temporary Road
- — Fence

0 50 100 150 m

Scale

—15— Resistivity contours in ohm-m(contour interval =2.5 ohm-m)

Figure 22. Isoresistivity map for the Essex County Landfill No. 1 at 4.6 m "a" spacing.

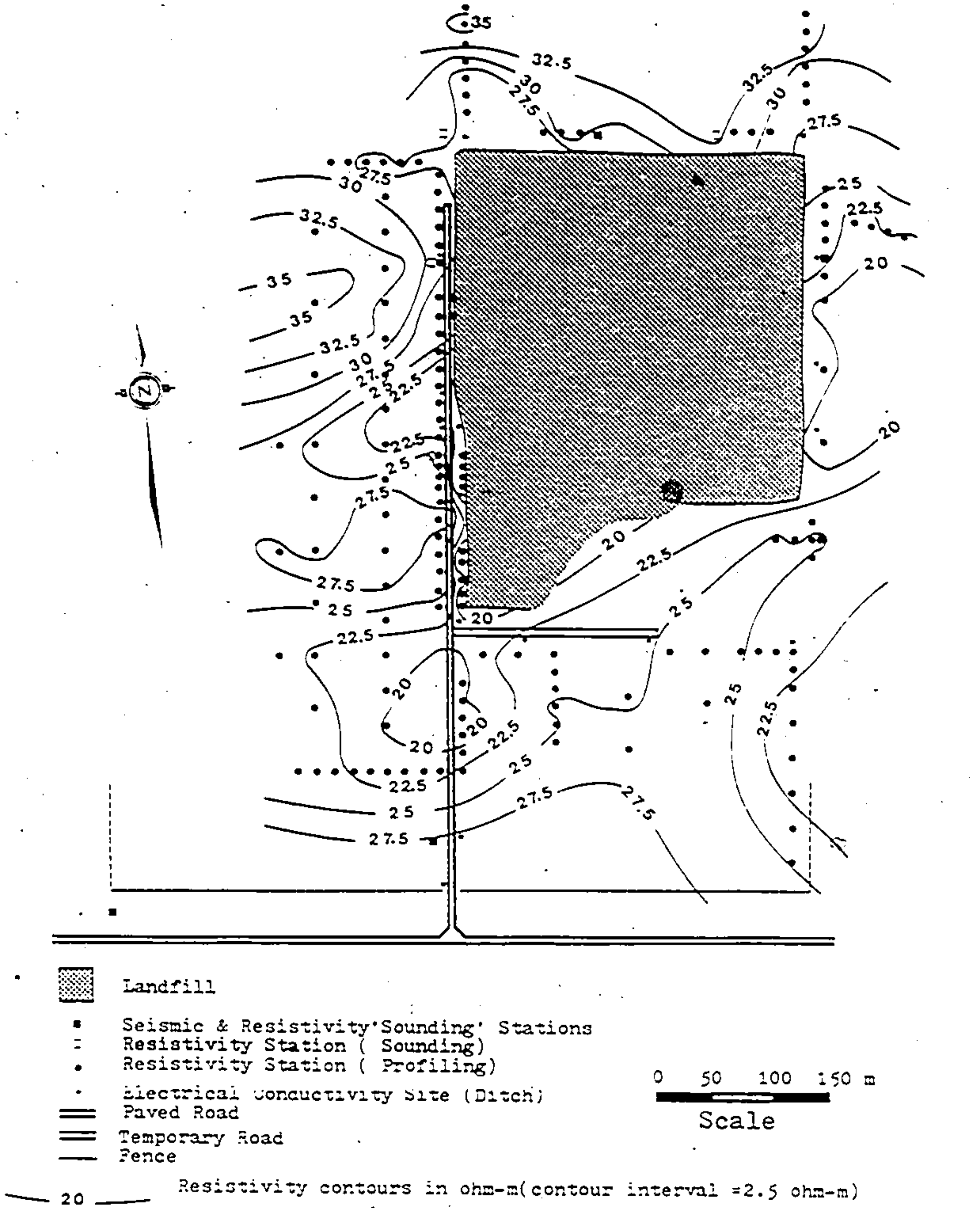


Figure 23. Isoresistivity map for the Essex County Landfill No. 1 at 12.2 m "a" spacing.

about 36 Ωm at Resistivity Station #75 (Fig. 15). The most striking feature of this map is also the wide area of low resistivity to the south and southwest of the landfill.

Generally, in both maps the apparent resistivity contours appear to be elongated towards the southwest. This may indicate that the contaminant plume is moving toward the southwest which is the same direction as that of the shallow groundwater flow (Fink and Aulenbach, 1974).

4.1.4 Electrical Conductivity Measurements

The electrical conductivity measurements for the water taken from the ditches around Essex County Landfill No. 1 are listed in Appendix I-4 and shown in Fig. 24.

The electrical conductivity values ranged from about 269 μS/cm at Electrical Conductivity Site #13, to about 2770 μS/cm at Electrical Conductivity Site #11 (Fig. 15). The low values of the electrical conductivity south of the landfill may indicate uncontaminated conditions. These values may represent rain water which is not affected by the seepage from the landfill.

The high values of the electrical conductivity measured in ditches close to the landfill may indicate highly contaminated conditions.

The measured electrical conductivity values may not represent the real values of the conductivity of the

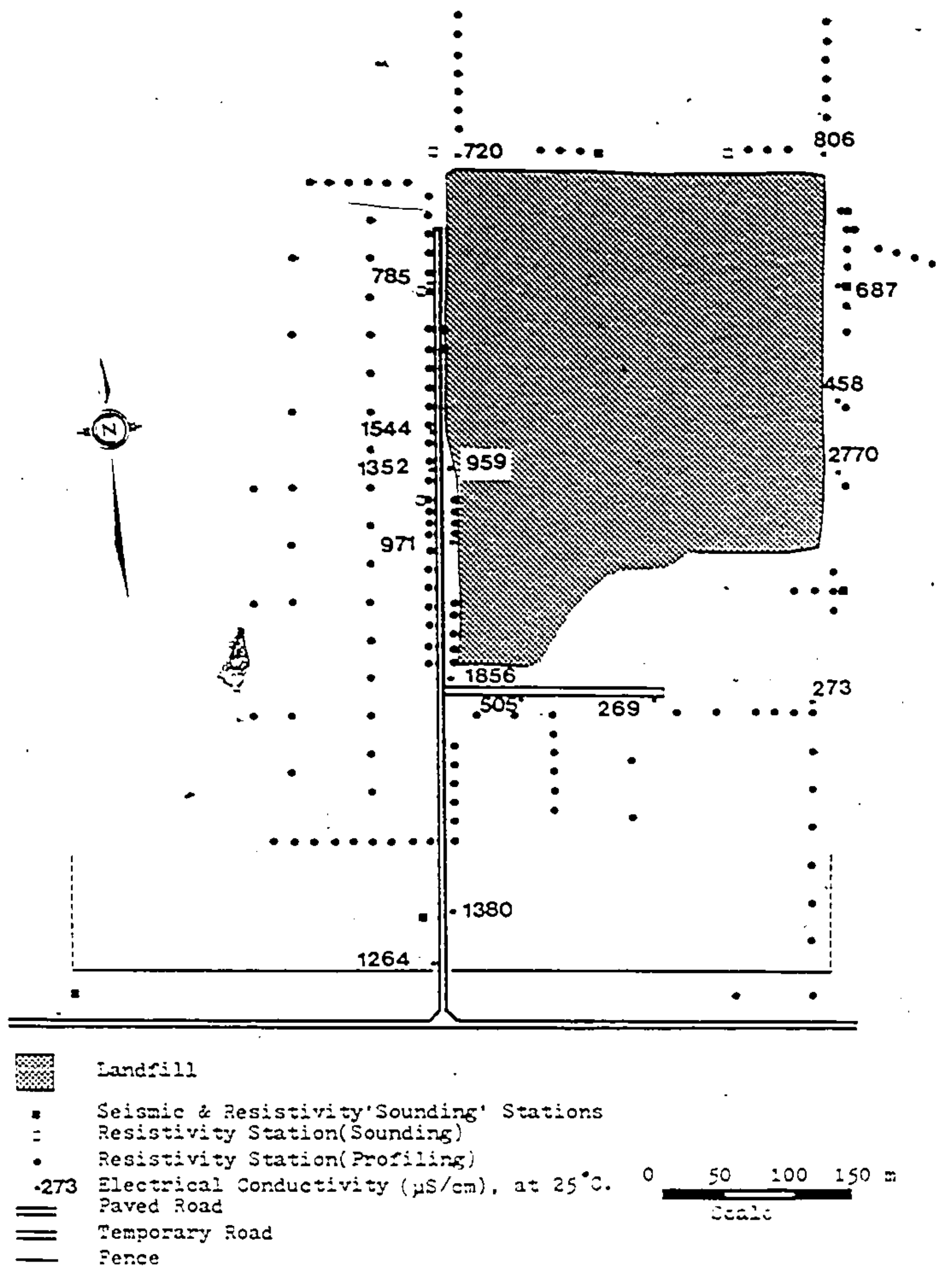


Figure 24. Electrical conductivity map for the Essex County Landfill No. 1.

groundwater because these measurements were taken after a rainy day. However, the distribution of the conductivity values may indicate that the contaminated water from the landfill is seeping towards the southeast and southwest where the high electrical conductivities are found.

4.1.5 Evaluation of the Essex County Landfill No. 1

The general decrease in the apparent resistivity values towards the landfill (Figs. 22 and 23) suggests that these resistivity values are affected by water quality changes because of the landfill. Apparent resistivity changes related to lateral variations in earth material, however, are not evident on the isoresistivity maps with the exception of small areas north of the landfill, and just west of the southwestern corner of the landfill where the relatively high resistivity values may be caused by the heterogeneity of the silty clay layer and the presence or absence of sand or gravel.

Sounding Profile 10 was made in an area (about 1 km northwest of the landfill) thought to be unaffected by contamination from the landfill. This sounding profile was compared with Sounding Profiles 1 to 9 (Figs. 25 and 26), which are located in the vicinity of the landfill, in order to evaluate the resistivity data. The comparison, however, shows that the unaffected area has generally lower resistivity values than the areas near the landfill.

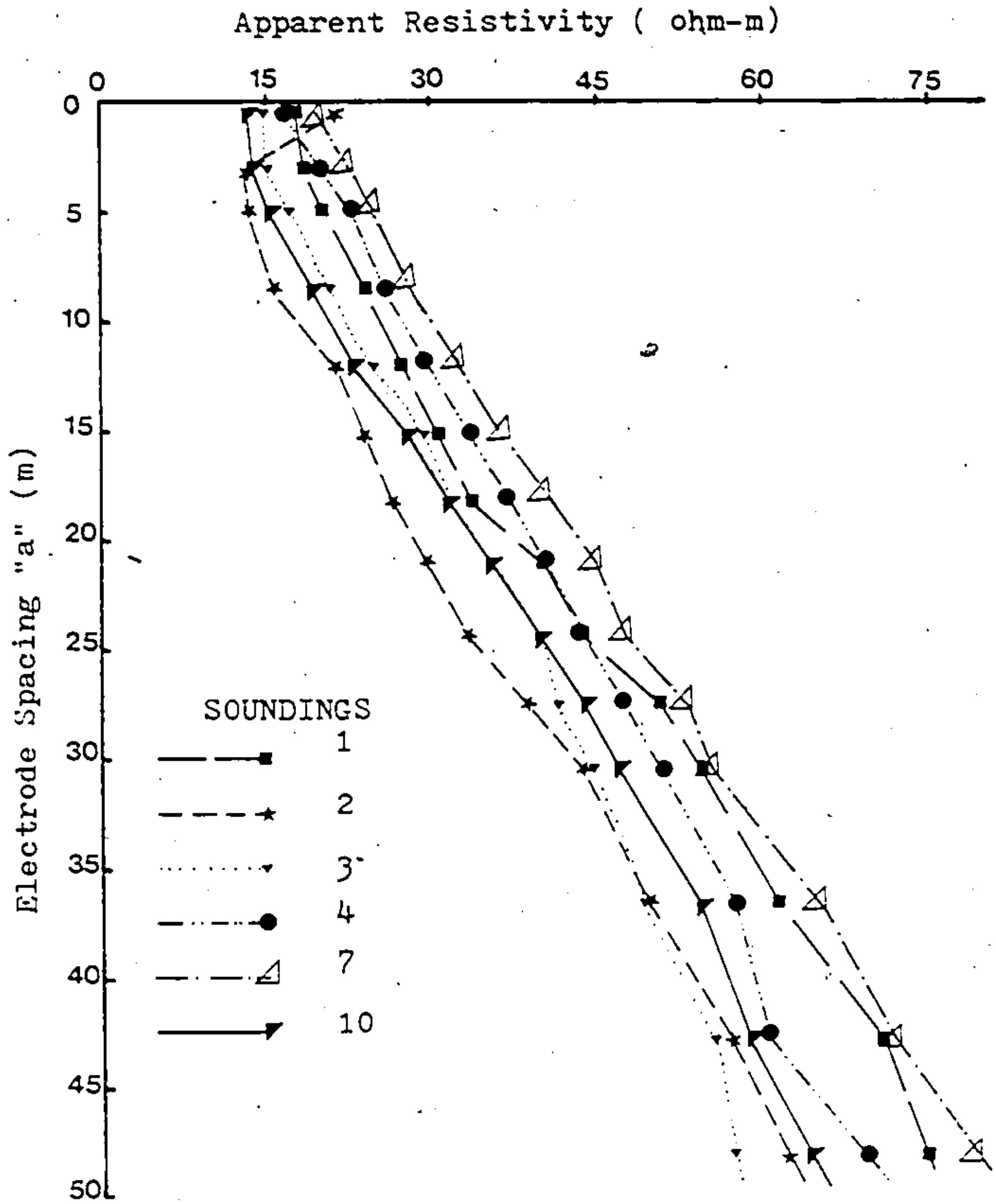


Figure 25. Comparison of electrical soundings
(Essex County Landfill No. 1).

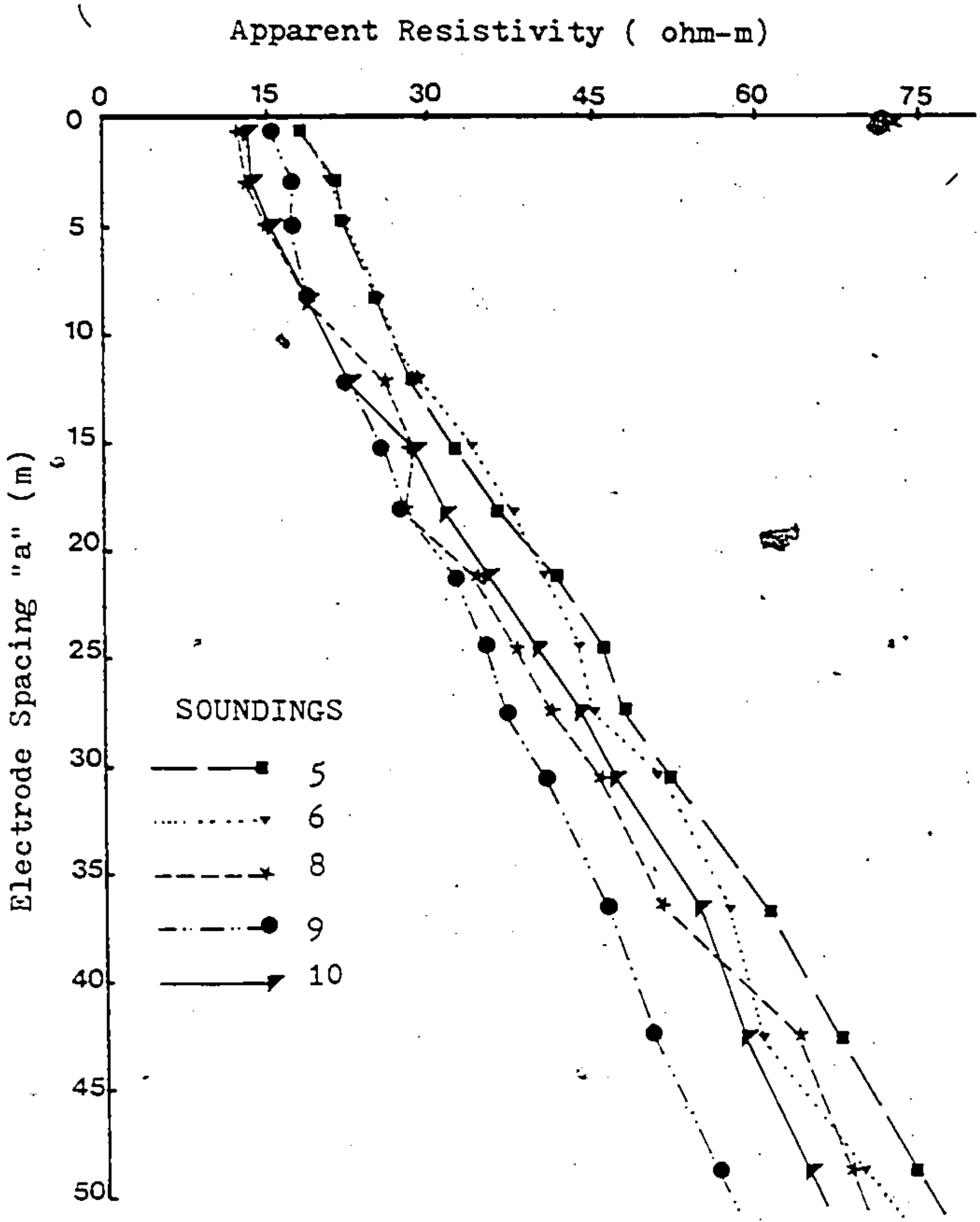


Figure 26. Comparison of electrical soundings
(Essex County Landfill No. 1).

This situation may be attributed to differences in subsurface lithology. Sounding Profile 10, therefore, cannot be used as a reference to evaluate the resistivity data.

A comparison of Sounding Profiles 1 to 9, however, indicates that the area north (up gradient) of the landfill is less affected by contamination from the landfill. The comparison also indicates that the effect of the landfill is less in the area farther to the south of the landfill (about 200 m). The true resistivity values of the silty clay and sand determined from Sounding Profiles 1 to 9, by curve matching (Table 3), were also found to be higher in the area north of the landfill, and at farther distances to the south of the landfill.

Based on the evaluation of the resistivity data (electrical sounding and profiling) which indicated that the contaminant plume is moving to the southwest, and that the area north of the landfill is less affected by the contamination from the landfill, apparent resistivities of approximately 25 and 33 Ωm measured in the area farther to the north are assumed to represent the unaffected silty clay and sand, respectively. These values are used as limiting values to separate the contaminated and uncontaminated zones. Resistivity zones of (0-25) and (0-33) Ωm are assumed to represent the contaminated zones for the 4.6 and 12.2 m 'a' spacings isoresistivity maps.

An interpretation of the general extent of the contaminant plume at 4.6 and 12.2 m depths, based on the classification of the apparent resistivity data, is illustrated in Figs. 27 and 28. These figures show that the main body of the plume is moving to the south and southwest extending to distances between 300 to 350 m from the southwestern corner of the landfill. The boundary of the plume in these directions, however, cannot be determined accurately from the available data. The extent of the contaminant plume to the north is limited to within approximately 120 m, while to the east of the landfill the extent of the plume cannot be determined from the available data, however, it is expeected to be limited since the local groundwater flow direction in this area, is towards the south and southwest.

The isorestivity maps indicated that the contaminant plume is traveling at shallow depth (4.6 m) within the silty clay, and at lower depth (12.2 m) within the sand. However, it was not possible to determine from the available data whether the contaminant plume has moved even further in the buried sand.

4.2 Essex County Landfill No. 2

4.2.1 Topographical Survey

The terrain around Essex County Landfill No. 2 has been greatly altered by sand extraction and landfilling

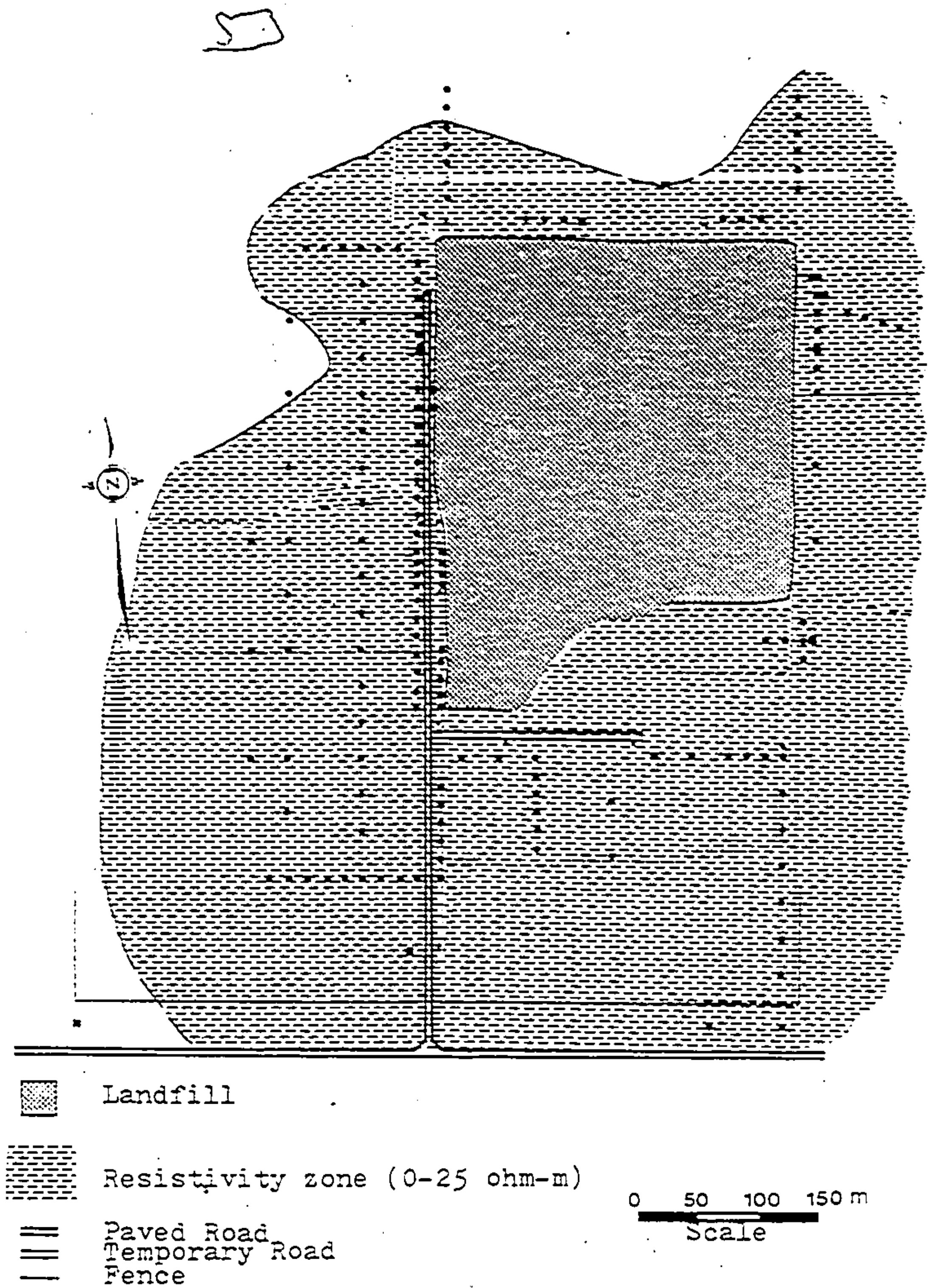


Figure 27. Summary interpretation of the general extent of the contaminant plume at 4.6 m depth for the Essex County Landfill No. 1.

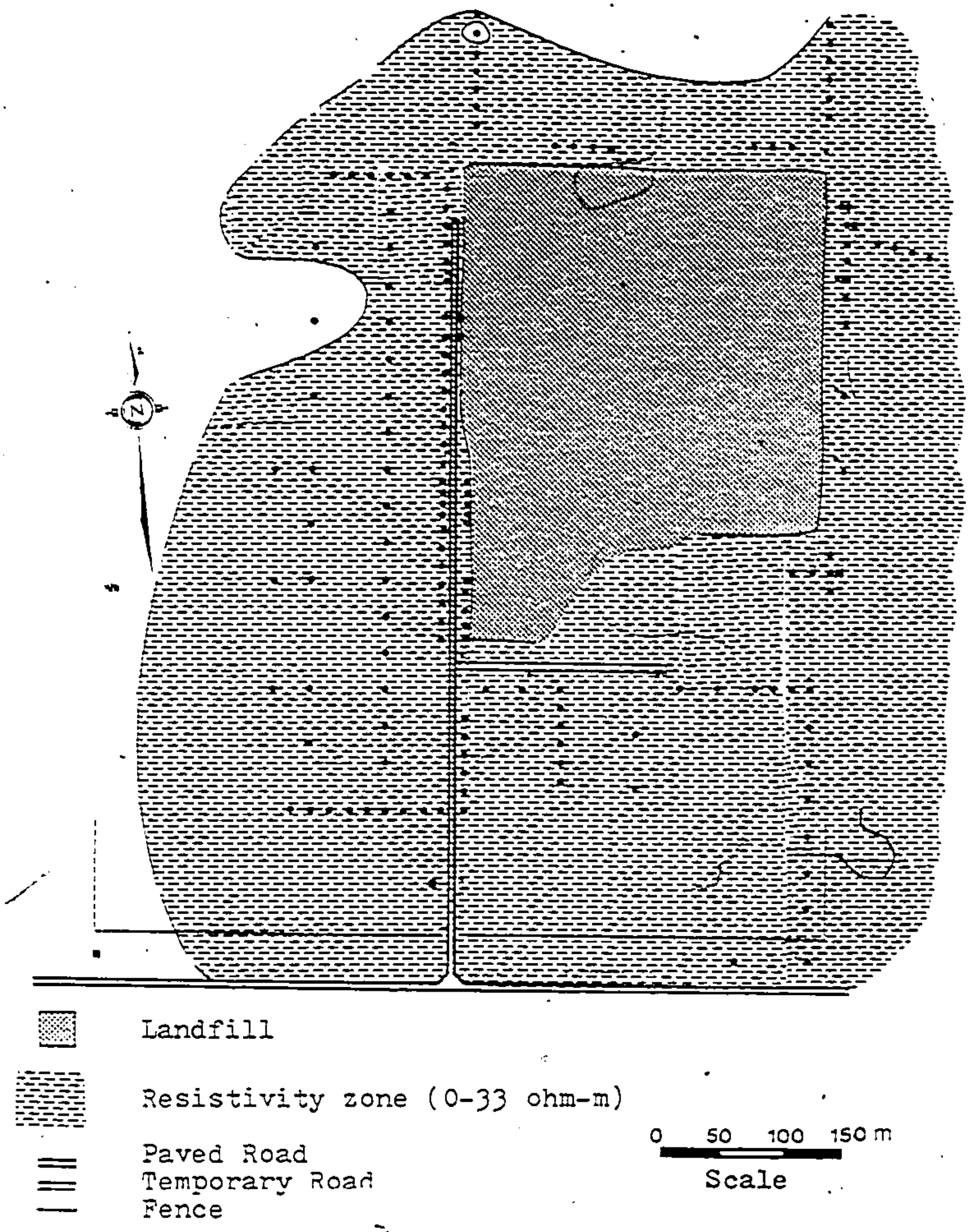


Figure 28. Summary interpretation of the general extent of the contaminant plume at 12.2 m depth for the Essex County Landfill No. 1.

operations. In order to allow more accurate interpretations of the geophysical surveys, a limited topographical survey was completed.

The results of the levelling survey are listed in Appendix II-6 and given in Fig. 29.

4.2.2 Seismic Refraction Survey

The results of the seismic refraction survey for Essex County Landfill No. 2 are plotted and listed in Appendix II-3. Table 4 summarizes the seismic velocities, intercept times, and interface depths determined for the four survey sites.

Two seismic velocity layers can be interpreted for this site. The upper layer has a seismic velocity range of approximately 213 to 428 m/s which probably represents the unsaturated (dry) sand and gravel. The lower layer has a seismic velocity range of approximately 1617 to 1890 m/s which probably represents the saturated compact moraine (sand and silty clay). Table 5 summarizes the seismic interpretations for Essex County Landfill No. 2.

The interpretation of seismic refraction was based on the comparison of the seismic velocity layers with the subsurface geology of the area and with the published data (Press, 1966; Parasnis, 1975).

In all seismic profiles, the v_1-v_2 (d_1) interface is likely to be the groundwater table rather than the contact

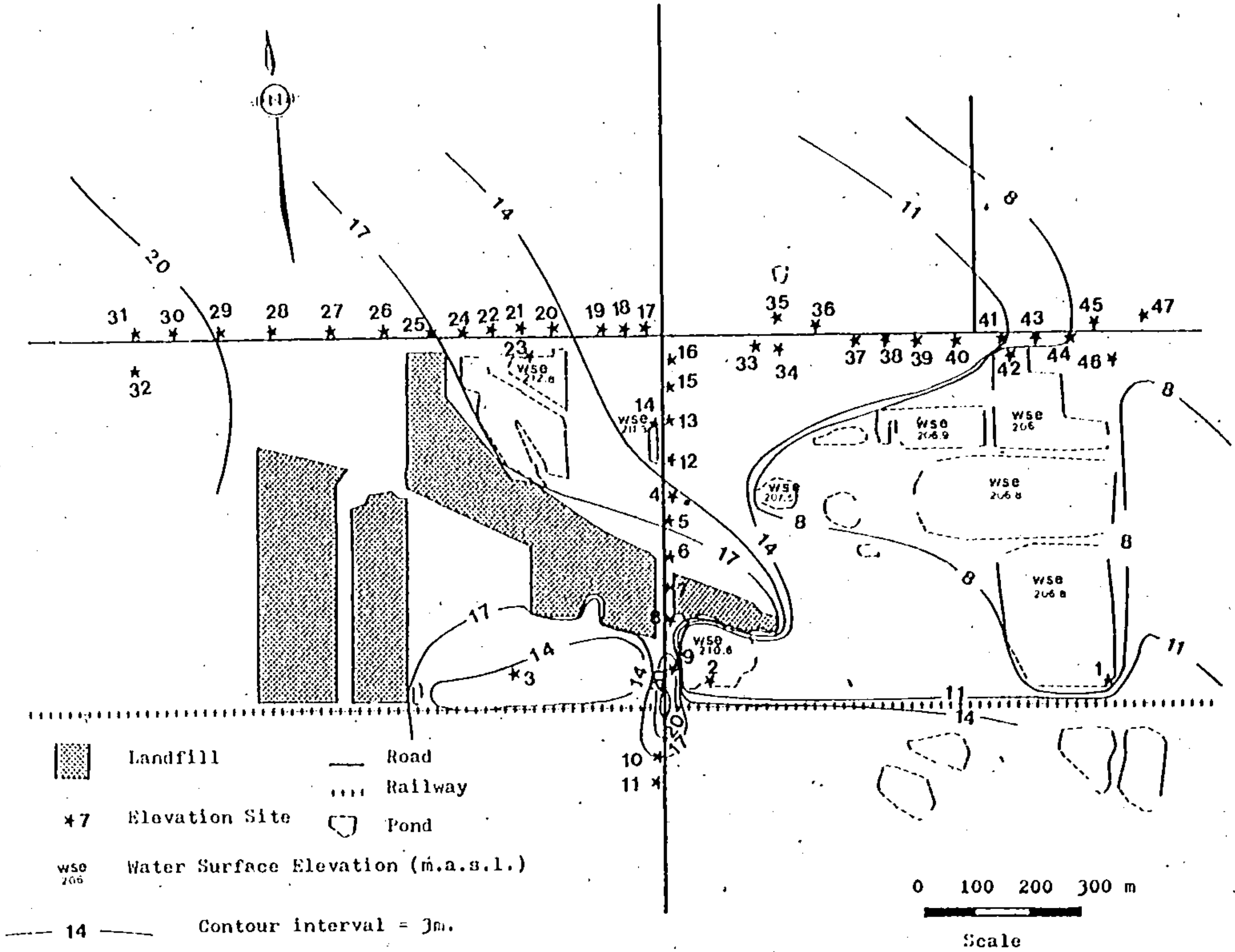


Figure 29. Topographical map for the Essex County Landfill 2.

Table 4

Seismic Velocities, Intercept Times, and Interface Depths for the Essex County Landfill No. 2

Seismic Profile	Seismic Velocity* V(m/s)		Intercept Time** Ti(s x 10^{-3})	Depth to Interface*** d(m)
	V_1	V_2	Ti_1	d_1
1	313	1890	10.3	1.6
4	231	1783	9.3	1.1
5	213	1617	7.0	0.7
7	428	1676	2.5	0.5

*Obtained directly from the time-distance plots (Appendix II-3)

**Obtained directly from the time-distance plots (Appendix II-3)

***Calculated by using Equation 2.3a

Table 5

Summary of Seismic Interpretation for the Essex County Landfill No. 2

Layer	Calculated Seismic Velocity (m/s)	Thickness range (m)	Probable Materials	Published Data	
				Seismic Velocity (m/s)	Reference
Upper	213-428	0.5-1.6	dry, loose sand to compact sand and gravel	200-500	Press (1966)
Lower	1617-1890	-	saturated compact moraine	1500-2700	Parasnis (1975)

of sand with the silty clay. This interpretation is based on the great increase in the seismic velocity across this interface which suggests that the v_2 is the seismic velocity of the unconsolidated deposits below the groundwater table. This velocity increase due to saturation is similar to that found by Sander (1978). Figure 30 shows that the interface (d_1) corresponds to the groundwater table which is at depth of about 1.5 m. Thus the calculated depth to the groundwater table determined by Seismic Profile 1 is in error by ± 10%. The calculated depth to the groundwater table determined by Seismic Profile 4 was found to be in error by ± 8% as compared to the actual depth to the groundwater table (1.2 m) measured in a nearby well (shallow-well no. 6 in Fig. 16).

In this study, the seismically determined depths to the groundwater table vary from 0.5 to 1.6 m. The 8-10% error in seismically determined depths to the groundwater is considered to be within the accuracy inherent of the seismic technique itself (Duguid, 1968).

4.2.3 Electrical Resistivity Sounding Survey

Apparent resistivity values determined from the sounding survey are tabulated in Appendix II-1. The electrical soundings have been interpreted quantitatively by comparing the plots of "ρ_a" versus "a" with theoretical master curves (Lazreg, 1972). The "ρ_a versus "a" plots

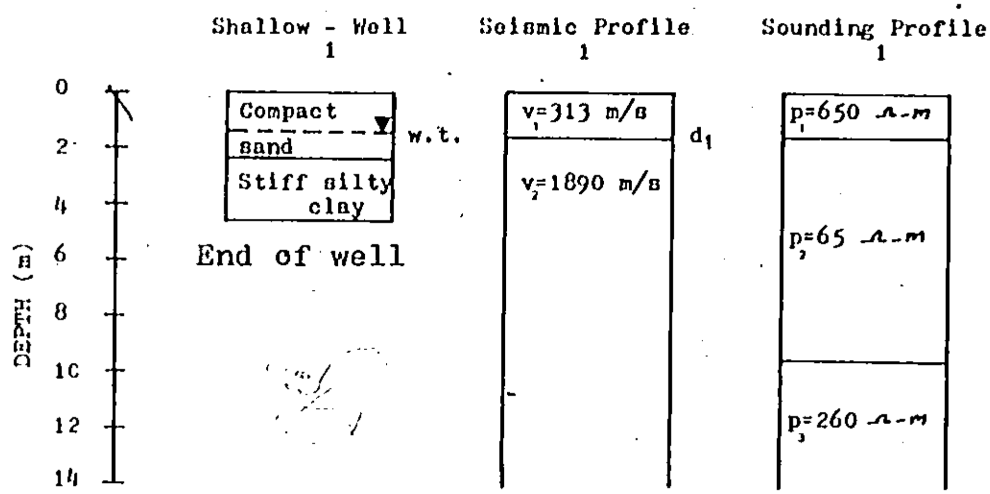


Figure 30. Comparison of Seismic and Sounding Profile 1 with borehole log (Essex County Landfill No. 2).

are given Appendix II-1 and a summary interpretation of the data appears in Table 6.

Three resistivity layers are revealed in all the electrical soundings. Figures 30 to 34 compare the available borehole information and seismic results with selected electrical sounding data. Based on these comparisons, it appears that the upper resistivity layer is dry loose to compact sand and gravel and that the first interface is the groundwater table. The groundwater table varies from 0.7 to 2.8 m. The second layer is the saturated compact moraine (silty clay and sand), however, in Sounding 3 this layer probably represents saturated sand and gravel. The third layer in Soundings, 1, 2, 4, 5, 6, and 7 is the buried sand, while in Sounding 3, the third layer is the silty clay.

It appears that the resistivity values of the upper layer are controlled by the presence of the gravel and by moisture content. The high resistivity in Sounding 1 is attributed to the dry sand and to the presence of gravel, while the low resistivity in Sounding 2 is due to wet sand.

The resistivity values of the second and third layers appear to be affected by groundwater contaminations. Soundings close to the landfill gave low resistivity values while away from the landfill, high resistivities were indicated.

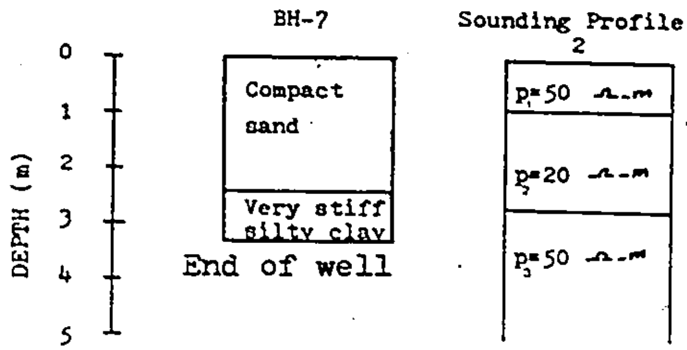


Figure 31. Comparison of Sounding Profile 2 with borehole log (Essex County Landfill No. 2).

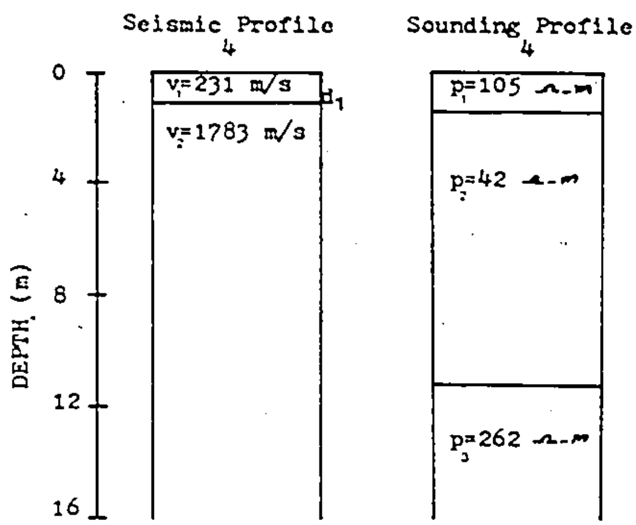


Figure 32. Comparison of Seismic and Sounding Profiles 4 (Essex County Landfill No. 2).

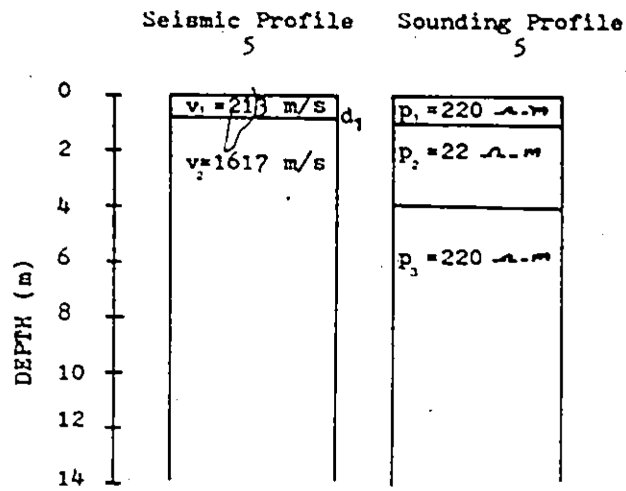


Figure 33. Comparison of Seismic and Sounding Profiles 5 (Essex County Landfill No. 2).

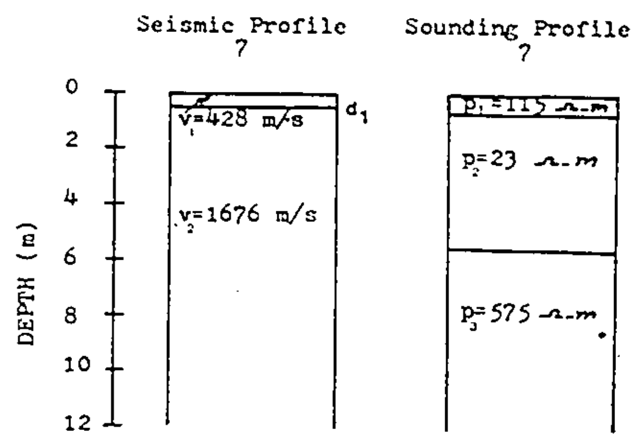


Figure 34. Comparison of Seismic and Sounding Profiles 7 (Essex County Landfill No. 2).

Table 6

Summary Results of Sounding Interpretation (Curve Matching) for the Essex County Landfill No. 2

Sounding Station	Resistivity Layer 1		Resistivity Layer 2		Resistivity Layer 3	
	ρ_1	h_1	ρ_2	h_2	ρ_3	h_3
1	650	1.6	65	8.0	260	-
2	50	0.9	20	1.8	50	-
3	300	2.8	195	14	60	-
4	105	1.4	42	9.8	262	-
5	220	1.0	22	3.0	220	-
6	105	1.0	21	5.2	275	-
7	115	0.7	23	4.9	575	-

The groundwater table is assumed to be the top of the contaminant plume. Although the bottom of the plume cannot be determined accurately, it appears from the resistivity values of the third layer (the buried sand) that the plume has entered this layer. This means that the plume may extend vertically in some places (Sounding 4) to depths of more than 11 m.

4.2.4 Electrical Resistivity Profiling Survey

Because the depth to the groundwater table in this area varies from about 1 to 7 m (as indicated by the seismic and sounding results and by direct measurements of the depths to the groundwater table) (Table 7), three electrical profiling surveys using 'a' spacings of 1.8, 3.0, and 6.1 m were carried out at the Essex County Landfill No. 2. The 1.8 m 'a' spacing was chosen for the area located south and southeast of the landfill (sand pits) where the groundwater was found to be within 1 m of the existing ground surface. The 3.0 and 6.1 m 'a' spacings were used for the entire area in order to determine the apparent resistivity variations at different depths and to ensure that the apparent resistivities were measured far enough below the water table (top of the plume).

The results of the electrical profiling surveys are tabulated in Appendix II-2. Figures 35, 36, and 37 are the isoresistivity maps for the 1.8, 3.0, and 6.1 m 'a' spacings, respectively.

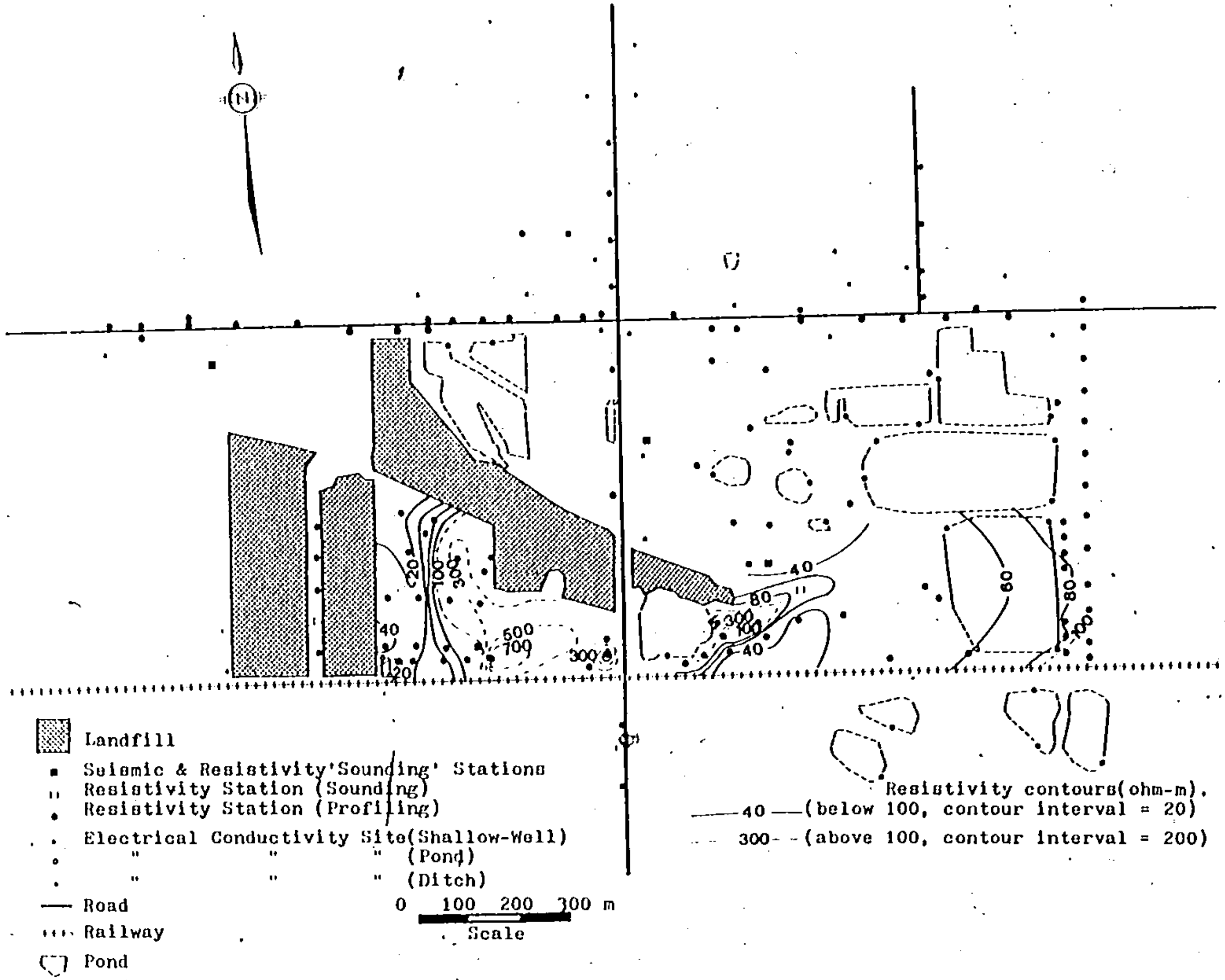


Figure 35. Isoresistivity map for the Essex County Landfill No. 2 at 1.8 m "a" spacing.

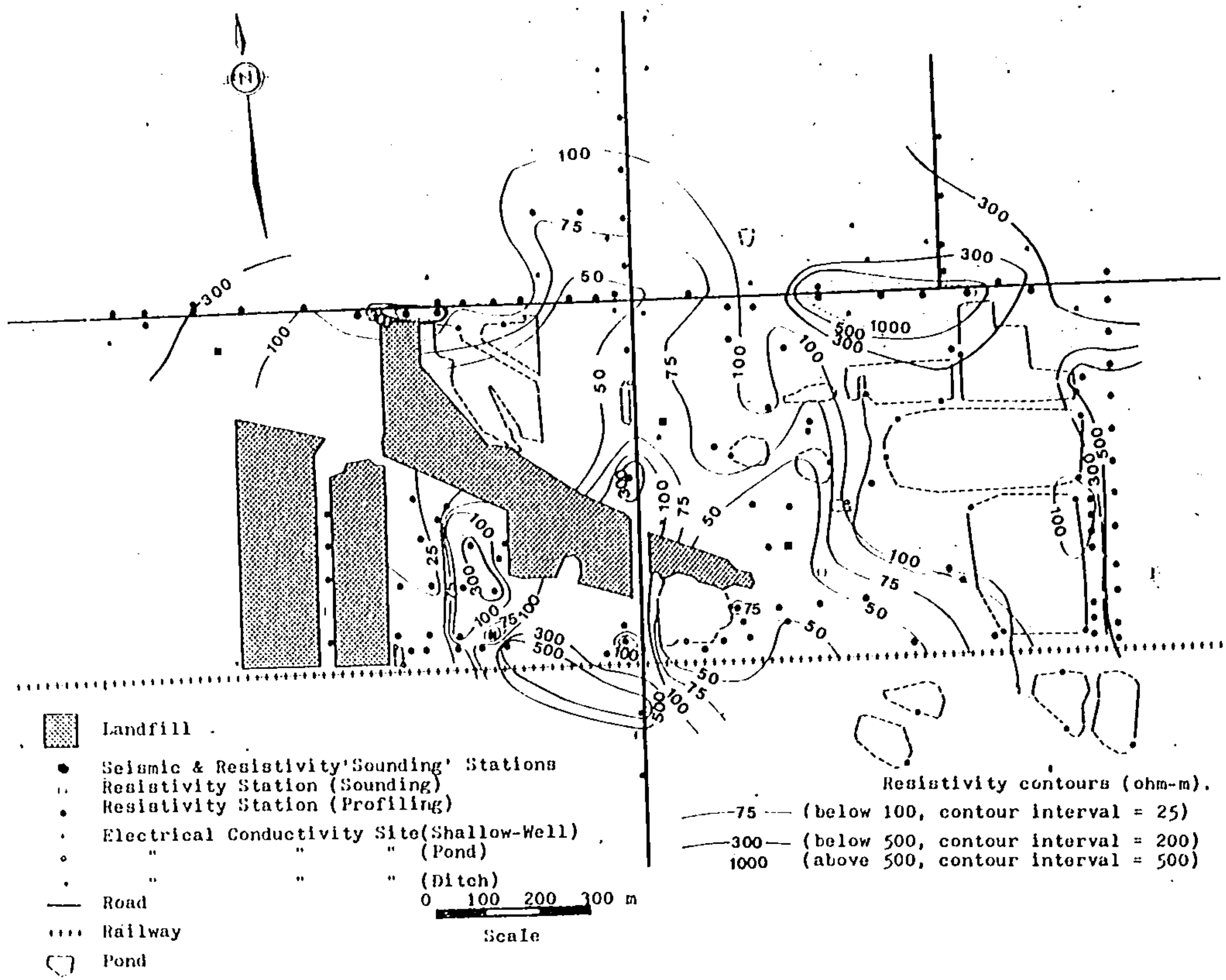


Figure 36. Isoresistivity map for the Essex County Landfill No. 2 at 3.0 m "a" spacing.

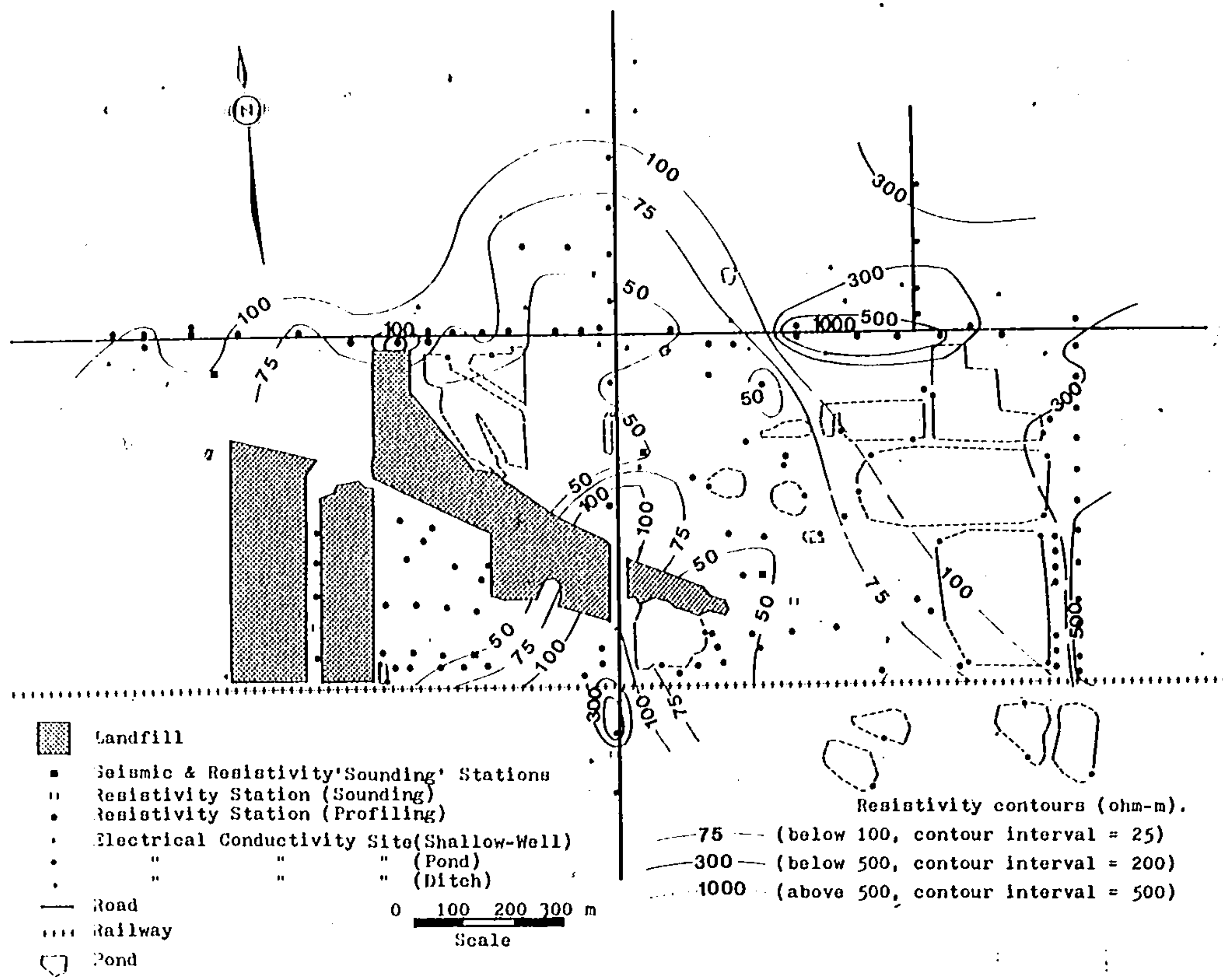


Figure 37. Isoresistivity map for the Essex County Landfill No. 2 at 6.1 m "a" spacing.

Table 7

Depths to Groundwater Table Measured in Selected Shallow-wells at the Essex County Landfill No. 2

Well No.*	Depth to Groundwater Table (m)
1	1.5
3	1.8
5	7.1
6	1.2
7	1.6
12	3.5
14	4.5
16	1.6
17	2.4

*Locations of these wells are shown in Fig. 16.

Figure 35 shows that for the 1.8 m 'a' spacing, a general decrease in the apparent resistivities occurs as the landfill is approached, however, increases in apparent resistivities towards the landfill are found just south of the small eastern landfill. Apparent resistivities range from a low value of about 12.5 Ωm at Resistivity Station #47, to a high value of about 822 Ωm at Resistivity Station #31 (Fig. 16).

The prominent features of the map are the low resistivity area just east of the western part of the landfill, the wide area with relatively low resistivity further to the east of the small eastern landfill, and the area with high to very high resistivities south of the landfill.

Figure 36 shows that for the 3.0 m 'a' spacing, a general decrease in the apparent resistivity occurs towards the landfill. Apparent resistivity values range from a low of about 14.7 Ωm at Resistivity Station #46, to a high of about 1471 Ωm at Resistivity Station #75 (Fig. 16).

The most striking features of the map are the low resistivity area just east of the western part of the landfill, the relatively low resistivity areas east and northeast of the landfill, the high resistivity areas south of the landfill and at the extreme east of the map, and the very high resistivity area northeast of the landfill. Small areas with relatively high to very high resistivities are found in several scattered areas.

Figure 37 shows that the 6.1 m 'a' spacing results are similar to the previous map as the apparent resistivities tend to decrease towards the landfill. Apparent resistivity values range from a low of about 33 Ωm at Resistivity Station #16, to a high of about 1396 Ωm at Resistivity Station #75 (Fig. 16).

The prominent features of the map are the low resistivity areas northeast and north of the landfill, the high resistivity area at the extreme east of the map, and the extremely high resistivity area northeast of the landfill. Small areas with high or low resistivities are found scattered throughout the map area.

Generally, the dominant features in the isoresistivity maps are the low resistivity areas within the landfill site, east and northeast of the landfill, and the high resistivity areas south of the landfill, at the extreme east of the area, and northeast of the landfill.

The general trends of the apparent resistivity values which decrease to the northeast and east indicate that the contaminant plume is moving in these directions.

4.2.5 Electrical Conductivity Measurements

The electrical conductivity measurements for the water samples are tabulated in Appendix II-4. Selected data are plotted in Fig. 38.

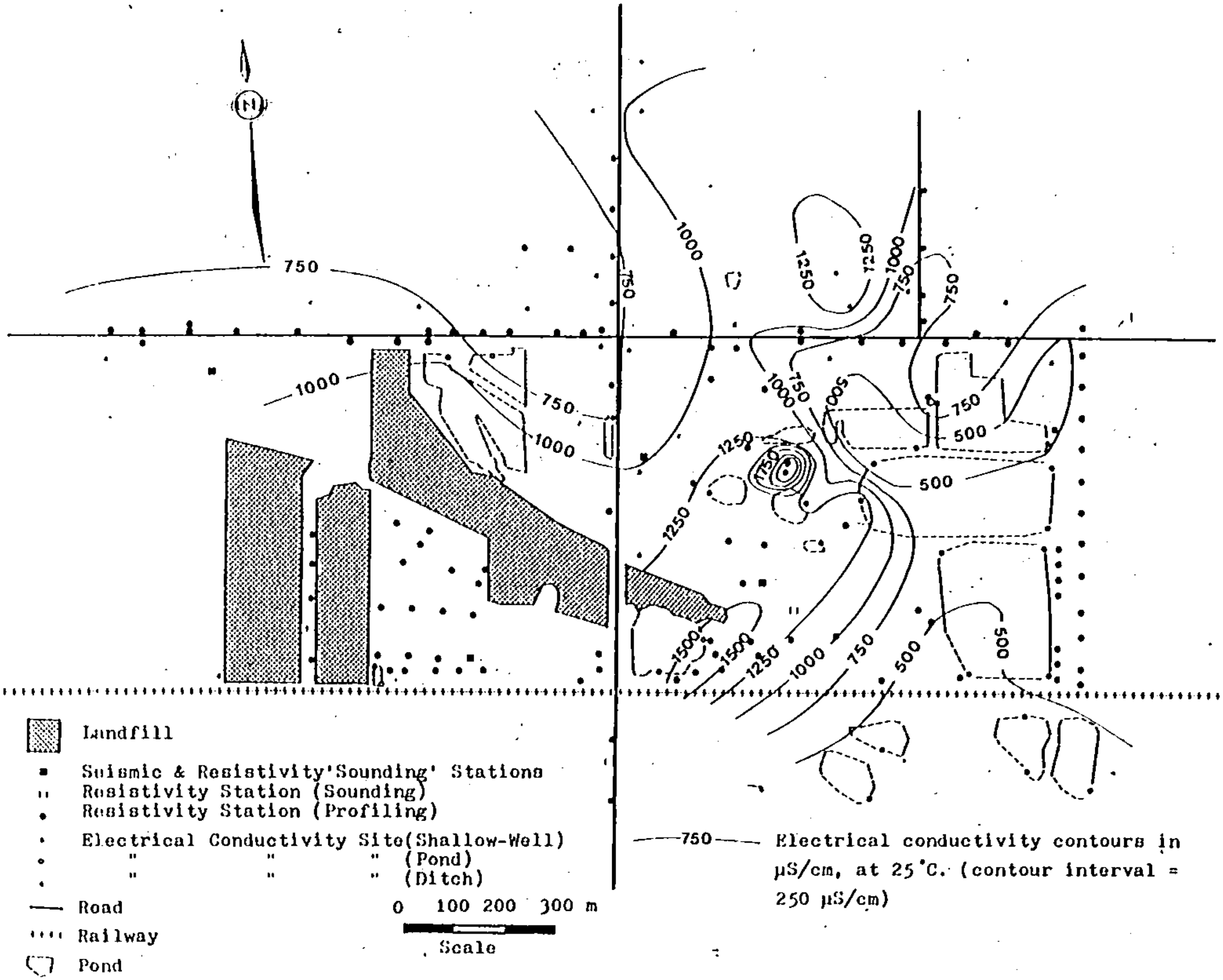


Figure 38. Electrical conductivity map for the Essex County Landfill No. 2.

Generally, Fig. 38 shows that the electrical conductivity values of the groundwater increase towards the landfill suggesting that the landfill is responsible for the increase. The map also shows high electrical conductivity in localized areas away from the landfill, such as those located in the north and northeast. These increases in the electrical conductivity may be attributed to a local effect such as greenhouse operations.

The electrical conductivity of the groundwater ranges from a low value of about 378 μS/cm at the small pond in the south of the map (Electrical Conductivity Site #44 in Fig. 16), to a high value of about 2505 μS/cm found in the small pond just east of the western part of the landfill (Electrical Conductivity Site #40 in Fig. 16). The highest electrical conductivity value of about 5931 μS/cm was measured in a ditch just west of the landfill (Electrical Conductivity Site #42 in Fig. 16). This water may represent direct drainage of leachate from the landfill.

The electrical conductivity values of the groundwater are related to the total ion concentrations in the water, and, therefore, reflect the quality of the groundwater. A study by Essop and Brown (1980) indicated the presence of elevated levels of ammonia, sodium, iron, potassium, chloride, nitrate, and other chemical and organic substances. They attributed these elevated concentrations to the landfill, the greenhouses, domestic septic tanks, and the fertilizer used in the agriculture.

There is a strong linear relationship between the electrical conductivity measured in this study and the chloride concentrations of the groundwater measured by Essop and Brown in 1980 (Table 8). The comparison generally shows that there is a direct linear relationship between electrical conductivity and chloride concentration (correlation coefficient is 0.96). Based on the electrical conductivity-chloride relationship, an electrical conductivity of about 500 μS/cm may reflect uncontaminated groundwater. However, since the groundwater in this area is affected by other contaminant sources besides the landfill (greenhouse operations, fertilizers, etc.), the background groundwater in the area northwest (up gradient) of the landfill was found to be approximately 750 μS/cm. Sklash and Farvolden (1979) have also indicated that the average background electrical conductivity is 750 μS/cm. Therefore, this value will be used to delineate the contaminated groundwater caused by the landfill.

Figure 38 shows that the contaminant plume from the landfill may extend to distances of approximately 600 and 400 m east and southeast of the landfill, respectively. The contaminant plume appears to extend to a distance of approximately 1 km or more to the northeast of the land-

Table 8

Comparison of Electrical Conductivity Measurements and Chloride Concentrations of Groundwater at the Essex County Landfill No. 2

Electrical Conductivity Site	Electrical Conductivity (μS/cm) measured at 25°C, 1982	Chloride Concentrations (mg/l), 1980
1	811	124
2	756	132
3	722	95
4	599	115
5	1240	170
6	1040	149
7	868	133
8	620	124
12	1067	188
21	750	83.5
23	1549	225
40	2505	350
43	429	20.5

fill, however, this contamination may not be related only to the landfill. The high electrical conductivity values in a small isolated area northeast of the landfill suggests that the groundwater may be affected locally by other sources. Extensive greenhouse operations were found in that area. Therefore, the extent of the contamination caused by the landfill cannot be determined accurately to the northeast. To the north, the extent of the plume from the landfill appears to be limited to approximately 200 m.

4.2.6 Evaluation of the Essex County Landfill No. 2

The variation of the apparent resistivities indicated by the isoresistivity maps (Figs. 35 to 37) suggests that the control of resistivity values is by the water quality and character of the earth material. The general decrease in apparent resistivity values towards the landfill indicates the affect of water quality changes due to contamination from the landfill on the apparent resistivities, however, due to the extensive lateral and vertical inhomogenity in earth material at the Essex County Landfill No. 2, apparent resistivities appear to be affected strongly by the character of earth material. The true resistivities of the earth material determined from the electrical sounding data, by curve matching (Table 6), and the comparison of sounding profiles (Fig. 39), also indicate

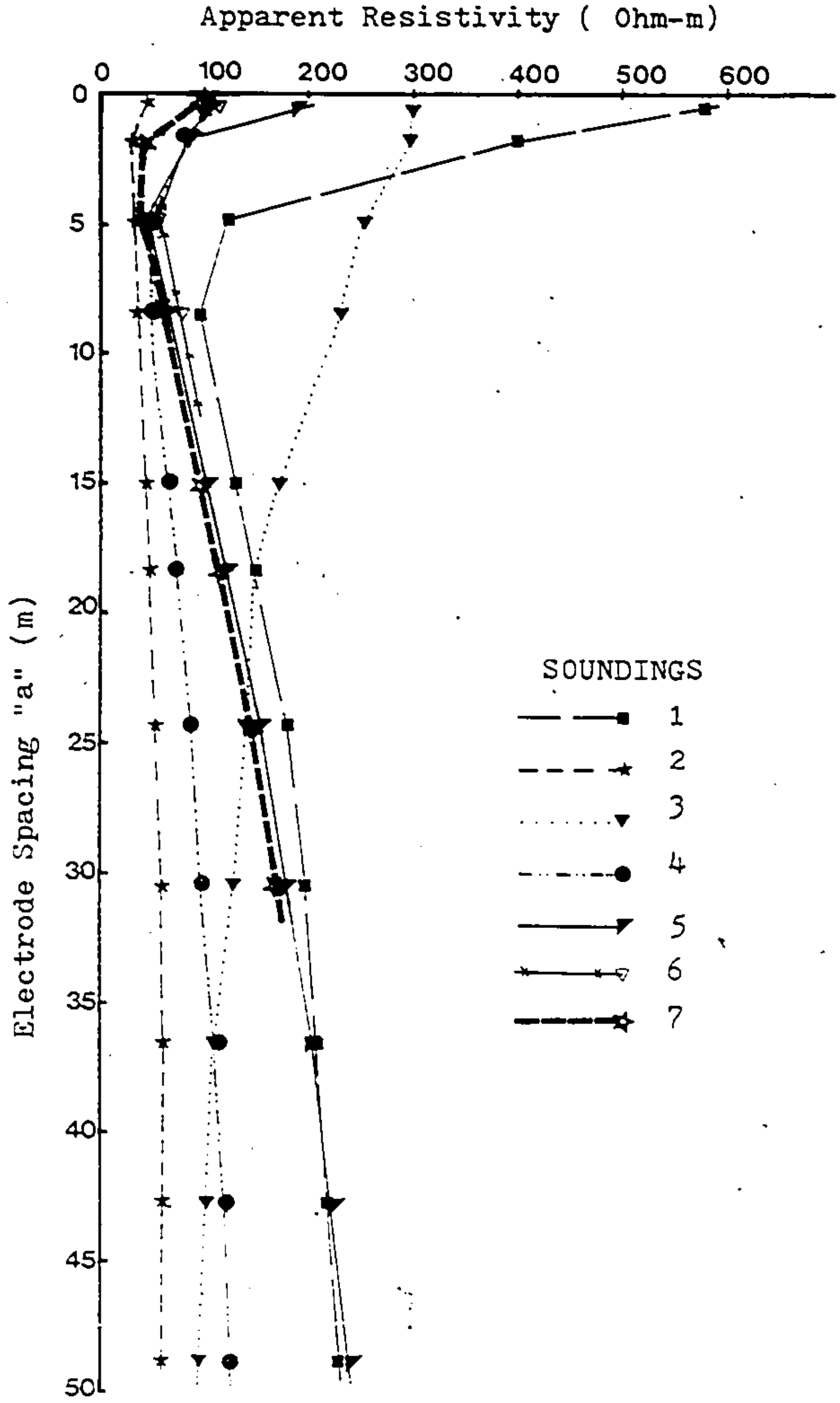


Figure 39. Comparison of Electrical Soundings 1 to 7 (Essex County Landfill No. 2).

that the resistivity values are controlled both by water quality change and by variation in earth materials.

The lateral variation in earth materials occurs as the upper layer varies laterally from loose sand to compact sand and gravel, to gravel. Also, the thickness of this layer varies from about 1 m at the landfill site to about 12 m northeast of the site. Vertical inhomogenity also occurs, as the depth to water table in this area varies from about 1 to 7 m.

In order to determine the general extent of the contaminant plume, limiting values of resistivity should be used to separate the contaminated and uncontaminated conditions.

To determine if the variations in apparent resistivity values are related to changes in water quality, the electrical conductivity of the groundwater was compared with apparent resistivity values (Table 9). The comparison indicates a poor correlation between water quality and apparent resistivities (correlation coefficients are: -0.01,-0.29, and -0.25 for the "a" spacings of 1.8, 3.0 and 6.1 m, respectively). Most of the apparent resistivity variation can therefore be attributed to geological, water table depth, and topographical variations.

Apparent resistivity values of approximately 50, 100, and 75 ohm-m are assumed to represent the leading

Table 9

Comparison of Electrical Conductivity and Apparent Resistivity Values Measured at the Essex County Landfill No. 2

Electrical Conductivity		Apparent Resistivity (ohm-m)			
Site	Value (µS/cm) measured at 25°C	Station	Value for a=1.8 m	Value for a=3.0 m	Value for a=6.1 m
1	811	1	-	414	100
2	755	11	-	235	95
3	722	14	-	123	62
4	598	17	-	47	41
5	1240	25	-	438	155
8	620	18	-	62	48
9	871	21	-	135	96
12	1066	72	-	103	59
13	564	75	-	1470	1395
15	609	81	-	262	374
16	905	73	-	1228	946
17	495	86	-	455	368
21	750	24	-	63	52
22	1473	48	86	37	-
23	1549	49	586	74	-
24	2268	63	-	61	-
26	445	60	-	90	-
28	584	68	119	122	-
	584	96	-	626	602
29	576	67	92	77	-
30	1288	62	-	137	-
34	446	84	-	586	377
35	835	66	-	389	-
40	2505	35	16	34	-

edge of the contaminant plume caused by the landfill for the 1.8, 3.0, and 6.1 m "a" spacings isoresistivity maps, respectively. The choice of these limiting values was arbitrary but was partially based on the evaluation of the apparent resistivity and true resistivity values measured in areas considered to be background by electrical conductivity measurements. Resistivity zones of 0-50, 0-100, and 0-75 ohm-m, therefore, are assumed to represent the contaminated zone from the landfill for the various "a" spacings.

This classification of apparent resistivity values, however, is not totally applicable in areas where the resistivity is controlled by variation in earth materials. Examples of these are the areas with high to extremely high resistivities, south, north, northeast, and to the extreme east of the landfill.

The general extent of the contaminant plume at various depths, based on the evaluation and classification of resistivity data, is illustrated in Figs. 40, 41, and 42.

Figure 40 shows that the plume extends to a distance of approximately 700 m east of the landfill. It can be interpreted from the map that the areas south and southeast of the landfill are uncontaminated. Electrical conductivity measurements, however, indicated that these areas are highly contaminated. The high resistivity

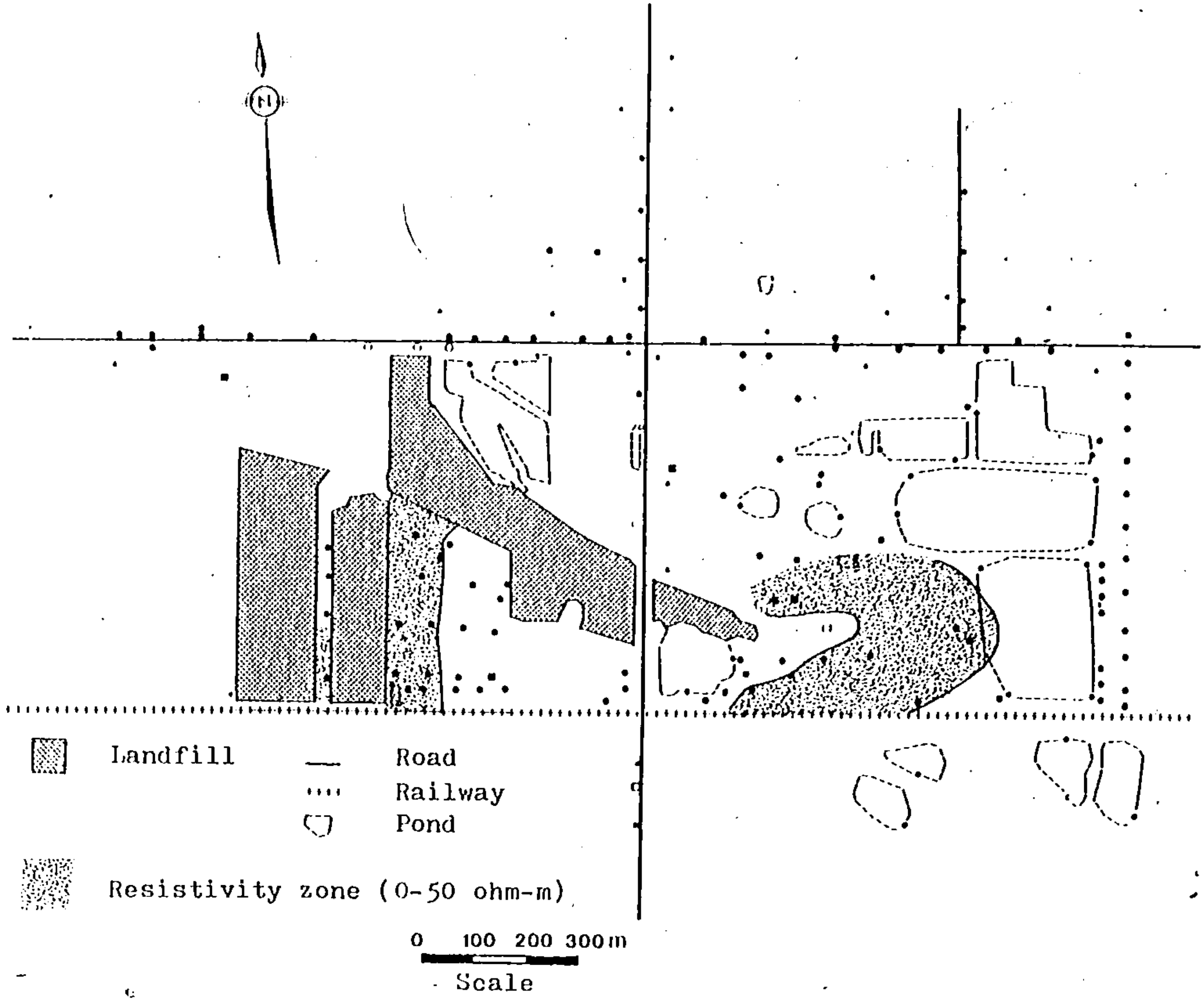


Figure 40. Summary interpretation of the general extent of the contaminant plume at 1.8 m depth for the Essex County Landfill No. 2.

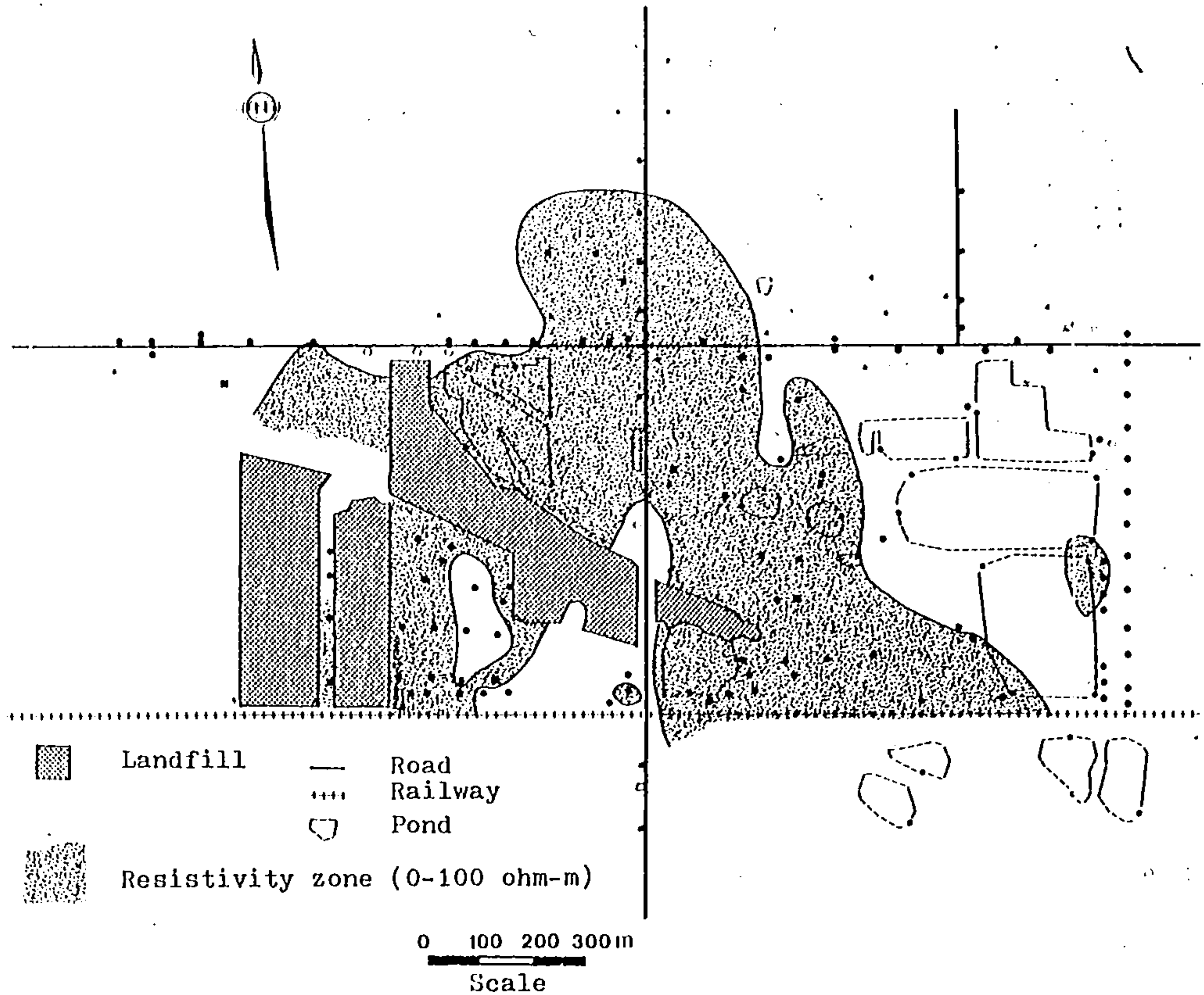


Figure 41. Summary interpretation of the general extent of the contaminant plume at 3.0 m depth for the Essex County Landfill No. 2.

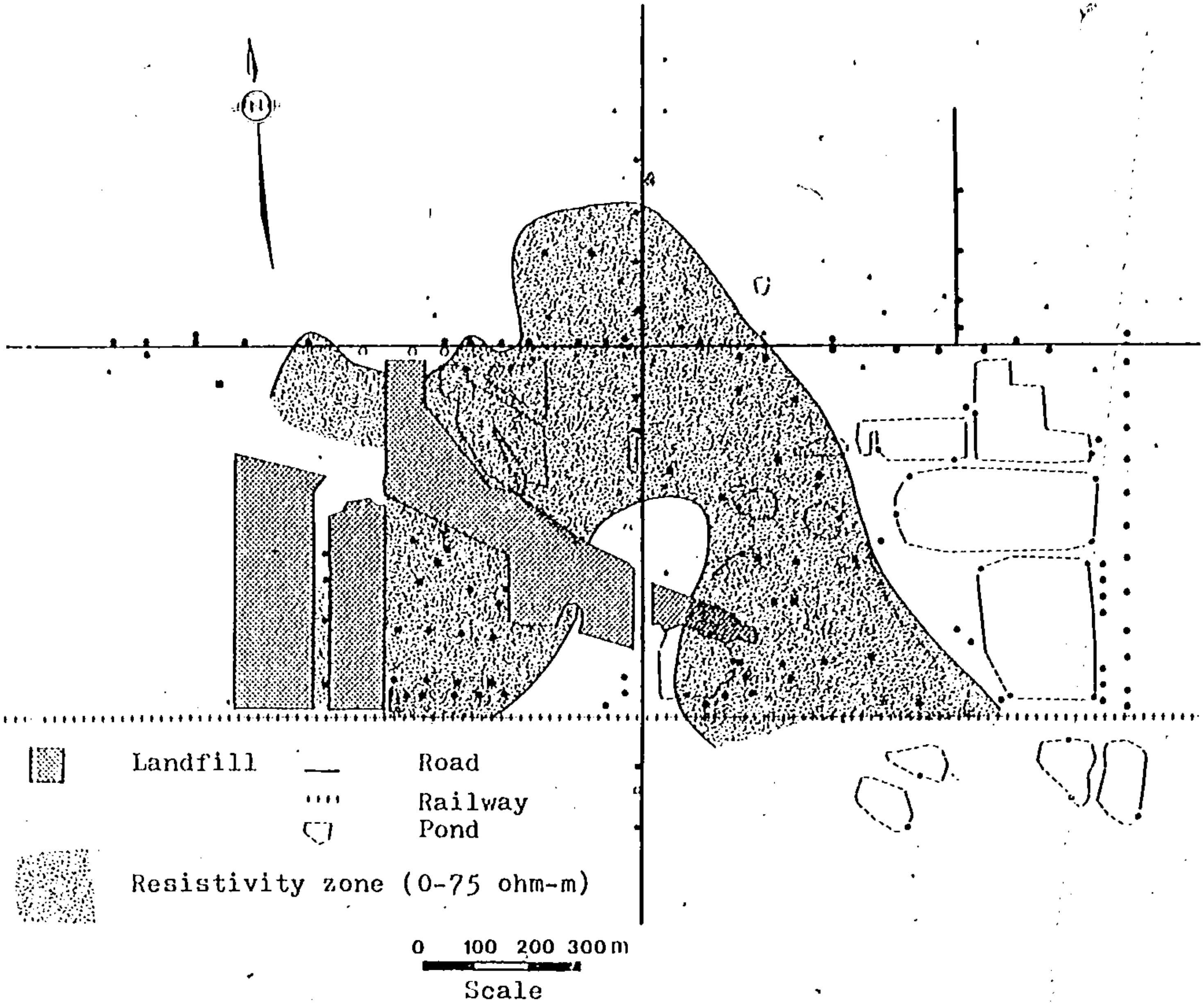


Figure 42. Summary interpretation of the general extent of the contaminant plume at 6.1 m depth for the Essex County Landfill No. 2.

values in these areas are probably caused by gravel, and it is also possible that the "a" spacing of 1.8 m probably was not sufficient in some locations to encounter the groundwater table.

Figures 41 and 43 show that the contaminant plume caused by the landfill extends to approximately 750 and 650 m east of the landfill at 3.0 and 6.1 m depths, respectively. The maps also show that the edge of the plume is approximately 500 m northeast of the landfill for the various depths. Electrical conductivity measurements, however, indicated that the area beyond this limit is highly contaminated (possibly by greenhouse operations). The high to extremely high resistivities in this area are known to be caused by thick unsaturated gravel deposits.

It can be interpreted from Figs. 41 and 42 that the area north of the landfill is contaminated. Electrical conductivity measurements (Fig. 38), however, indicated that this area is uncontaminated. The relatively low resistivity values in this area are probably attributed to the shallow-water table, absence of gravel, and the effect of fertilizers applied in agriculture.

4.3 Windsor West End Landfill

4.3.1 Seismic Refraction Survey

The results of the seismic refraction survey for the Windsor West End Landfill are plotted and listed in

Appendix III-3. Table 10 summarizes the seismic velocities, intercept times, and interface depths determined for the five survey sites.

Three seismic velocity layers can be interpreted for this site. The upper layer has a seismic velocity range of approximately 120 to 202 m/s which probably represents the near-surface weathered layer. The second and third layers have seismic velocity ranges of approximately 480 to 533 and 1385 to 1610 m/s, respectively. These layers are probably unsaturated (dry) sand and saturated till (silty clay), respectively. Table 11 summarizes the seismic interpretation for the Windsor West End Landfill. The interpretation of seismic refraction was based on the comparison of the seismic velocity layers with the borehole data (Figs. 43 to 47), and with the published data (Press, 1966; Heiland, 1968).

The significant increase in the seismic velocity across the first interface (d_1) in Seismic Profiles, 2, 3, and 4, and the second interface (d_2) in Seismic Profiles 1 and 5, suggests that the velocity below these interfaces is the seismic velocity of the saturated deposits (sand and silty clay), and the depths to the interfaces are the depths to the groundwater table. Birch (1976) recorded similar increases in seismic velocity due to saturation. In this area, seismically determined depths

Table 10

Seismic Velocities, Intercept Times, and Interface Depths for the Windsor West End Landfill

Seismic Profile	Seismic Velocity* (V(m/s))			Intercept Time** Ti(s x 10^{-3})		Depth to Interface d(m)	
	V_1	V_2	V_3	Ti_1	Ti_2	d_1	d_2
1	137	480	1610	8.0	13.0	0.6	1.7
2	135	1524	-	12.0	-	0.8	-
3	126	1516	-	13.5	-	0.8	-
4	202	1348	-	11.0	-	1.1	-
5	120	533	1480	13.7	20.3	0.8	2.6

*Obtained directly from the time-distance plots (Appendix III-3)

**Obtained directly from the time-distance plots (Appendix III-3)

***Calculated by using Equations 2.3a and 2.3b

Table 11

Summary of Seismic Interpretation for the Windsor West End Landfill

Layer	Calculated Seismic Velocity (m/s)	Thickness range (m)	Probable Materials	Published Data: Seismic Velocity (m/s)	Published Data: Reference
Upper	120-202	0.6-1.1	Top soil or fill	169-305	Heiland (1968)
Middle	480-533	1.1-1.8	Unsaturated sand (glacial drift)	484-508	Heiland (1968)
Lower	1385-1610	-	Saturated glacial till (silty clay)	1730	Press (1966)

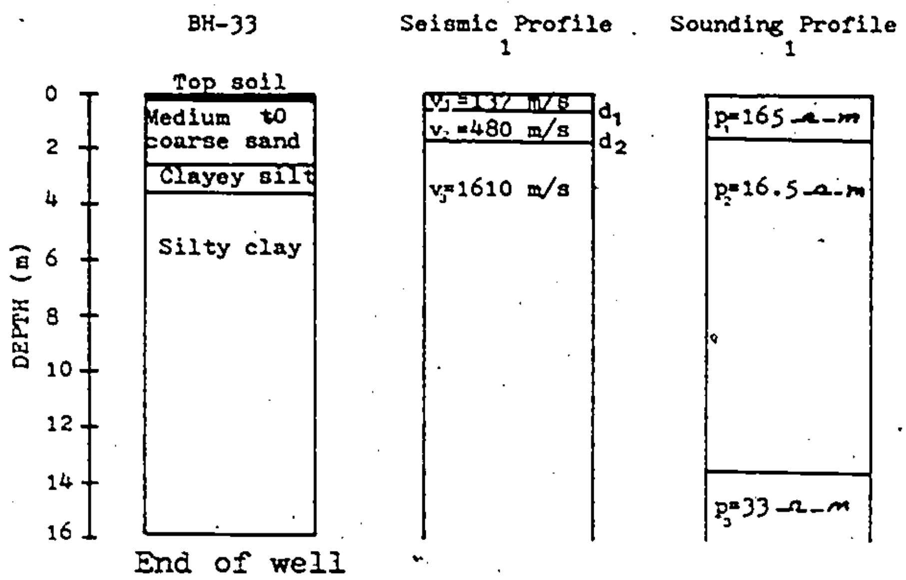


Figure 43. Comparison of Seismic and Sounding Profile 1 with borehole log (Windsor West End Landfill).

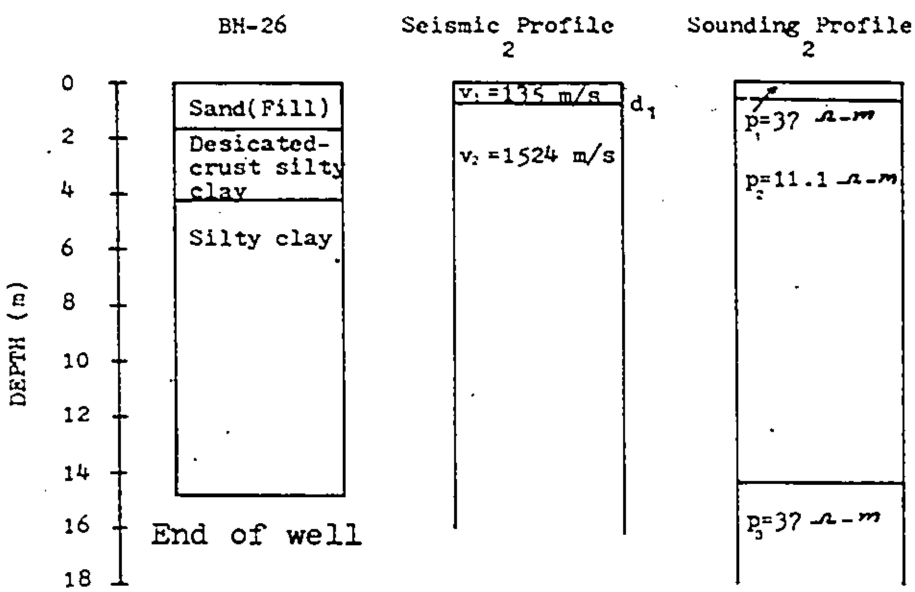


Figure 44. Comparison of Seismic and Sounding Profile 2 with borehole log (Windsor West End Landfill).

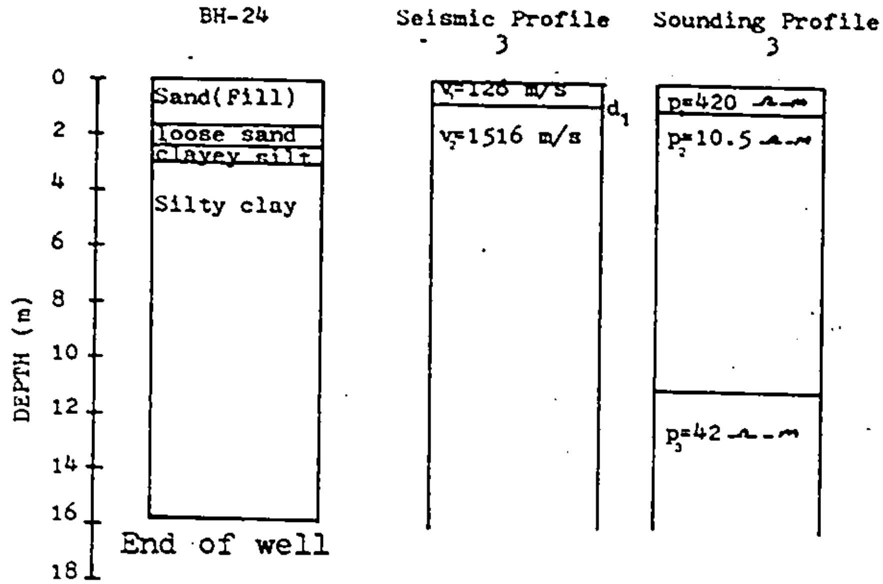


Figure 45. Comparison of Seismic and Sounding Profile 3 with borehole log(Windsor West End Landfill).

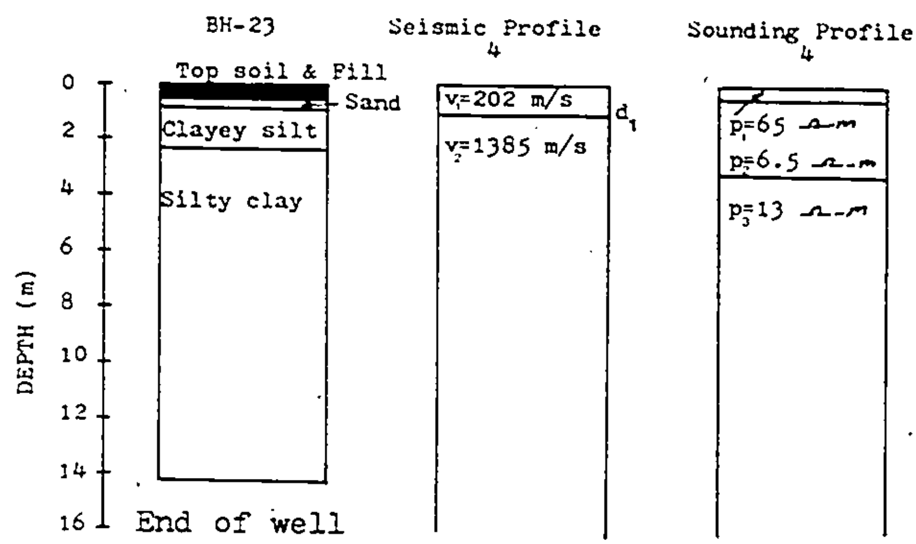


Figure 46. Comparison of Seismic and Sounding Profile 4 with borehole log (Windsor West End Landfill).

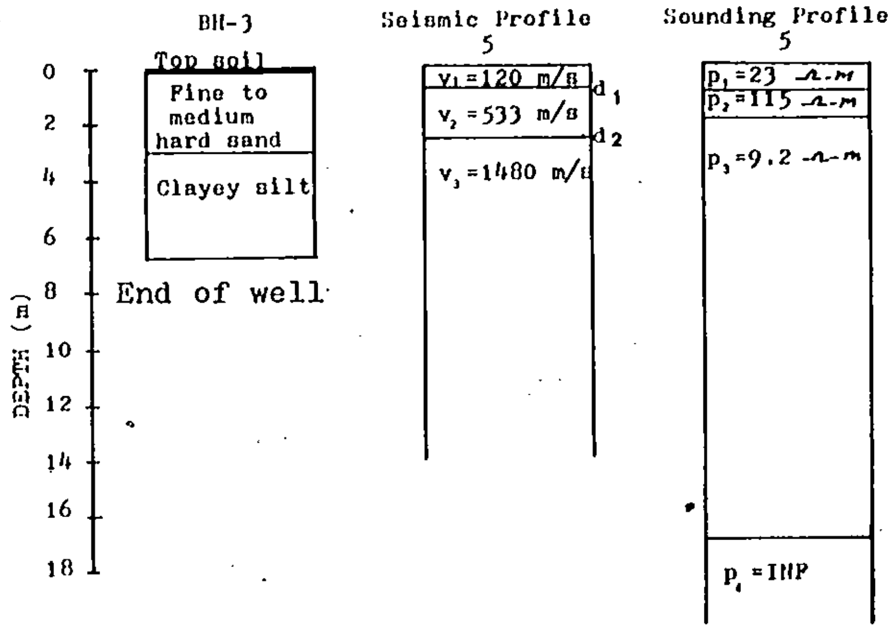


Figure 47. Comparison of Seismic and Sounding Profile 5 with borehole log (Windsor West End Landfill).

to the groundwater table vary from about 0.8 to 2.6 m.

4.3.2 Electrical Resistivity Sounding Survey

Apparent resistivity values determined from the sounding survey are tabulated in Appendix III-1. The electrical soundings have been interpreted quantitatively by comparing the plots of "ρ_a versus a" with theoretical master curves (Larzeg, 1972). The "ρ_a" versus "a" plots are given in Appendix III-1 and a summary interpretation of the data appears in Table 12.

Three resistivity layers are evident in Soundings 1 to 4 while four layers are suggested by Sounding 5. Figures 43 to 47 compare the available borehole information and seismic results with the electrical sounding data. Based on the comparison, it appears that the upper resistivity layer in Soundings 1 to 4, and the upper and second resistivity layers in Sounding 5, are dry sand and topsoil. The first interface in Soundings 1 to 4, and the second interface in Sounding 5, are likely to be the groundwater table. The groundwater table varies from about 0.5 to 2.0 m. The comparison also indicates that the second resistivity layer in Soundings 1 to 4, and the third layer in Sounding 5, are saturated clayey silt and silty clay and that the second interface in Soundings 1 to 4, and the third interface in Sounding 5, are the boundary between the overlying low resistivity silty clay and

Table 12

Summary Results of Sounding Interpretation (Curve Matching) for the Windsor West End Landfill

Sounding Station	Resistivity Layer 1		Resistivity Layer 2		Resistivity Layer 3		Resistivity Layer 4	
	ρ_1	h_1	ρ_2	h_2	ρ_3	h_3	ρ_4	h_4
1	165	1.6	16.5	12.0	33	-	-	-
2	37	0.7	11.1	13.7	37	-	-	-
3	420	1.0	10.5	10.0	42	-	-	-
4	65	0.5	6.5	2.7	13	-	-	-
5	23	1.0	115	1.0	9.2	15	Inf	-

underlying silty clay with higher resistivity.

It appears that the resistivity values of the upper layer are mostly controlled by the moisture content and the presence of clay and organic materials. The high resistivity in Sounding 3 may be attributed to the presence of organic materials, while the low resistivity in Sounding 5 may be due to clayey deposits.

The resistivity value of the saturated silty clay appears to be mostly controlled and affected by groundwater contamination. Saturated silty clay exhibits lower resistivities as the source of contamination is approached.

The groundwater table is assumed to represent the top of the contaminant plume, while the bottom of the plume may be the second interface in Soundings 1 to 3, and the third interface in Sounding 5. This interpretation is based on the observation that the silty clay layer showed increases in the resistivity across these interfaces. This suggests that this interface probably represents the boundary between the contaminated and uncontaminated silty clay. In Sounding 4, the bottom of the plume cannot be determined from the available resistivity data. Accordingly, the bottom of the contaminant plume probably lies between 11 and 17 m below the existing ground surface in the area around the landfill.

4.3.3 Electrical Resistivity Profiling Survey

Based on the seismic and sounding results which indicated that the groundwater table varies between approximately 0.5 to 2.6 m below the existing ground surface, two electrical profiling surveys using "a" spacings of 3.0 and 4.6 m were carried out in this area. The "a" spacing of 3.0 m was chosen in order to determine the apparent resistivity variations within the surficial sand, while the "a" spacing of 4.6 m was used to ensure that the apparent resistivities were measured far enough below the top of the contaminant plume. The results of the profiling surveys are tabulated in Appendix III-2. Figures 48 and 49 are the isoresistivity maps for the 3.0 and 4.6 m electrode spacings.

Figure 48 shows that for the 3.0 m "a" spacing, a general decrease in the apparent resistivities occurs as the landfill is approached, with the exception of the area north of the landfill where the apparent resistivities increase towards the landfill. Apparent resistivities range from a low value of about 1.3 Ωm at Resistivity Station #61, to a high value of about 511 Ωm at Resistivity Station #23 (Fig. 17).

The most striking features of the map are the wide area of low resistivity south of the landfill, a small area with very low resistivity just west of the southwest

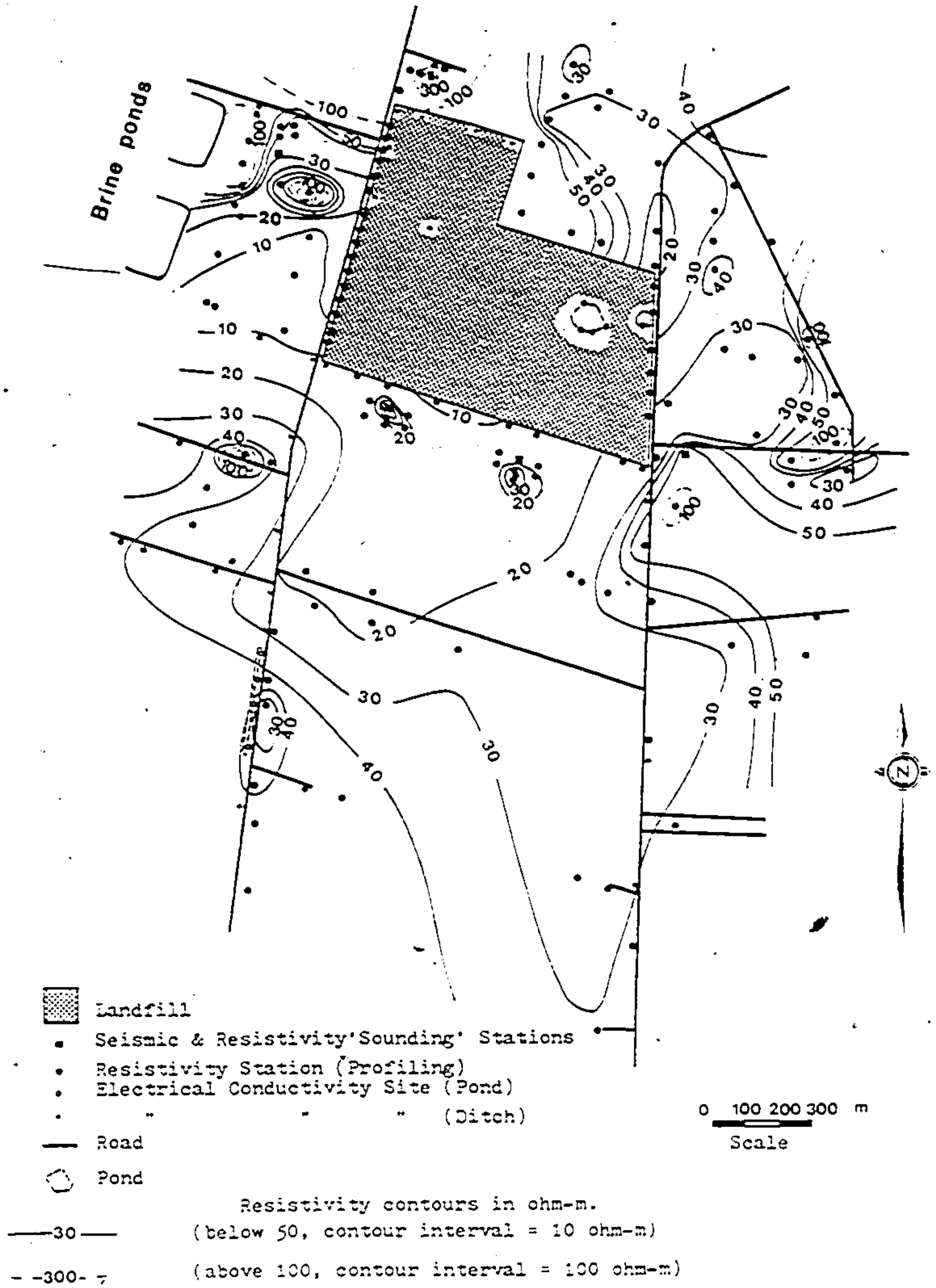


Figure 48. Isoresistivity map for the Windsor West End Landfill at 3.0 m "a" spacing.

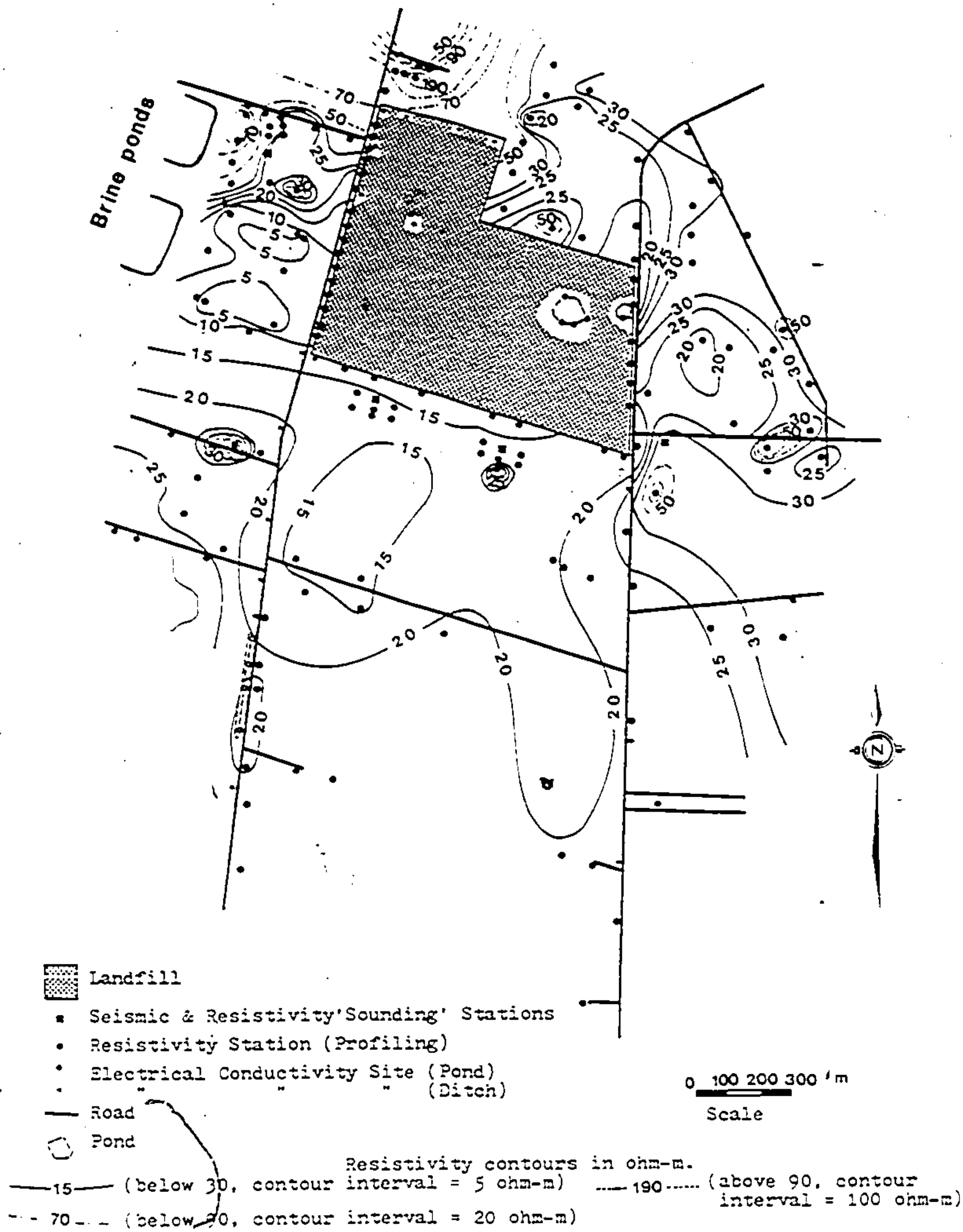


Figure 49. Isoresistivity map for the Windsor West End Landfill at 4.6 m "a" spacing.

corner of the landfill, and a small area with relatively low resistivity at the northeast corner of the landfill. This map also shows isolated small areas with extremely high resistivities. Such areas are located north, northwest, southwest, and southeast of the landfill. Small areas with relatively high or low resistivities can be found scattered throughout the map.

Figure 49 shows that the 4.6 m "a" spacing results are generally similar to the previous map as the apparent resistivities tend to decrease towards the landfill. Apparent resistivities range from a low value of about 1.6 Ωm at Resistivity Station #61, to a high value of about 273 Ωm at Resistivity Station #23 (Fig. 17).

The prominent features of the map are also the large area of low resistivity south of the landfill, the small area of very low resistivity west of the southwest corner of the landfill, and the low resistivity area east of the landfill. Small areas of extremely high resistivities, and relatively low or high resistivities are scattered throughout the map area.

Generally in both isoresistivity maps, the dominant feature is the large area of low resistivity south of the landfill. Apparent resistivity contours in this area tend to be elongated towards the south away from the landfill. This may indicate that the groundwater flow direction and subsequently the movement of the contaminant plume is to the south (Fink and Aulenbach, 1974).

4.3.4 Electrical Conductivity Measurements

The electrical conductivity measurements for the water samples taken from ponds and ditches around the Windsor West End Landfill are listed in Appendix III-4 and plotted in Fig. 50.

Figure 50 shows that the electrical conductivity of the water increases towards the landfill. The electrical conductivity values range from a low of about 411 μS/cm measured at about 1.4 km southwest of the landfill (conductivity Site #23 in Fig. 17), to a high of about 3613 μS/cm measured at the landfill (conductivity Site #7 in Fig. 17).

Electrical conductivity values are related to the total ion concentrations in the ground and surface waters and reflect the level of contamination. The low electrical conductivity of about 411 μS/cm probably represents uncontaminated conditions while the high value of about 3613 μS/cm probably represents highly contaminated conditions.

The shape of the conductivity contours suggests that the contaminant plume is moving to the south and southeast. The electrical conductivity contour line of 500 μS/cm can be assumed to represent the boundary of the contaminated zone in the southwest of the landfill. Using this value

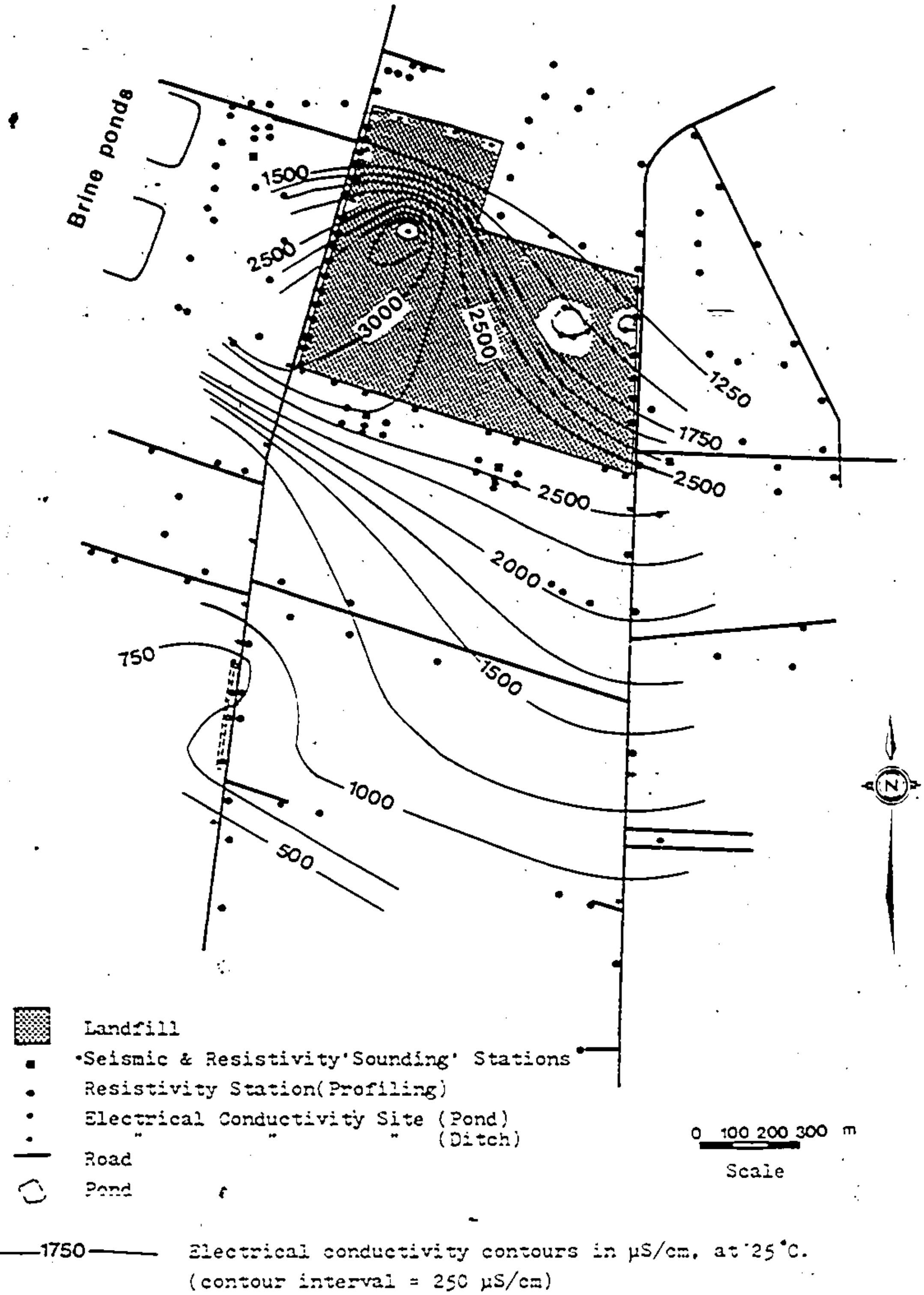


Figure 50. Electrical conductivity map for the Windsor West End Landfill.

as a leading edge of the contaminant plume, it appears that the extent of the plume is approximately 1.3 km to the southwest of the landfill, while to the south, the contaminant plume may extend to approximately 1.7 km.

4.3.5 Evaluation of the Windsor West End Landfill

The general decrease in the apparent resistivities as the landfill is approached (Figs. 48 and 49) suggests that these resistivity values are affected by water quality changes due to contamination from the landfill. However, because of the lateral variations in earth materials (as shown in Figs. 9a, 9b), not all changes in apparent resistivity values are related to changes to groundwater quality. For example, the relatively high resistivity areas north, southwest, and southeast of the landfill are known to be caused by a relatively thick layer of unsaturated coarse to medium sand. However, the extremely high resistivities in small areas northwest, southwest, and east of the landfill are possibly caused by fill materials such as gravel. The organic nature of the fill materials around the landfill (Golder Associates, 1969) could have contributed to the increase in the apparent resistivities in some places.

The true resistivity values for the saturated materials determined from Soundings 1 to 5 by curve matching (Table 12), tend to decrease in areas affected by contamination from the landfill. Comparisons of Soundings 1 to 5 (Fig. 51) indicate that Sounding 4 is strongly affected by contamination. Sounding 5 was also found to be highly affected by contamination, however, since Sounding 5 is close to brine ponds (Fig. 17), it is possible that the low resistivity values of the saturated materials in this area are related to contamination from these ponds. The very low apparent resistivity values measured in the area just east of the lower pond may indicate that the brine could have contributed to the contamination of the groundwater. However, the high apparent resistivity values measured for the area west of the upper brine pond may be because the groundwater table is relatively deep in this area as Seismic and Sounding Profile 5 indicated that.

In order to determine the general extent of the contaminant plume, limiting values of apparent resistivity should be used to separate the contaminated and uncontaminated zones. The electrical conductivity, which is a good indicator of groundwater contamination, is used to relate apparent resistivity variations to groundwater quality change. A comparison is made between electrical conductivity and apparent resistivity values measured in an area about 1 km southwest of the landfill (Table 13). The comparison shows that there is an inverse linear relationship between electrical conductivity and apparent resistivity (correlation coefficients are -0.93 and -0.88

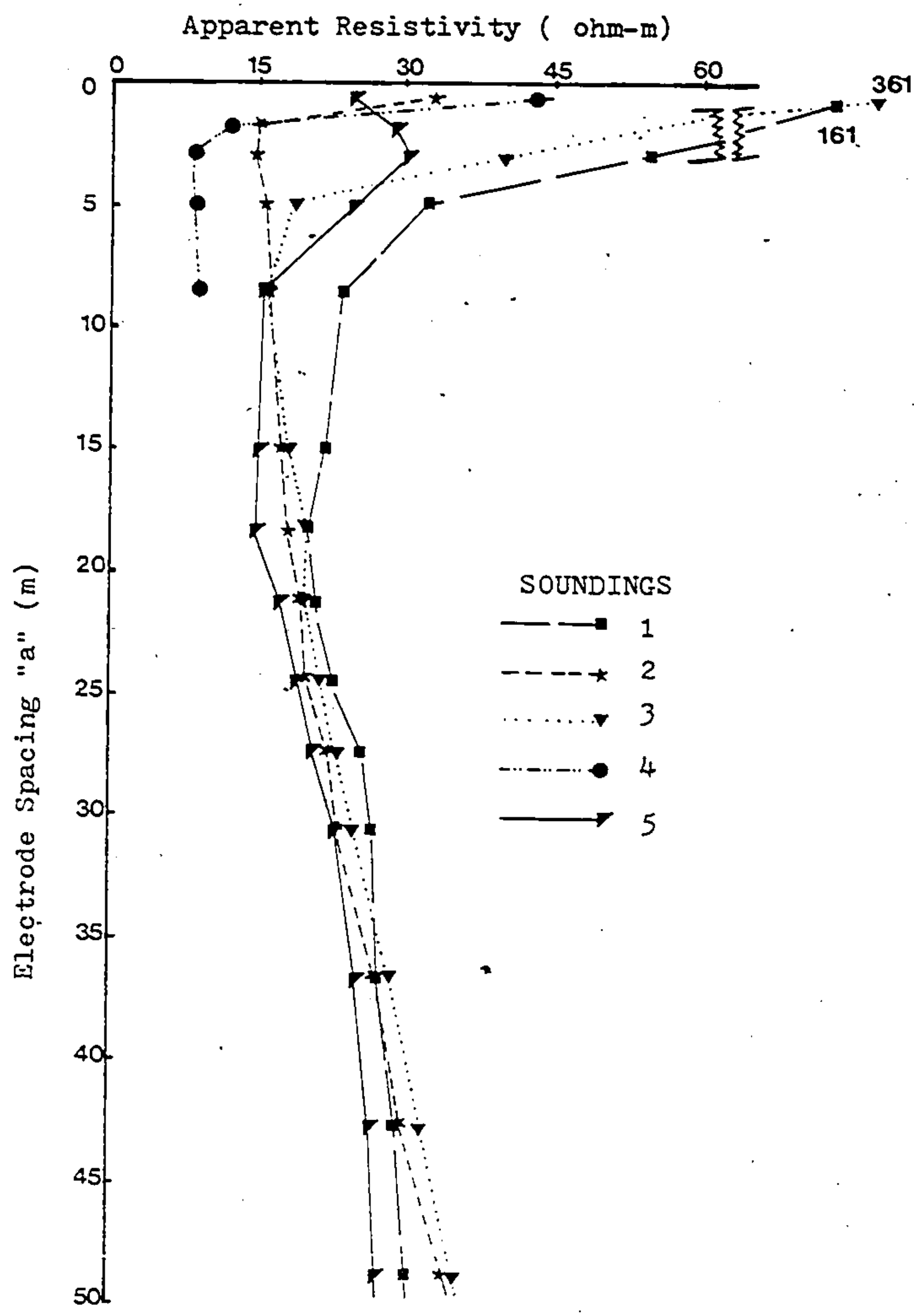


Figure 51. Comparison of Electrical Soundings 1 to 5 (Windsor West End Landfill).

Table 13

Comparison of Electrical Conductivity and Apparent Resitivity Values Measured at the Windsor West End Landfill

Electrical Conductivity		Apparent Resistivity (ohm-m)		
Site	Value (μS/cm) measured at 25°C	Station	Value for a=3.0 m	Value for a=4.6 m
23	411	134	47.5	23.0
21	872	131	25.3	16.4
20	648	116	44.4	23.3
18	859	129	29.7	16.7

for "a" spacings of 3.0 and 4.6 m, respectively).

An electrical conductivity value of 500 μS/cm was considered as the upper limit of uncontaminated water. Accordingly, resistivity zones of (0-45 Ωm) and (0-22 Ωm) have been assumed to be contaminated zones for the 3.0 and 4.6 m "a" spacings isoresistivity maps, respectively. This classification may not be applied in some areas where extremely high resistivity values are caused by inhomogenity in earth materials rather than by uncontaminated groundwater.

An interpretation of the general extent of the contaminant plumes at 3.0 and 4.6 m depths, based on the classification and evaluation of the resistivity data, is illustrated in Figs. 52 and 53. Both maps show that the main body of the contaminant plume is moving to the south and that the edge of the plume is approximately 1.8 km south of the landfill. The maps also show that the contaminant plume extends to approximately 500 m east and northeast of the landfill at 3.0 m depth, while at 4.6 m depth the plume extent appears to be limited to within 200 m. To the west of the landfill, the maps show that the area is also contaminated, however, the very low resistivity measured in that area may suggest that the area is affected by the brine ponds. The extent to the west, however, cannot be determined from the available resistivity data.

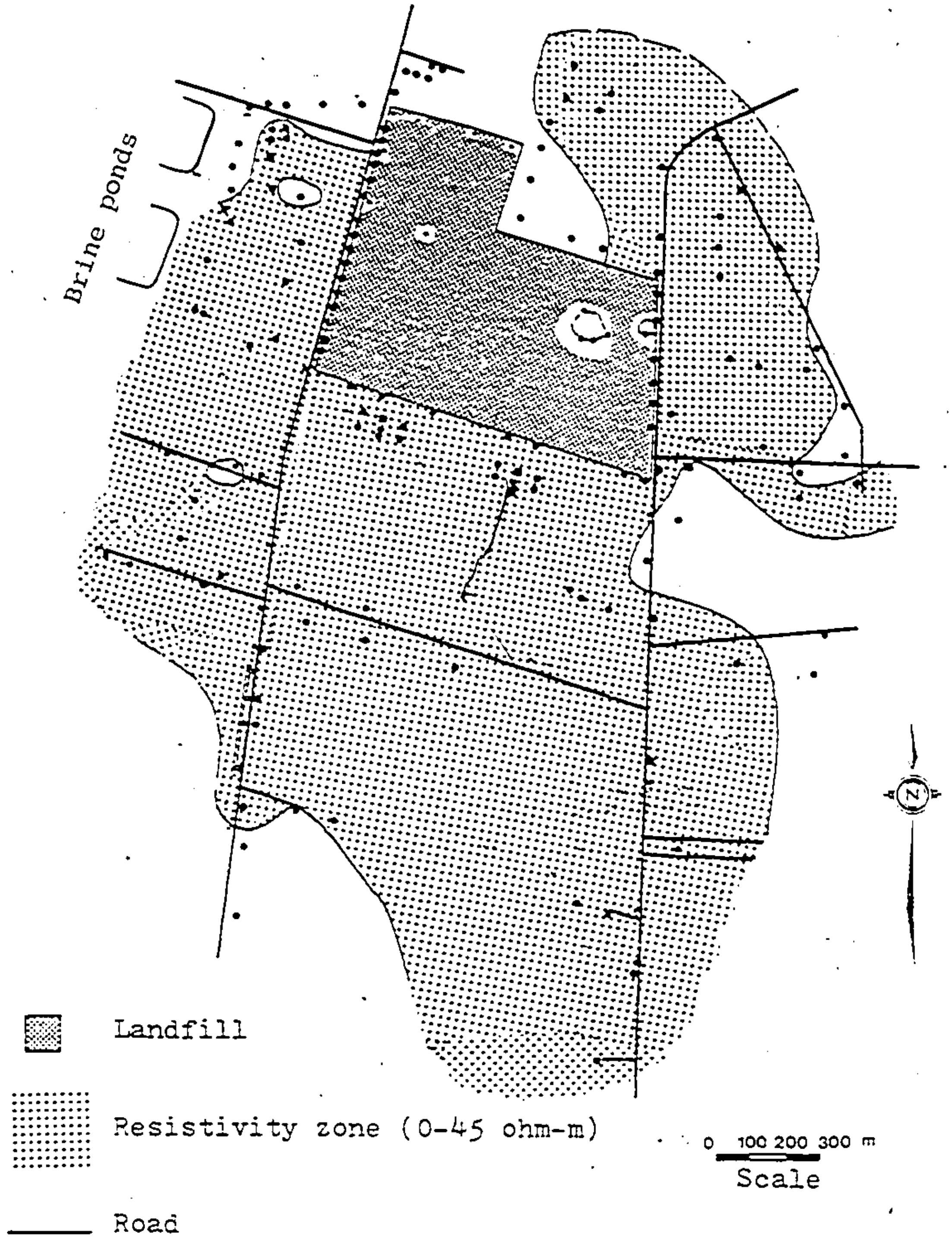


Figure 52. Summary interpretation of the general extent of the contaminant plume at 3.0 m for the Windsor West End Landfill.

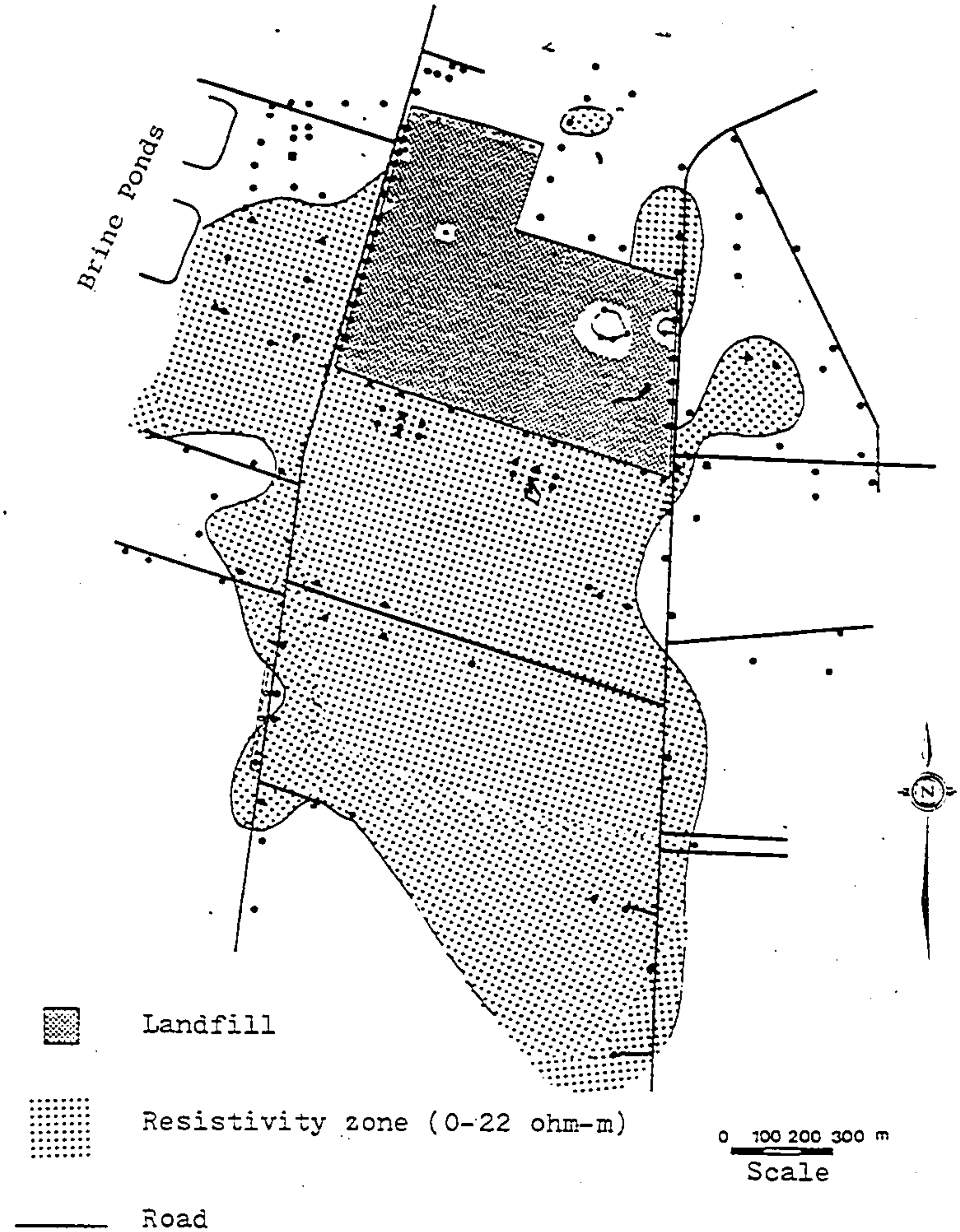


Figure 53. Summary interpretation of the general extent of the contaminant plume at 4.6 m for the Windsor West End Landfill.

4.4 Summary of Results

1. The depths to the water table were accurately determined by seismic refraction.

2. Resistivity and velocity layers, revealed from the sounding and seismic surveys, were generally comparable in definition with those indicated by borehole logs.

3. Apparent resistivity values, measured in the profiling surveys, appeared to be controlled by both the character of the earth material and the quality of the groundwater.

4. Isoresistivity maps showed a general decrease in the apparent resistivity values towards the landfill sites.

5. Electrical conductivity maps showed an increase in the electrical conductivity of near-surface water towards the landfill sites.

6. The movement of the contaminant plumes were consistent with groundwater flow directions.

7. The travel rate of the contaminants in coarse-grained material was greater than in fine-grained material.

Table 14 summarizes the results of this study.

4.5 Discussion of Results

1. The general decrease in the apparent resistivity values towards the landfill sites manifests the inverse relationship between groundwater quality and the electrical resistivity of groundwater, and emphasizes the contamination

Table 14

Summary Table

Site	Years of Operation	Type of Waste	Potential Contamination Sources	Electrical Conductivity of Near-surface Water (μS/cm)	Type of Hydrogeological Unit	RESISTIVITY RESULTS: Depth of Investigation (m)	Length of Plume (m)	Direction of Plume	Rate m/year
Landfill No. 1	1970-present	Domestic, Municipal	Na, K, SO_4, Cl, Ca, Fe, Pb, Hg, Mn, NH_4, bacteria*	269-2770	Silty clay (Till)	4.6	300-350	S & SW	29
					Sand	12.2	300-350	S & SW	29
Landfill No. 2	1970-present	Domestic, Commercial, Sewage sludge	(ppm)**: Na 6.1-465; K 2-188; SO_4 31-260; Cl 20.5-350; Ca 31-133; Fe 0.01-10; Mg 7.8-46.4; NH_3 (as N) <0.01-108; NO_3 (as N) <0.01-45.7; Total coliform bacteria 0-20/100 ml	378-2505	Sand & Gravel	1.8	700	E	58
					Sand & Gravel	3.0	750 500	E NE	62.5 41.5
					Sand & Gravel - Silty clay (Till)	6.1	650 500	E NE	54 41.5
Windsor's Landfill	1956-1973	All categories, of waste	Na, K, SO_4, Cl, Ca, Fe, Pb, Hg, Mn, NH_4, bacteria*	411-3613	Sand	3.0	1800	S	69
					Silty Clay (Till)	4.6	1800	S	69

*Typical constituents in leachate from landfills, general data (Miller, 1980).

**Chemical and bacteriological analyses of water at Essex County Landfill No. 2 (Essop and Brown, 1980).

of groundwater to the presence of the landfill sites.

2. Since the electrical resistivity (or the inverse, the electrical conductivity) is related to the total ionic concentration in groundwater, electrical resistivity methods, therefore, only detect and assess the extent of the ionic contaminants in groundwater. However, since the rate of contaminants removal with distance (attenuation rate) of constituents such as bacteria, viruses, organic materials, heavy metals, and most radioactive materials is higher than those of the common ions (Miller, 1980), it is, therefore, thought that the extent of the contaminant plume that was indicated by resistivity methods is much farther than that of non-ionic contaminants.

3. The short travel distance of the plume at Landfill No. 1 as compared with that at Landfill No. 2 and Windsor's landfill is caused by the former's high attenuation rate. The high attenuation rate reflects the fine-grained material in Landfill No. 1 compared to the coarse-grained material present in the other two landfills (Miller, 1980).

4. The interface between the contaminated and non-contaminated zones is not as sharp as indicated by resistivity maps. This likely reflects variations caused by local differences in the density and permeability of the earth material at the landfills plus the infiltration of other local contamination sources of surface water such as fertilizers, greenhouse operations, road salting, etc.

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The combination of seismic refraction and electrical sounding techniques was of great importance in extending hydrogeologic and geologic control at the study areas. Seismic refraction was successful in determining the depths of the water table at the three landfill sites. At Landfill No. 2, the seismically calculated depths to the water table were found to be within the accuracy inherent in the seismic technique itself. Resistivity and velocity layers, revealed from the sounding and seismic surveys, were found to be generally comparable with borehole data. The importance of the combined geophysical techniques was clearly evinced at Landfill No. 1, where the inability of electrical sounding to detect the water table was overcome with seismic refraction. Also, a seismically-undetected hidden layer was successfully detected and located at this site with electrical sounding.

Apparent resistivity values, measured in the profiling surveys, were found to be related to the character of the earth material and the quality of the groundwater. A general decrease in apparent resistivity values towards the landfill sites suggested the control of these values by changes in groundwater quality caused by contamination from the landfill sites. However, changes in apparent resistivity were also found to be caused by lateral variations in the earth materials. This was strongly evident at Landfill No. 2. Electrical conductivity measurements of near-surface indicated that water quality was altered by leachate from the landfill sites.

The analysis of the resistivity data indicated that, at Landfill No. 1, the extent of the contaminant plume was approximately 300 to 350 m towards the south and southwest at depths of both 4.6 and 12.2 m. At Landfill No. 2, the contaminant plume extended approximately 700, 750, and 650 m to the east at depths of 1.8, 3.0, and 6.1 m, respectively. Towards the northeast, the plume extended to approximately 500 m at depths of both 3.0 and 6.1 m. At Windsor's landfill, the extent of the plume was approximately 1.8 km to the south at depths of both 3.0 and 4.6 m.

The results of this study demonstrate the capabilities of surface electrical resistivity methods to detect and trace contaminated groundwater bodies associated with landfill sites. The study showed that the successfulness of these methods depends on several conditions among which the electrical contrast between contaminated and natural groundwater, the depth to water table, and the homogeneity of earth materials are the most important. Surface electrical resistivity surveys are not a substitute for water sampling programmes, but can be most helpful in planning and selectively locating water quality monitoring wells.

5.2 Recommendations

Based on the results of this study the following recommendations are suggested:

1. A number of monitoring wells should be installed to allow a groundwater sampling programme at the three landfill sites. The majority of these wells should be located in the paths of the advancing contaminant plumes. Some wells, however, should be placed at uncontaminated areas for checking.

2. Hydrogeologic investigation should be carried out at Essex County Landfill No. 1 to examine the possibility of fracturing in the silty clay soil. The spread of the contaminant plume in this area appears to be much larger than has been reported in the literature.

3. Additional resistivity work should be done south of Windsor's landfill site at places as far as possible from roads and ditches; these obstacles may cause errors in the resistivity readings.

4. Geophysical or hydrogeological investigation should be carried out at Windsor's site to study the contribution of the brine ponds to groundwater contamination. The brine represents a very concentrated form of

natural electrolytes (Grant and West, 1965).

5. Surface electrical resistivity techniques could be used at other landfill sites as methods for detecting and delineating zones of contaminated groundwater wherever a relatively simple, uniform geological environment exists.

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APPENDIX I

ESSEX COUNTY LANDFILL No. 1 DATA

APPENDIX I-1 Results of Electrical Sounding Survey (Tables and Plots).

St.	a(m)	0.6	1.2	1.8	2.4	3.0	3.6	4.3	4.9
1	I	100	100	100	100	100	100	100	100
	**SP	20.0	-22.0	50.0	-3.5	5.0	1.8	-1.1	34.0
	V	494.4	219.3	210.0	120.0	103.3	85.0	74.0	100.5
	P_a	18.16	18.48	18.38	18.92	18.82	19.13	20.13	20.36
2	I	100	100	100	100	100	100	100	100
	SP	89.5	-98.5	111.5	84.2	145.3	184.6	137.8	110.5
	V	651.6	136.2	248.5	177.3	215.1	140.3	186.1	154.3
	P_a	21.52	17.98	15.74	14.26	13.37	12.81	12.96	13.43
3	I	100	100	100	100	100	100	100	100
	SP	83.5	23.0	-49.5	-29.0	-18.0	-12.5	-9.9	-36.0
	V	474.7	208.3	75.0	69.5	61.2	56.7	52.7	20.5
	P_a	14.97	14.19	14.30	15.08	15.17	15.91	16.78	17.31
4	I	100	100	100	100	100	100	100	100
	SP	-18.6	5.4	36.5	-9.5	-3.6	5.0	-23.8	23.5
	V	420.0	232.7	192.8	116.7	102.7	98.2	58.1	97.7
	P_a	16.80	17.41	17.95	19.33	20.36	21.43	21.95	22.75
5	I	100	100	100	100	100	100	100	100
	SP	3.4	21.0	230.0	30.0	31.0	25.0	20.0	-4.0
	V	478.0	253.5	402.0	161.4	145.5	120.5	102.2	68.0
	P_a	18.17	17.80	19.75	20.13	21.93	21.94	22.03	22.06

** SP value has been subtracted from V prior to calculating p_a

APPENDIX I-1 cont'd.

St.	a(m)	5.5	6.1	7.3	8.5	9.7	11.0	12.2	15.2
1	I	100	100	100	100	100	100	100	100
	SP	38.0	-15.0	-10.0	34.6	72.0	-16.0	40.0	30.0
	V	100.0	43.2	42.4	80.0	112.0	21.0	76.0	62.5
	P_a	21.37	22.29	24.08	24.37	24.51	25.51	27.58	31.12
2	I	100	100	100	100	100	100	100	100
	SP	86.9	52.1	45.9	21.0	45.0	15.8	106.8	84.0
	V	127.5	89.0	79.4	50.2	75.7	43.7	134.8	109.3
	P_a	14.01	14.13	15.42	15.68	18.84	19.23	21.45	24.22
3	I	100	100	100	100	100	100	100	100
	SP	-35.4	-35.8	-48.7	-2.4	-26.0	-19.4	-28.3	-38.5
	V	17.7	13.3	-6.2	36.9	10.4	13.7	4.4	-7.8
	P_a	18.30	18.81	19.55	21.07	22.31	22.82	25.05	29.44
4	I	100	100	100	100	100	100	100	100
	SP	-18.4	-8.9	-17.0	-24.5	-9.8	-10.0	13.5	-12.0
	V	49.1	54.3	38.3	24.3	34.2	32.0	52.4	22.9
	P_a	23.27	24.21	25.32	26.19	26.96	28.95	29.80	33.42
5	I	100	100	100	100	100	100	100	100
	SP	-22.0	-50.4	-118.0	-66.3	6.5	-137.5	-114.0	-102.5
	V	42.0	10.5	-66.0	-18.4	50.7	-95.4	-76.8	-68.7
	P_a	22.06	23.33	23.90	25.68	27.12	29.06	28.50	32.36

APPENDIX I-1 cont'd.

St.	a(m)	18.3	21.3	24.4	27.4	30.5	36.6	42.7	48.8
1	I	100	100	100	100	100	100	100	100
	SP	131.0	59.3	42.9	30.6	26.7	62.3	15.5	32.6
	V	160.3	89.0	71.5	60.0	55.2	89.0	41.9	57.0
	P_a	33.73	39.88	43.81	50.75	54.57	61.47	70.78	74.76
2	I	100	100	100	100	100	100	100	100
	SP	88.5	-86.7	-49.2	-139.9	-167.2	-92.2	-120.0	-106.3
	V	111.5	-64.5	-27.5	-117.5	-144.5	-70.6	-98.7	-86.0
	P_a	26.42	29.76	33.32	38.69	43.57	49.75	57.10	62.35
3	I	100	100	100	100	100	100	100	100
	SP	-180.5	-48.9	-50.0	16.5	-24.3	26.5	-35.6	12.3
	V	-152.8	-22.5	-24.0	40.5	-1.0	48.0	-14.9	31.0
	P_a	31.82	35.39	39.91	41.36	44.71	49.41	55.49	57.29
4	I	100	100	100	100	100	100	100	100
	SP	210.0	2.0	39.0	23.4	2.6	62.5	40.0	1.2
	V	242.5	31.8	67.7	50.7	29.2	87.5	62.6	23.8
	P_a	37.34	39.94	43.97	47.05	50.94	57.45	60.59	69.40
5	I	100	100	100	100	100	100	100	100
	SP	-202.0	-146.0	-169.0	-96.9	-119.0	-180.5	-22.9	-59.5
	V	-170.0	-115.0	-139.0	-69.3	-172.0	-153.8	2.3	-35.3
	P_a	36.76	41.55	45.96	47.57	51.70	61.36	67.56	74.30

APPENDIX I-1 cont'd.

St.	a(m)	0.6	1.2	1.8	2.4	3.0	3.6	4.3	4.9
6	I	100	100	100	100	100	100	100	100
	SP	23.7	75.0	25.0	1.0	43.0	16.0	100.0	48.0
	V	503.1	318.0	195.0	135.7	155.0	111.0	183.0	121.0
	P_a	18.35	18.61	19.53	20.64	21.45	21.83	22.25	22.36
7	I	100	100	100	100	100	100	100	100
	SP	4.3	-21.0	-254.0	-63.0	-35.0	-130.0	30.6	-15.1
	V	528.5	247.0	-68.0	83.0	84.0	-26.0	120.5	66.5
	P_a	20.07	20.52	21.37	22.36	22.79	23.90	24.10	25.01
8	I	100	100	100	100	100	100	100	100
	SP	9.1	87.0	40.0	-44.5	59.0	30.9	210.0	90.0
	V	335.8	257.0	156.1	39.1	128.3	91.2	275.0	139.3
	P_a	12.51	13.02	13.34	12.81	13.27	13.86	14.42	15.11
9	I	100	100	100	100	100	100	100	100
	SP	-67.0	-52.8	-47.0	-37.0	-52.0	17.0	-3.7	33.0
	V	337.4	163.1	103.5	78.5	42.5	94.0	64.0	89.8
	P_a	15.48	16.53	17.29	17.69	18.10	17.69	18.14	17.42
10	I	100	100	100	100	100	100	100	100
	SP	-18.6	89.0	-134.0	-21.0	-5.5	39.9	69.0	21.0
	V	335.0	262.0	-20.7	65.5	66.8	101.0	125.0	72.0
	P_a	13.50	13.25	13.02	13.25	13.84	14.04	15.01	15.60

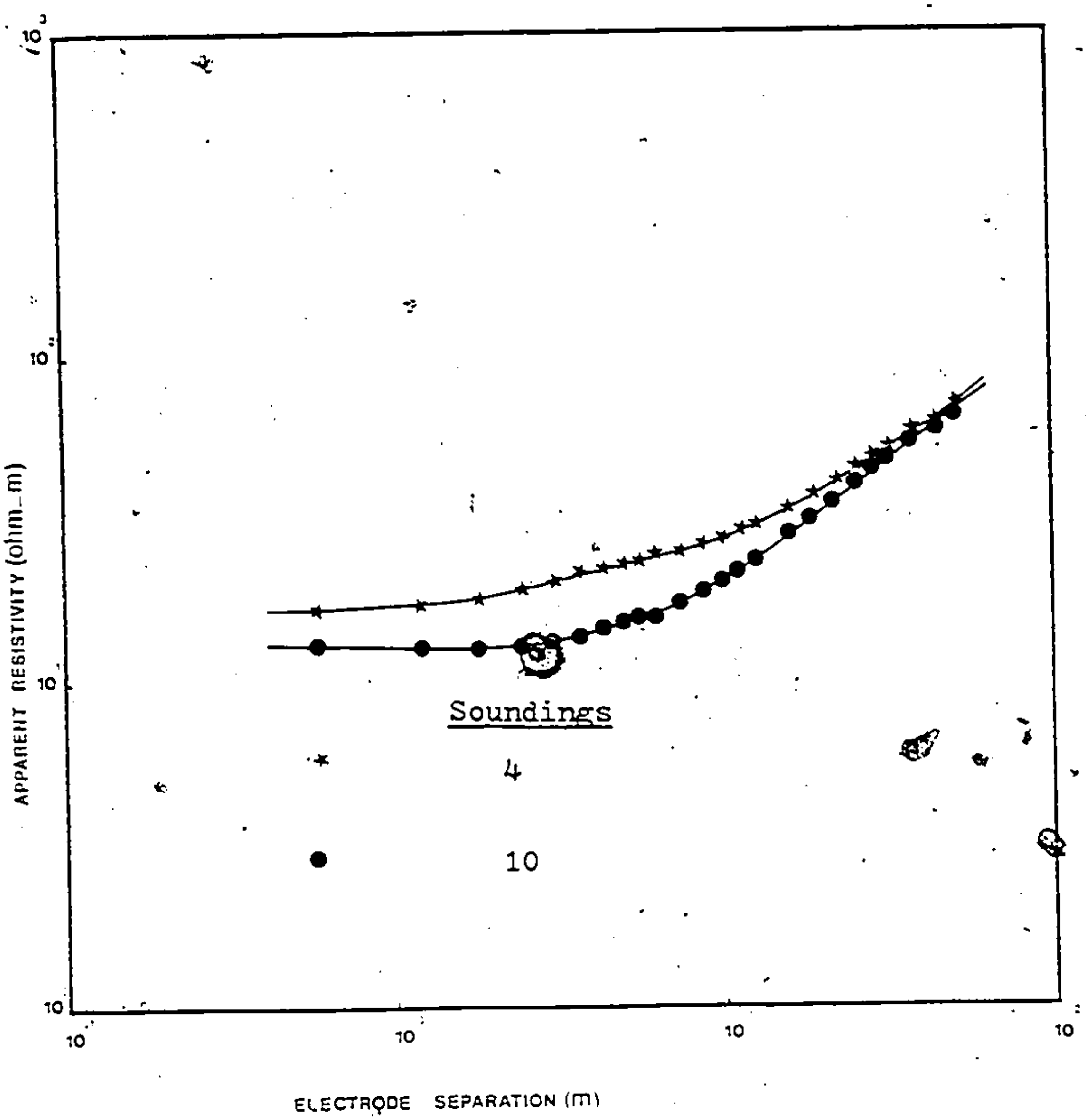
APPENDIX I-1 cont'd.

St.	a(m)	5.5	6.1	7.3	8.5	9.7	11.0	12.2	15.2
6	I	100	100	100	100	100	100	100	100
	SP	245.0	-21.0	353.0	96.0	65.0	149.0	78.5	1.0
	V	313.0	41.5	407.0	143.0	107.0	189.0	117.2	36.5
	P_a	23.44	23.94	24.82	25.20	25.73	27.58	29.65	33.99
7	I	100	100	100	100	100	100	100	100
	SP	-157.0	-34.4	-173.0	-83.4	-70.0	-215.0	80.5	-98.5
	V	-81.0	35.7	-111.5	-30.6	-21.1	-169.5	-37.5	-60.4
	P_a	26.19	26.85	28.26	28.31	29.96	31.37	32.94	36.48
8	I	100	100	100	100	100	100	100	100
	SP	-106.0	74.0	155.9	70.0	67.5	-51.3	115.0	45.1
	V	-59.6	118.3	195.0	105.4	100.5	-19.5	149.1	75.2
	P_a	16.00	16.97	17.97	18.98	20.22	21.92	26.12	28.82
9	I	100	100	100	100	100	100	100	100
	SP	16.0	-28.0	-50.0	-20.0	-36.5	74.5	17.0	-12.5
	V	67.0	18.6	-10.2	15.9	-3.8	105.9	46.5	14.5
	P_a	17.58	17.85	18.29	19.25	20.05	21.68	22.60	25.84
10	I	100	100	100	100	100	100	100	100
	SP	141.9	-26.5	79.3	24.5	-3.3	69.0	119.0	14.5
	V	189.0	15.0	118.0	60.6	30.0	101.0	149.0	44.0
	P_a	16.23	15.90	17.80	19.35	20.37	22.06	22.98	28.24

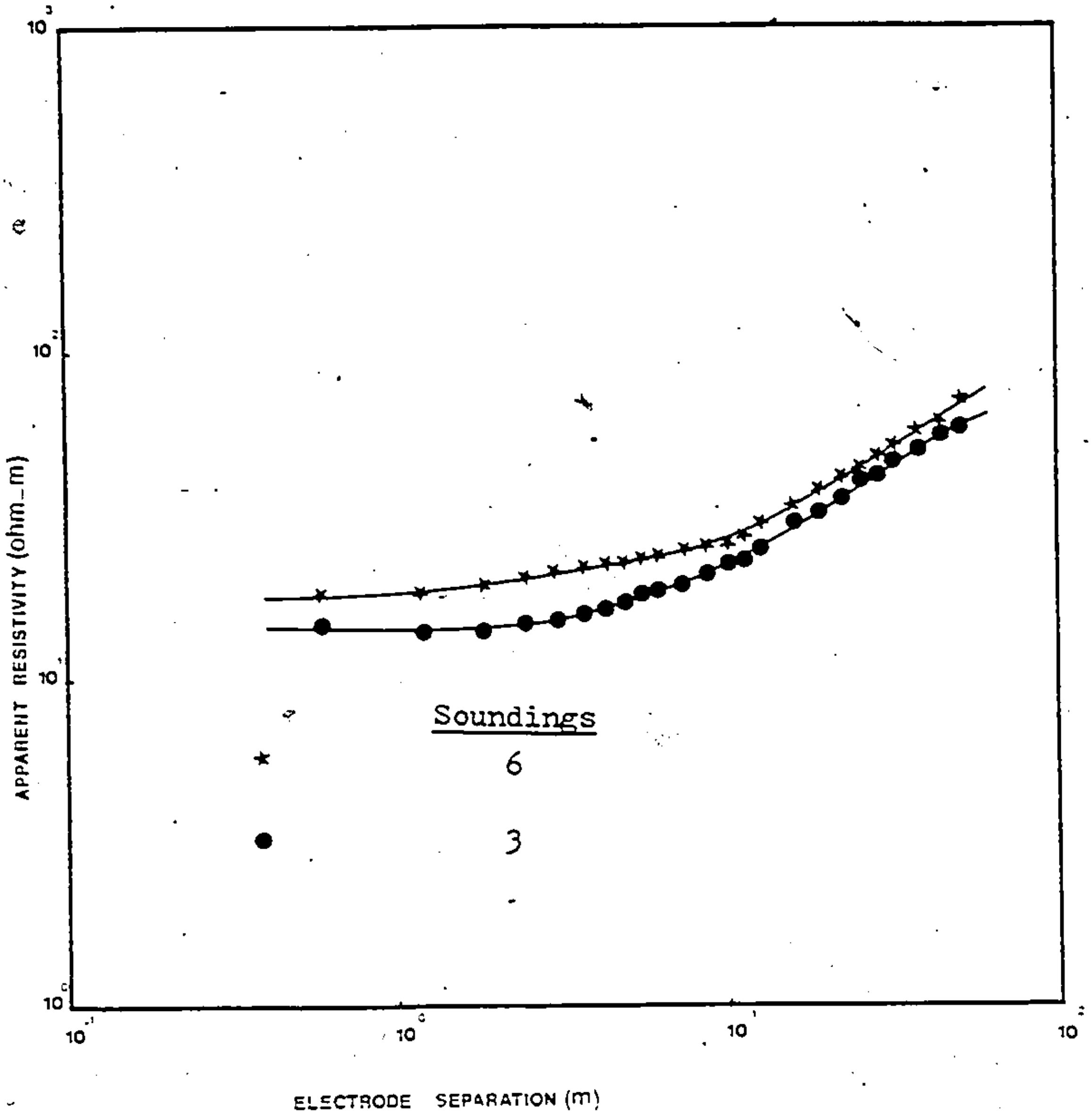
APPENDIX I-1 cont'd.

St.	a(m)	18.3	21.3	24.4	27.4	30.5	36.6	42.7	48.8
6	I	100	100	100	100	100	100	100	100
	SP	-107.0	7.0	47.0	32.0	-2.3	-76.0	26.0	18.4
	V	-74.2	38.0	75.5	59.2	24.4	-51.0	48.5	141.2
	P_a	37.74	41.55	43.66	46.96	51.22	57.45	60.32	69.86
7	I	100	100	100	100	100	100	100	100
	SP	-119.0	-119.0	-110.0	-93.0	47.0	-52.4	-29.8	-18.8
	V	-83.3	-85.5	-79.0	-62.1	75.9	-24.1	-3.0	7.0
	P	41.07	44.91	47.57	53.25	55.34	65.15	71.85	79.05
8	I	100	100	100	100	100	100	100	100
	SP	176.0	58.8	120.0	10.0	20.0	75.5	33.5	91.0
	V	200.2	84.2	144.6	33.7	43.8	97.6	57.1	113.3
	P_a	27.80	34.05	37.69	40.85	45.58	50.79	63.27	68.48
9	I	100	100	100	100	100	100	100	100
	SP	94.3	16.4	-36.3	-50.7	-2.8	-48.5	9.4	29.8
	V	118.6	40.5	-13.5	-29.3	18.4	-28.5	28.2	48.2
	P_a	27.97	32.31	34.99	36.97	40.59	46.07	50.40	56.38
10	I	100	100	100	100	100	100	100	100
	SP	39.0	-37.0	-47.0	36.5	21.6	54.7	112.6	89.4
	V	66.5	-10.5	-21.0	62.0	46.2	78.5	134.5	110.5
	P_a	31.59	35.52	39.83	43.95	47.00	54.58	58.71	64.50

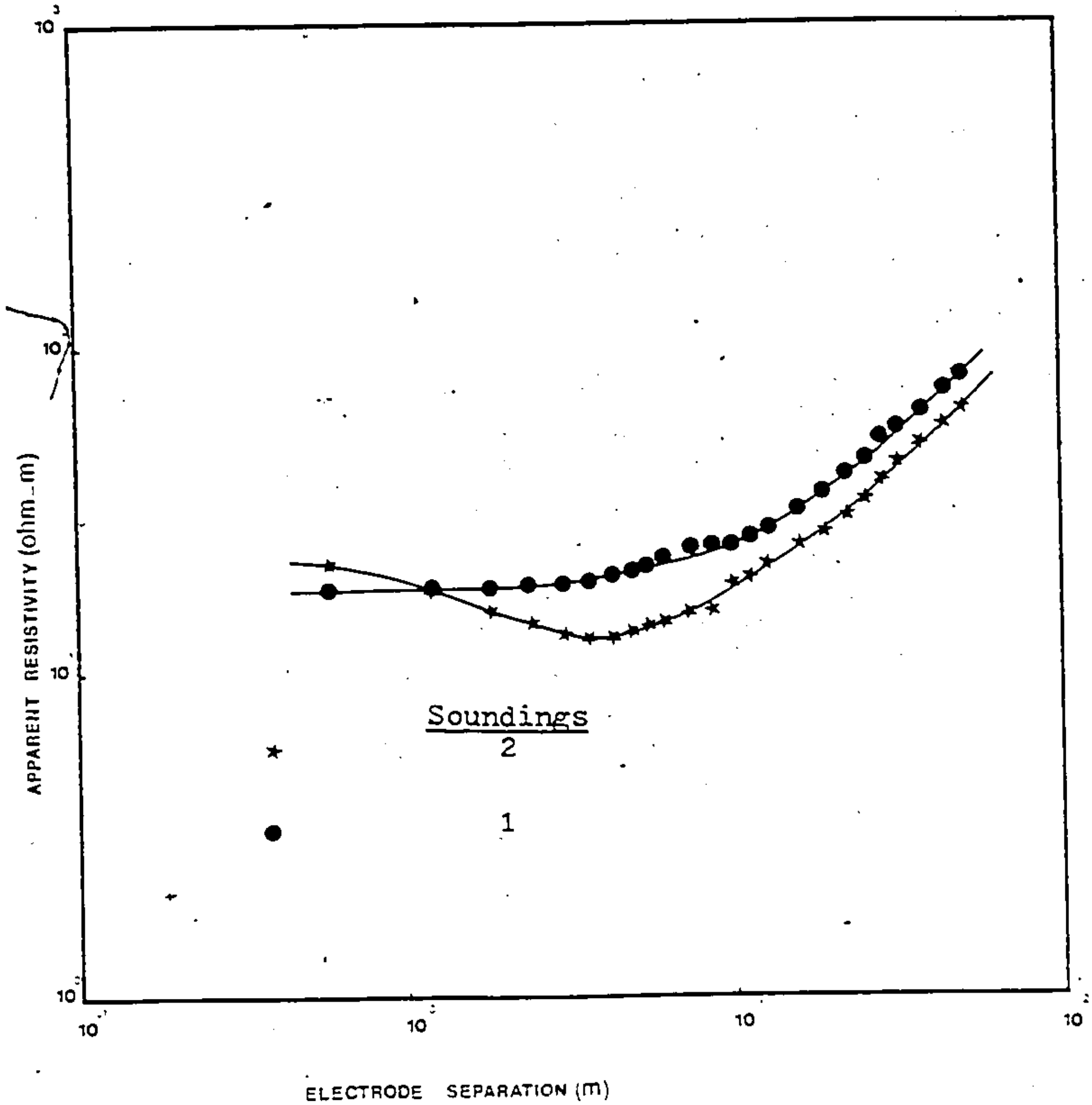
APPENDIX I-1 cont'd.



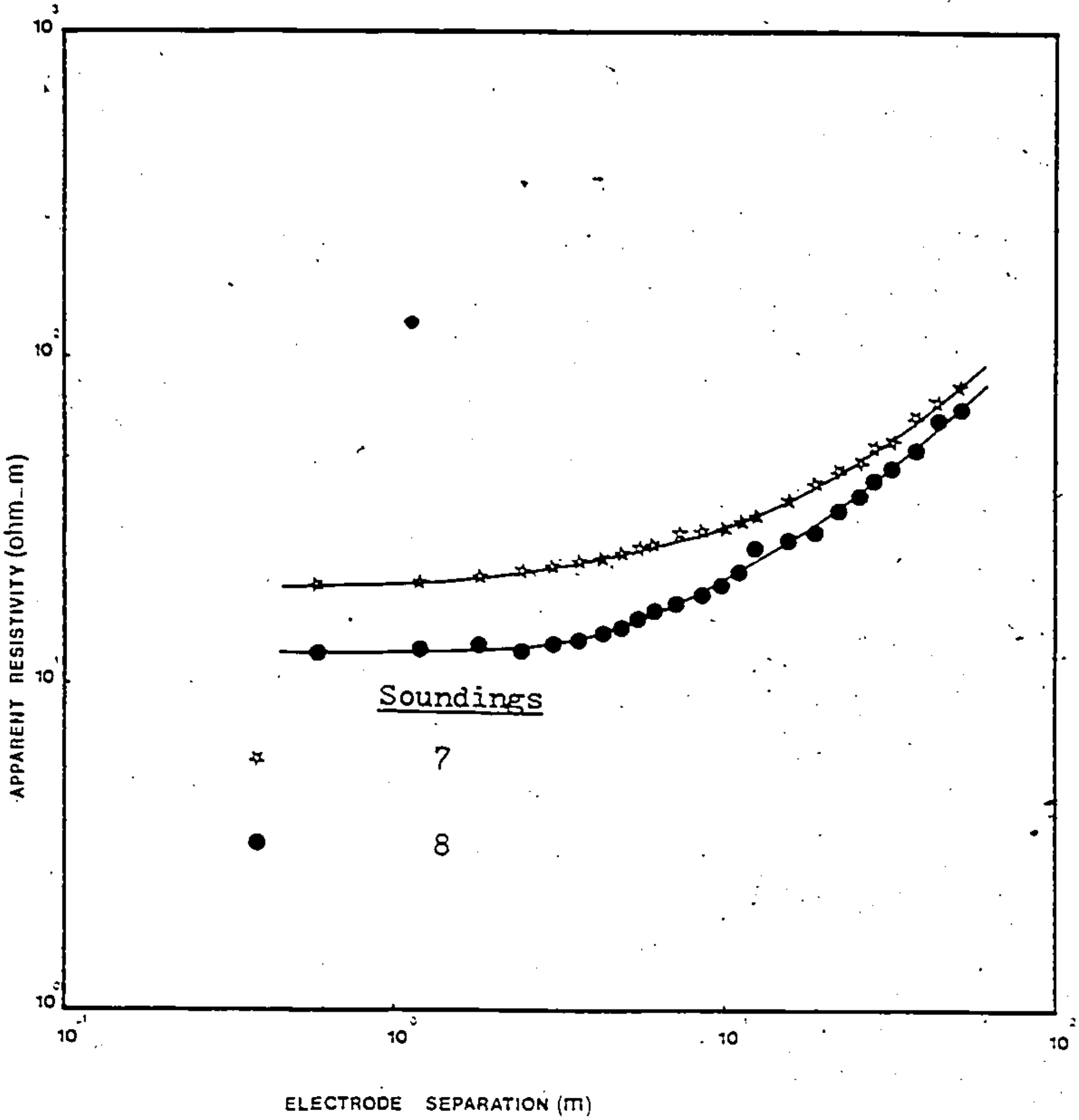
APPENDIX I-1 cont'd.



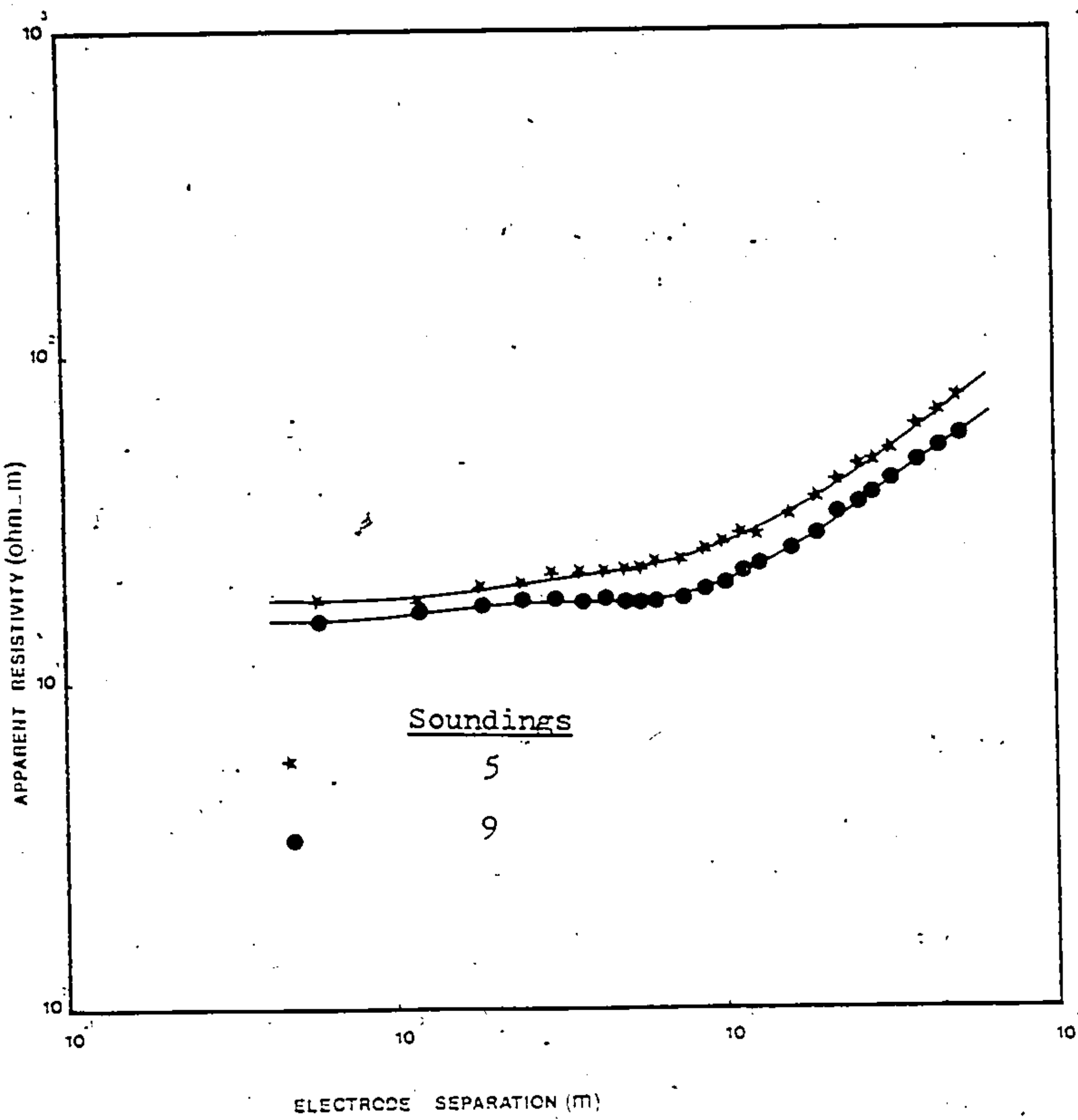
APPENDIX I-1 cont'd.



APPENDIX I-1 cont'd.



APPENDIX I-1 cont'd.



APPENDIX I-2 Results of Electrical Profiling Survey (Tables).

Station	a (m)	I (mA)	SP* (mV)	V (mV)	P_a (ohm-m)
1	4.6	100	-70.0	-18.8	14.71
	12.2	100	-50.0	-22.0	21.45
2	4.6	100	19.0	71.2	14.99
	12.2	100	-19.0	9.5	21.83
3	4.6	100	-3.0	49.1	14.96
	12.2	100	-20.0	9.0	22.21
4	4.6	100	158.0	209.0	14.65
	12.2	100	-94.0	-65.0	22.21
5	4.6	100	49.0	100.0	14.65
	12.2	100	20,0	49.0	22.21
6	4.6	100	-13.0	37.0	14.36
	12.2	100	-13.0	15.5	21.83
7	4.6	100	-17.0	36.0	15.22
	12.2	100	-49.0	-18.9	23.06
8	4.6	100	-48.8	6.2	15.80
	12.2	100	-24.5	6.5	23.75
9	4.6	100	16.0	69.0	15.22
	12.2	100	103.0	134.0	23.75
10	4.6	100	45.0	92.0	13.50
	12.2	100	-57.5	-26.0	24.13
11	4.6	100	-51.3	4.8	16.11
	12.2	100	-27.5	6.5	26.04
12	4.6	100	49.0	106.0	16.37
	12.2	100	70.0	103.0	25.28
13	4.6	100	-24.0	39.3	18.18
	12.2	100	102.0	137.0	26.81

* SP value has been subtracted from V prior to calculating P_a

APPENDIX I-2 cont'd.

14	4.6	100	-40.0	25.5	18.81
	12.2	100	-65.0	-30.0	26.81
15	4.6	100	41.5	118.8	22.20
	12.2	100	-60.0	-21.8	29.26
16	4.6	100	-40.9	22.5	18.21
	12.2	100	24.0	63.2	26.20
17	4.6	100	-18.0	42.3	17.32
	12.2	100	18.0	51.9	25.97
18	4.6	100	179.0	237.0	16.66
	12.2	100	17.0	49.8	25.12
19	4.6	100	12.0	70.0	16.66
	12.2	100	34.0	66.0	24.51
20	4.6	100	37.5	91.0	15.37
	12.2	100	27.0	57.0	22.98
21	4.6	100	62.0	115.0	15.22
	12.2	100	30.0	59.6	22.67
22	4.6	100	23.7	70.9	13.56
	12.2	100	69.0	97.0	21.45
23	4.6	100	-105.0	-55.8	14.13
	12.2	100	-7.6	19.3	20.61
24	4.6	100	60.6	118.8	16.72
	12.2	100	50.0	79.5	22.60
25	4.6	100	-40.9	12.4	15.31
	12.2	100	-51.5	-23.4	21.52
26	4.6	100	-31.8	24.5	16.17
	12.2	100	64.0	96.5	24.90
27	4.6	100	7.7	71.2	18.24
	12.2	100	-77.0	-43.0	26.04
28	4.6	100	7.0	73.0	19.10
	12.2	100	-2.5	31.7	26.20
29	4.6	100	4.0	64.8	17.46
	12.2	100	16.0	50.0	26.04

APPENDIX I-2 cont'd.

30	4.6	100	-30.5	35.0	18.81
	12.2	100	-15.8	20.7	27.96
31	4.6	100	-65.5	6.0	20.54
	12.2	100	-6.5	31.8	29.34
32	4.6	100	-65.0	3.5	19.68
	12.2	100	-23.0	14.6	28.80
33	4.6	100	119.0	186.0	19.25
	12.2	100	109.0	145.5	27.96
34	4.6	100	-17.4	45.4	18.04
	12.2	100	95.0	131.0	27.58
35	4.6	100	80.0	149.7	20.02
	12.2	100	-8.5	28.5	28.34
36	4.6	100	-17.5	49.1	19.13
	12.2	100	-17.0	18.6	27.27
37	4.6	100	9.0	80.5	20.54
	12.2	100	-54.0	-18.0	27.58
38	4.6	100	-1.0	63.0	18.38
	12.2	100	42.0	77.0	26.81
39	4.6	100	-4.5	56.3	17.46
	12.2	100	45.2	79.0	25.89
40	4.6	100	-3.5	70.0	21.11
	12.2	100	40.0	79.0	29.87
41	4.6	100	-8.0	66.0	21.26
	12.2	100	66.5	104.0	28.73
42	4.6	100	-34.0	43.0	22.12
	12.2	100	-35.0	4.0	29.87
43	4.6	100	2.0	75.0	20.97
	12.2	100	-110.0	-70.0	30.64
44	4.6	100	41.0	126.0	24.42
	12.2	100	-63.0	-18.0	34.47
45	4.6	100	-33.0	39.0	20.68
	12.2	100	-57.0	-15.0	32.17

APPENDIX I-2 cont'd.

46	4.6	100	-38.0	38.0	21.83
	12.2	100	-18.0	24.0	32.17
47	4.6	100	-30.0	30.0	17.23
	12.2	100	-6.0	28.0	26.04
48	4.6	100	-34.0	13.0	13.50
	12.2	100	-14.0	15.0	22.21
49	4.6	100	-40.0	3.0	12.35
	12.2	100	2.0	31.0	22.21
50	4.6	100	-40.0	20.0	17.23
	12.2	100	-13.0	21.0	26.04
51	4.6	100	-65.0	5.0	20.11
	12.2	100	-28.0	11.0	29.87
52	4.6	100	-3.0	64.0	19.25
	12.2	100	36.0	75.0	29.87
53	4.6	100	-17.0	47.0	18.38
	12.2	100	-15.0	21.0	27.58
54	4.6	100	12.0	63.0	14.65
	12.2	100	-40.0	-8.0	24.51
55	4.6	100	-36.0	7.0	12.35
	12.2	100	-36.0	-9.0	20.68
56	4.6	100	30.0	74.0	12.64
	12.2	100	-58.0	-31.0	20.68
57	4.6	100	25.0	67.0	12.06
	12.2	100	-20.0	6.0	19.92
58	4.6	100	65.0	110.0	12.93
	12.2	100	-35.0	-5.0	22.98
59	4.6	100	23.0	68.0	12.93
	12.2	100	29.0	58.0	22.21
60	4.6	100	39.0	103.0	18.38
	12.2	100	-35.0	1.0	27.58
61	4.6	100	80.0	138.0	16.66
	12.2	100	19.0	54.0	26.81

APPENDIX I-2 cont'd.

62	4.6	100	6.0	66.0	17.23
	12.2	100	71.0	106.0	26.81
63	4.6	100	-33.0	20.0	15.22
	12.2	100	-13.0	19.0	24.51
64	4.6	100	-36.0	41.0	22.12
	12.2	100	-70.0	-29.0	31.41
65	4.6	100	-50.0	40.0	25.85
	12.2	100	-45.0	2.0	36.00
66	4.6	100	-10.0	78.0	25.28
	12.2	100	-1.0	42.0	32.94
67	4.6	100	-10.0	51.0	17.52
	12.2	100	-25.0	10.0	26.81
68	4.6	100	14.0	80.0	18.96
	12.2	100	-20.0	16.0	27.58
69	4.6	100	75.0	125.0	14.36
	12.2	100	47.0	78.0	23.75
70	4.6	100	-1.0	72.0	20.97
	12.2	100	20.0	55.0	26.81
71	4.6	100	-59.0	15.0	21.26
	12.2	100	43.0	78.5	27.19
72	4.6	100	-18.0	51.0	19.82
	12.2	100	9.0	42.5	25.66
73	4.6	100	-5.0	69.0	21.26
	12.2	100	66.0	104.0	29.11
74	4.6	100	-67.0	12.5	22.84
	12.2	100	-20.0	23.0	32.94
75	4.6	100	236.0	339.0	29.59
	12.2	100	301.0	348.0	36.00
76	4.6	100	10.0	123.0	32.46
	12.2	100	-155.0	-112.0	32.94
77	4.6	100	6.0	70.0	18.38
	12.2	100	26.5	61.5	26.81

78	4.6	100	-44.0	33.0	22.12
	12.2	100	-43.0	-2.8	30.79
79	4.6	100	29.0	98.5	19.96
	12.2	100	77.0	118.0	31.41
80	4.6	100	-24.0	58.0	23.55
	12.2	100	13.0	56.5	33.32
81	4.6	100	-33.0	48.5	23.41
	12.2	100	3.5	43.5	30.64
82	4.6	100	36.0	115.5	22.84
	12.2	100	22.0	61.0	29.87
83	4.6	100	-7.0	62.0	19.82
	12.2	100	-2.0	34.5	27.96
84	4.6	100	61.0	124.0	18.10
	12.2	100	5.0	43.5	29.49
85	4.6	100	-8.0	61.0	19.82
	12.2	100	-4.0	35.0	29.87
86	4.6	100	-4.0	80.0	24.13
	12.2	100	-37.0	7.5	34.10
87	4.6	100	21.0	103.0	23.55
	12.2	100	44.5	87.0	32.56
88	4.6	100	37.0	121.0	24.13
	12.2	100	25.0	68.0	32.94
89	4.6	100	-22.0	41.5	18.24
	12.2	100	-16.0	17.5	25.66
90	4.6	100	24.0	88.5	18.53
	12.2	100	-15.5	15.0	23.36
91	4.6	100	-19.0	46.5	18.81
	12.2	100	-31.0	-0.5	23.36
92	4.6	100	-47.0	11.5	16.80
	12.2	100	-40.0	-8.8	23.90
93	4.6	100	10.0	68.2	16.72
	12.2	100	42.0	70.0	21.45

APPENDIX I-2 cont'd.

94	4.6	100	-21.5	31.0	15.10
	12.2	100	-40.0	-11.5	21.83
95	4.6	100	-53.0	1.0	15.51
	12.2	100	-6.0	23.0	22.21
96	4.6	100	5.8	57.0	14.71
	12.2	100	12.0	41.5	22.60
97	4.6	100	-40.0	10.0	14.36
	12.2	100	-17.0	11.5	21.83
98	4.6	100	90.0	142.0	14.94
	12.2	100	6.2	36.1	22.90
99	4.6	100	12.0	62.0	14.36
	12.2	100	-14.0	13.0	20.68
100	4.6	100	-36.0	8.5	12.78
	12.2	100	6.5	32.1	19.61
101	4.6	100	-55.0	-13.5	11.92
	12.2	100	-9.0	16.3	19.38
102	4.6	100	55.0	98.0	12.35
	12.2	100	59.0	85.1	19.99
103	4.6	100	-6.5	36.0	12.21
	12.2	100	-39.0	-14.0	19.15
104	4.6	100	-41.0	11.9	15.20
	12.2	100	-53.0	-24.9	21.52
105	4.6	100	52.5	114.0	17.66
	12.2	100	-65.8	-33.9	24.43
106	4.6	100	27.5	82.0	15.65
	12.2	100	12.0	43.9	24.43
107	4.6	100	-7.5	49.0	16.23
	12.2	100	10.0	40.4	23.29
108	4.6	100	-46.0	15.2	17.58
	12.2	100	-59.0	-27.0	24.51
109	4.6	100	-6.0	53.0	16.95
	12.2	100	60.0	93.0	25.28

APPENDIX I-2 cont'd.

110	4.6	100	-19.0	36.0	15.80
	12.2	100	-56.0	-23.5	24.90
111	4.6	100	-11.0	43.0	15.51
	12.2	100	14.0	47.0	25.28
112	4.6	100	1.0	56.0	15.80
	12.2	100	-48.0	-16.0	24.51
113	4.6	100	-41.0	20.0	17.52
	12.2	100	5.0	40.0	26.81
114	4.6	100	-45.5	16.0	17.66
	12.2	100	-18.0	15.0	25.28
115	4.6	100	71.0	140.2	19.88
	12.2	100	-65.0	-30.0	26.81
116	4.6	100	31.0	96.5	18.81
	12.2	100	-35.2	-2.5	25.05
117	4.6	100	-24.4	37.4	17.75
	12.2	100	20.2	52.6	24.82
118	4.6	100	-27.0	27.5	15.65
	12.2	100	4.0	34.0	22.98
119	4.6	100	30.0	87.2	16.43
	12.2	100	-35.0	-5.0	22.98
120	4.6	100	19.0	70.5	14.79
	12.2	100	-34.0	-4.6	22.52
121	4.6	100	-2.0	47.0	14.07
	12.2	100	33.0	62.0	22.21
122	4.6	100	4.0	51.2	13.56
	12.2	100	3.0	31.8	22.06
123	4.6	100	14.5	60.0	13.07
	12.2	100	4.0	31.6	21.14
124	4.6	100	-11.2	39.5	14.56
	12.2	100	54.2	82.1	21.37
125	4.6	100	21.4	79.5	16.69
	12.2	100	-80.5	-49.0	24.13

126	4.6	100	-13.0	47.5	17.38
	12.2	100	-51.0	-18.4	24.97
127	4.6	100	51.0	111.0	17.23
	12.2				
128	4.6	100	-54.0	9.0	18.10
	12.2				
129	4.6	100	69.0	133.0	18.38
	12.2	100	40.0	72.3	24.74
130	4.6	100	18.4	75.6	16.43
	12.2	100	122.0	155.6	25.74
131	4.6	100	4.5	68.4	18.36
	12.2	100	-22.2	10.3	24.90
132	4.6	100	-5.2	51.2	16.20
	12.2	100	36.6	69.5	25.20
133	4.6	100	-84.0	16.6	19.36
	12.2	100	27.5	58.6	23.82
134	4.6	100	-38.0	8.0	13.21
	12.2	100	-26.0	-2.0	18.38
135	4.6	100	-72.0	-14.0	16.66
	12.2	100	-21.0	6.0	20.68
136	4.6	100	9.0	53.0	12.64
	12.2	100	88.0	114.0	19.92
137	4.6	100	93.0	128.0	10.05
	12.2	100	-17.5	6.8	18.61
138	4.6	100	18.5	41.9	6.72
	12.2	100	-47.0	-24.0	17.62
139	4.6	100	-33.0	-2.4	8.79
	12.2	100	-35.0	-7.0	21.45
140	4.6	100	-83.0	105.0	6.32
	12.2	100	25.0	44.0	14.55
141	4.6	100	-71.0	-36.0	10.05
	12.2	100	24.0	49.5	19.53

APPENDIX I-2 cont'd.

142	4.6	100	27.9	97.5	19.99
	12.2	100	-87.0	-68.0	14.55
143	4.6	100	50.0	101.6	14.82
	12.2	100	30.0	53.0	17.62
144	4.6	100	148.0	192.0	12.78
	12.2	100	3.0	23.0	15.32
145	4.6	100	-120.0	-81.0	11.20
	12.2	100	6.0	21.5	11.87
146	4.6	100	11.8	71.2	17.06
	12.2				
147	4.6	100	-43.0	14.0	16.37
	12.2				
148	4.6	100	45.5	111.5	18.96
	12.2				
149	4.6	100	14.5	72.7	16.72
	12.2				
150	4.6	100	5.0	69.0	18.38
	12.2	100	-13.0	21.0	26.04

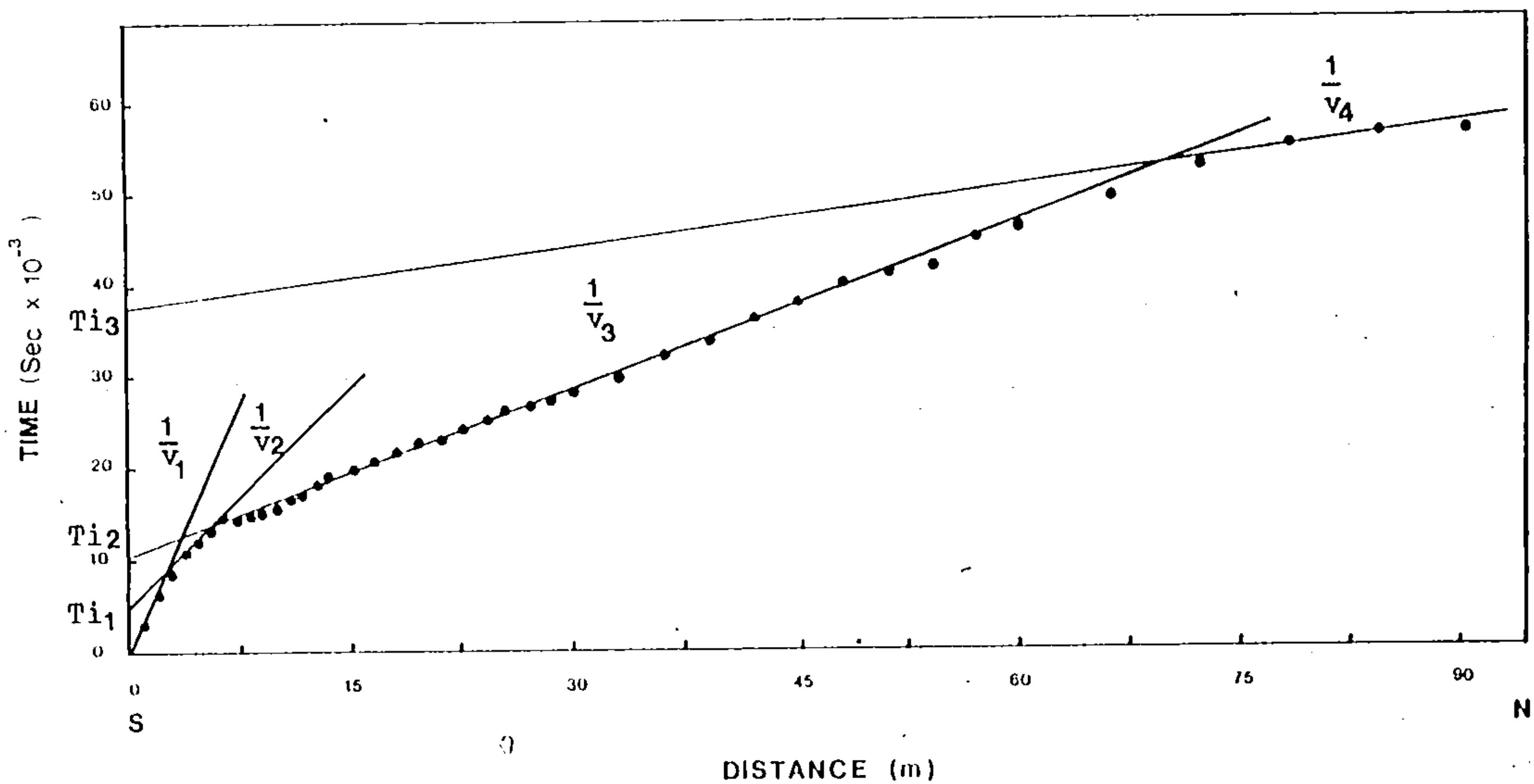
APPENDIX I-3 Results of Seismic Refraction Survey (Tables and Plots).

Distance(X) (m)	Time (s x 10^{-3})				
	Seismic St. 1	Seismic St. 2	Seismic St. 6	Seismic St. 8	Seismic St. 9
0.9	3.08	4.43	3.40	2.03	2.31
1.8	6.37	9.04	6.28	5.78	5.50
2.7	8.56	10.65	8.63	8.25	8.00
3.6	10.75	12.28	11.67	10.64	10.33
4.6	12.15	14.02	14.45	12.60	10.90
5.5	13.43	14.41	16.08	13.40	11.40
6.4	14.86	13.86	17.50	14.18	11.60
7.3	14.40	14.84	17.61	14.70	12.40
8.2	14.80	15.49	18.86	15.20	12.40
9.1	15.24	16.45	18.88	15.80	13.10
10.1	15.63	18.24	19.45	16.30	13.90
11.0	16.73	17.69	20.34	17.10	14.50
11.9	17.12	17.93	20.93	17.70	14.50
12.8	18.32	18.71	21.76	18.10	15.40
13.7	19.43	19.50	23.44	18.90	16.50
15.2	19.80	20.71	23.46	20.20	17.10
16.8	20.65	21.83	24.37	21.00	18.50
18.3	21.75	22.04	23.72	21.30	20.00
19.8	22.90	23.26	25.35	22.00	20.90
21.3	23.19	23.60	25.62	22.90	22.40

APPENDIX I-3 cont'd.

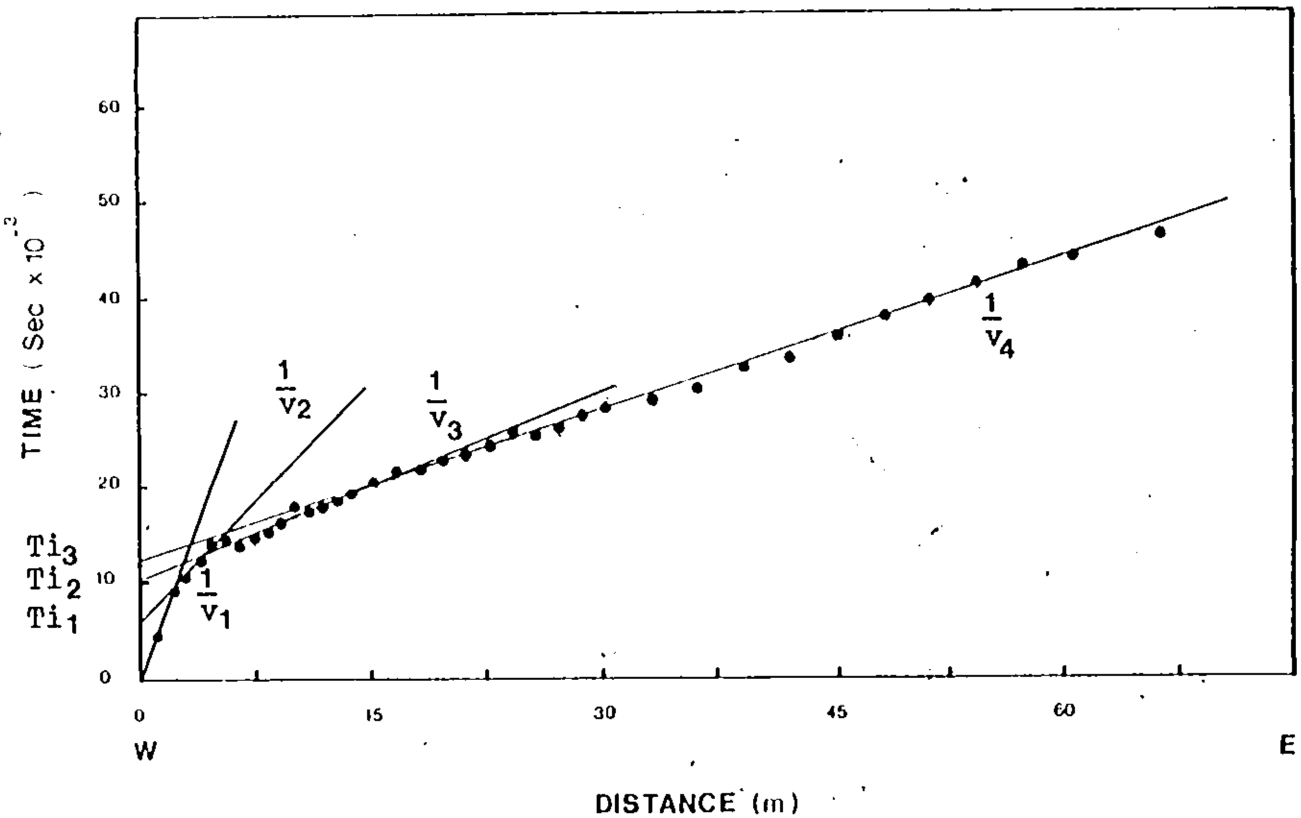
22.9	24.43	24.51	27.44	24.20	22.90
24.4	25.33	26.33	28.74	25.20	23.20
25.9	26.12	25.59	29.05	26.10	24.70
27.4	26.81	26.34	30.64	26.70	25.60
28.9	27.28	27.52	30.95	27.90	27.50
30.5	28.28	28.52	31.57	29.20	27.70
33.5	29.86	29.24	34.05	31.10	29.50
36.6	32.31	30.69	35.40	32.20	31.10
39.6	33.68	32.78	36.66	34.40	32.30
42.7	36.22	33.60	77.85	36.10	35.20
45.7	37.88	36.18	40.17	38.20	36.10
48.8	40.00	37.85	41.37	40.20	38.10
51.8	41.09	39.80	43.03	41.30	40.10
54.9	41.36	41.57	44.31	43.00	41.40
57.9	44.91	43.39	46.71	44.80	43.10
61.0	45.93	44.46	47.64	45.70	44.80
67.0	49.30	46.75	50.62	49.70	48.80
73.1	52.24		53.30	53.50	52.40
79.2	54.92		56.45	55.80	55.30
85.3	56.01		57.98	55.00	56.60
91.4	56.16		58.65	57.70	58.20

APPENDIX I-3 cont'd.



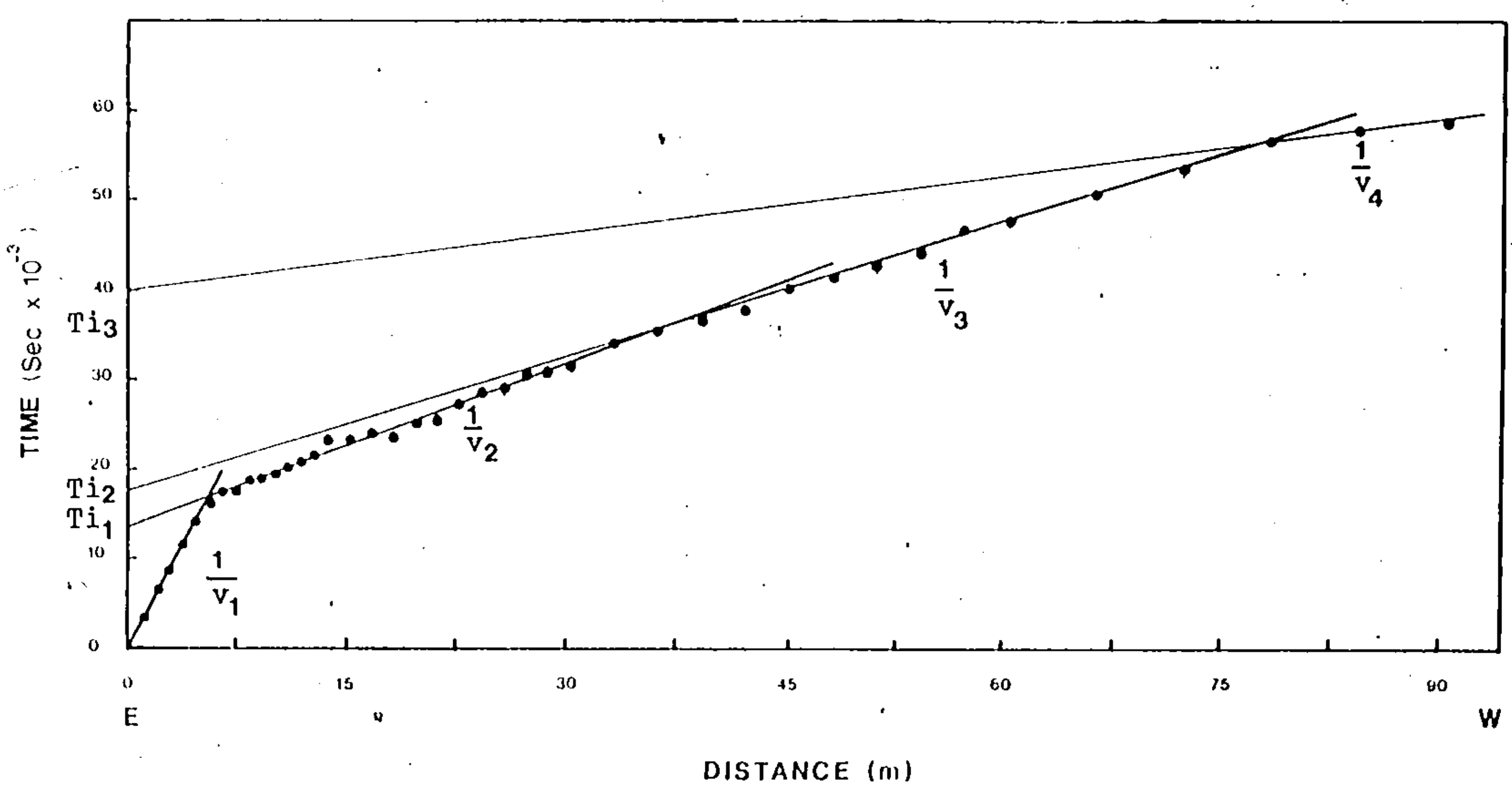
Time-distance curve(Seismic Profile 1)

APPENDIX I-3 cont'd.



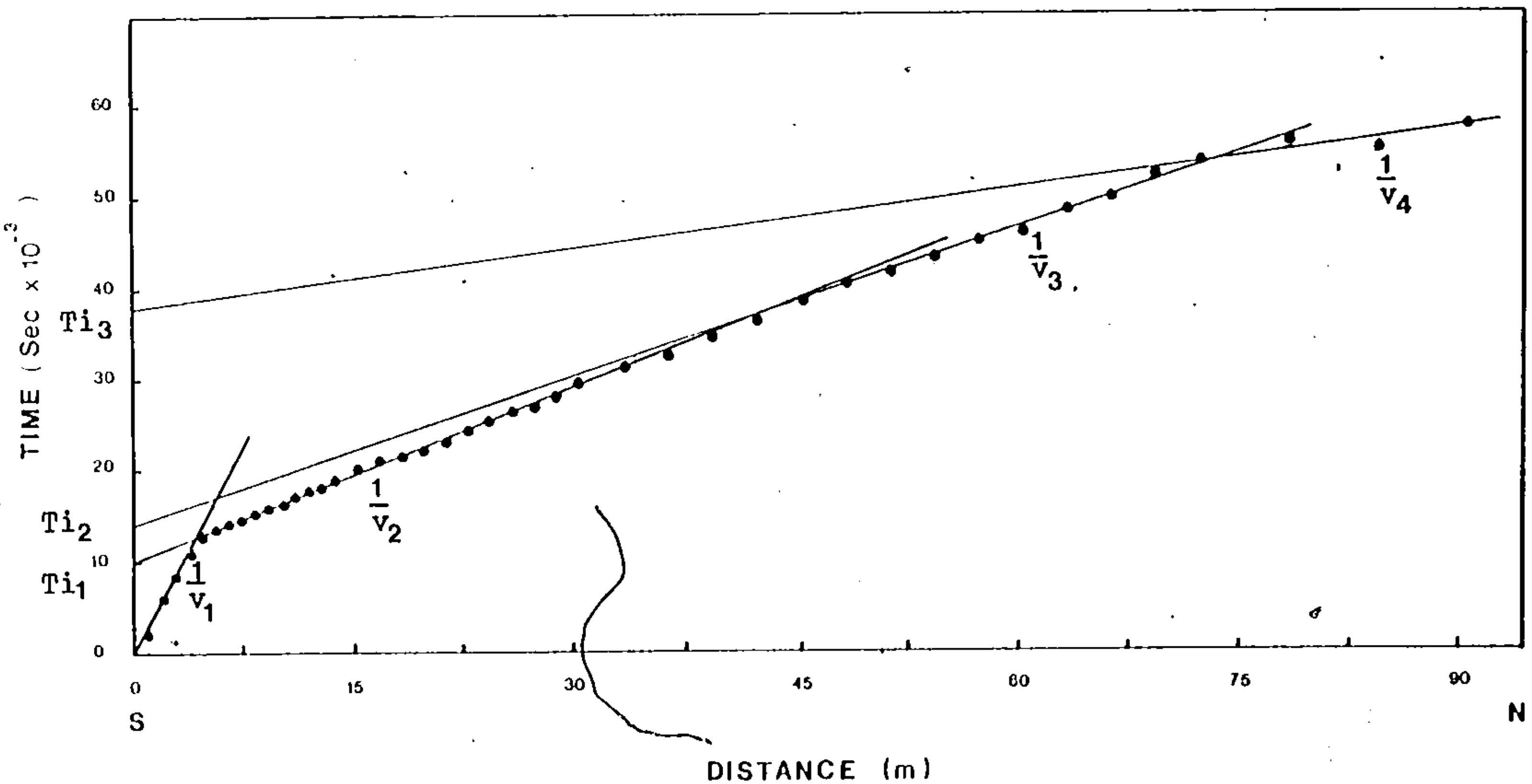
Time-distance curve(Seismic Profile 2)

APPENDIX I-3 cont'd.



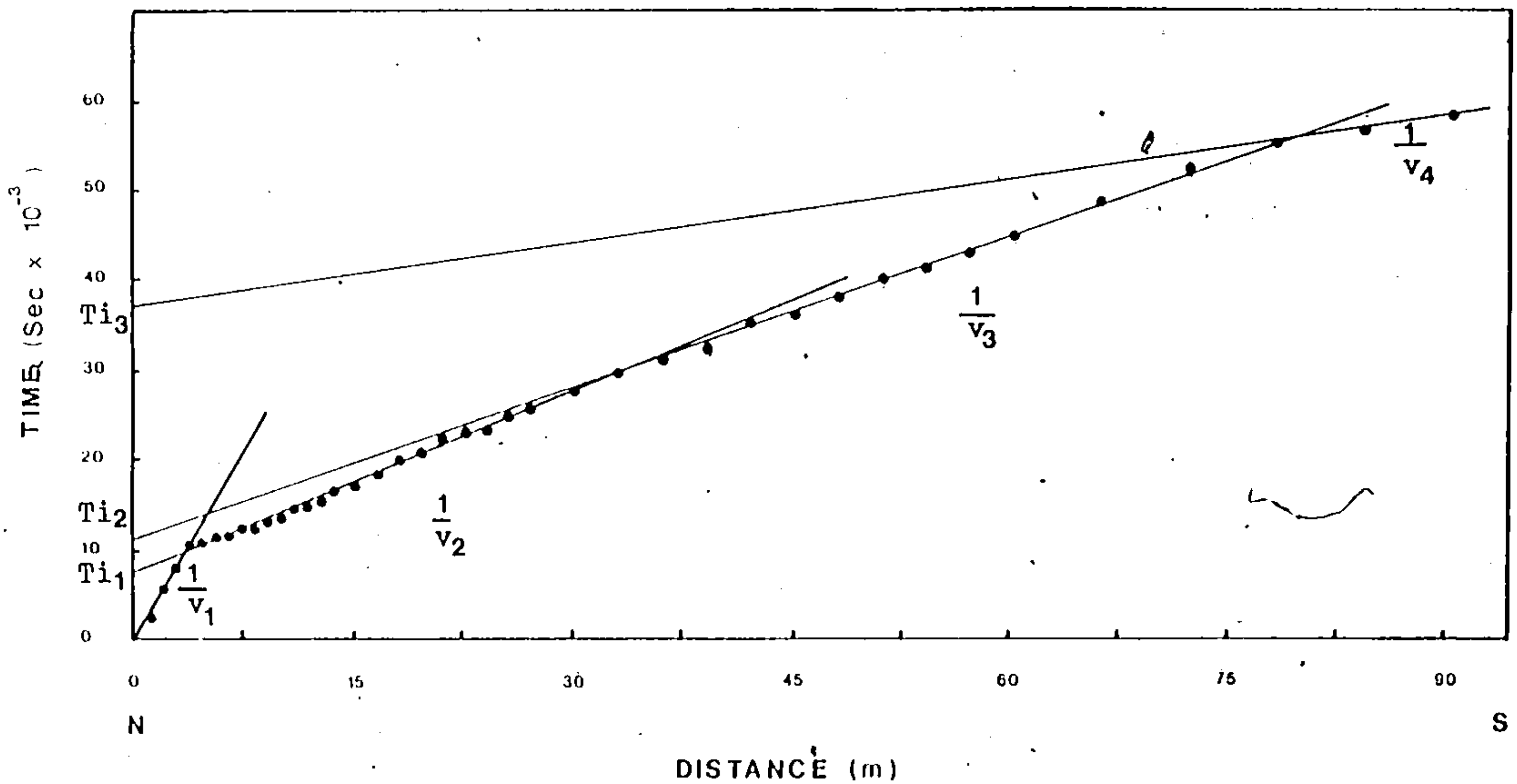
Time-distance curve(Seismic Profile 6)

APPENDIX I-3 cont'd.



Time-distance curve(Seismic Profile 8)

APPENDIX I-3 cont'd.



Time-distance curve(Seismic Profile 9)

APPENDIX I-4 Electrical Conductivity Measurements.

Site	Conductivity(µS/cm) at 25°C	Date		
		Day	Month	Year
1	720	05	11	1982
2	785	"	"	"
3	1544			
4	1352	"	"	"
5	959			
6	971			
7	1856	"	"	"
8	806			
9	687			
10	458	"	"	"
11	2770			
12	273			
13	269			
14	505	"	"	"
15	1380			
16	1264	"	"	"

APPENDIX I-5 Selected borehole logs for the Essex County Landfill No. 1.

Well	Elevation (m.a.s.l.)	Log (thickness in m)	Refernce
BH-1	-----	Top soil 0.1, very stiff grey and brown silty clay with some sand and occasional fine to medium gravel 3.4, stiff to firm grey silty clay with some sand and occasional fine medium gravel 2.9.	Golder Associates (1969a)
BH-2	-----	Top soil 0.1, very stiff grey and brown silty clay with some sand and occasional fine to medium gravel 4.8, stiff grey silty clay with some sand and occasional fine to medium gravel 1.5.	Golder Associates (1969a)
BH-3	-----	Top soil 0.1, very stiff grey and brown silty clay with some sand and occasional fine to medium gravel 3.9, stiff grey silty clay with some sand and occasional fine to medium gravel 2.4.	Golder Associates (1969a)

APPENDIX I-5 cont'd.

Well	Elevation (m.a.s.l.)	Log (thickness in m)	Reference
21-153	188.4	Clay 10.4, medium sand and clay 14.6, fine sand 3.6, limestone* 1.9.	Ontario Ministry of Environment (OME), 1977
21-158	187.4	Clay 24.4, medium sand 3.6, shale 0.3, sand 3.1, limestone 3.3.	OME, 1977
21-160	188.4	Blue clay 26.8, fine sand 3.3, limestone 1.9.	OME, 1977
21-494	185.3	Clay 9.7, medium sand 1.9, medium sand and clay 6.1, clay 3.9, limestone 2.8.	OME, 1977
21-3156	188.0	Top soil 0.6, yellow clay 3.0, blue clay 5.5, grey fine sand and clay 17.7, grey fine sand and gravel 2.2, grey limestone 3.9.	OME, 1977

* Sanford (1969) indicated that the bedrock at Essex County Landfill No. 1 is dolomite.

APPENDIX I-5 cont'd.

Well	Elevation (m.a.s.l.)	Log (thickness in m)	Reference
21-3243	189.0	Top soil 0.6, blue clay 4.0, grey clay 8.5, grey medium sand 5.8, grey clay 4.2, grey medium sand and gravel 7.1, limestone 2.1.	OME, 1977
21-3375	187.1	Top soil 0.3, blue clay 8.8, black medium sand 8.9, fine sand and gravel 1.5.	OME, 1977
21-3652	190.5	Top soil 0.3, red clay 5.5, blue clay 14.3, brown limestone 8.9.	OME, 1977

APPENDIX II

ESSEX COUNTY LANDFILL No. 2 DATA

APPENDIX II-1 Results of Electrical Sounding Survey (Tables and Plots).

St.	a(m)	0.6	1.2	1.8	2.4	3.0	3.6	4.3	4.9
1	I	70	100	100	90	100	100	100	100
	*SP	1.0	-80.0	1.0	-20.0	-20.0	10.0	-22.0	8.0
	V	10551.0	5600.0	3501.0	1400.0	950.0	710.0	535.0	414.0
	P_a	576.97	435.06	402.18	241.70	185.77	160.87	149.33	124.40
2	I	100	100	100	100	100	100	100	100
	SP	120.0	20.0	68.0	28.0	54.0	164.0	66.0	1.0
	V	1310.0	520.0	352.0	229.0	215.0	301.0	189.0	114.0
	P_a	45.55	38.30	32.63	30.79	30.83	31.48	32.97	34.62
3	I	100	100	100	100	100	100	100	100
	SP	20.0	50.0	40.0	-10.0	41.0	-2.0	-111.0	8.0
	V	7900.0	4080.0	2640.0	1870.0	1449.0	1153.0	882.0	846.0
	P_a	301.67	308.68	298.76	287.99	269.65	265.44	266.22	256.77
4	I	100	100	100	100	100	100	100	100
	SP	-20.0	82.0	-125.0	24.0	3.0	119.0	-25.0	25.0
	V	2690.0	1390.0	608.0	473.0	317.0	341.0	152.0	182.0
	P_a	103.70	100.20	84.23	68.78	60.13	51.02	47.45	48.10
5	I	100	100	100	100	100	100	100	100
	SP	20.0	1.0	173.0	-52.0	118.0	243.0	-87.0	30.0
	V	4960.0	1685.0	941.0	336.0	336.0	436.0	76.0	182.0
	P_a	189.11	128.98	88.25	59.44	47.49	44.35	43.70	46.57

* SP value has been subtracted from V prior to caculating P_a

APPENDIX II-1 cont'd.

St.	a(m)	5.5	6.1	7.3	8.5	9.7	11.0	12.2	15.2
1	I	100	100	100	100	100	100	100	100
	SP	15.0	14.0	12.0	-41.0	-45.0	9.0	-8.0	35.0
	V	351.0	273.0	223.0	145.0	130.0	174.0	146.0	173.0
	P_a	115.82	99.20	96.98	99.74	107.24	112.38	117.97	132.14
2	I	100	100	100	100	100	100	100	100
	SP	4.0	48.0	-11.0	-18.0	96.0	-72.0	-20.0	64.0
	V	111.0	150.0	79.0	61.0	166.0	-10.0	38.0	112.0
	P_a	36.88	39.07	41.36	42.36	42.89	42.74	44.43	45.96
3	I	100	100	100	100	100	100	100	100
	SP	-30.0	103.0	45.0	-2.0	18.0	14.0	60.0	8.0
	V	718.0	781.0	572.0	432.0	380.0	322.0	319.0	190.0
	P_a	257.85	259.69	242.22	232.72	221.84	212.35	198.41	174.27
4	I	100	100	100	100	100	100	100	100
	SP	-29.0	23.0	15.0	-34.0	185.0	53.0	93.0	-223.0
	V	166.0	150.0	125.0	62.0	276.0	137.0	174.0	-151.0
	P_a	47.22	48.64	50.26	51.47	55.76	57.91	62.05	68.94
5	I	100	100	100	100	100	100	100	100
	SP	104.0	10.0	-7.0	104.0	-108.0	20.0	250.0	95.0
	V	243.0	144.0	118.0	225.0	9.0	137.0	364.0	205.0
	P_a	47.91	51.32	57.45	64.88	71.45	80.66	87.33	105.33

APPENDIX II-1 cont'd.

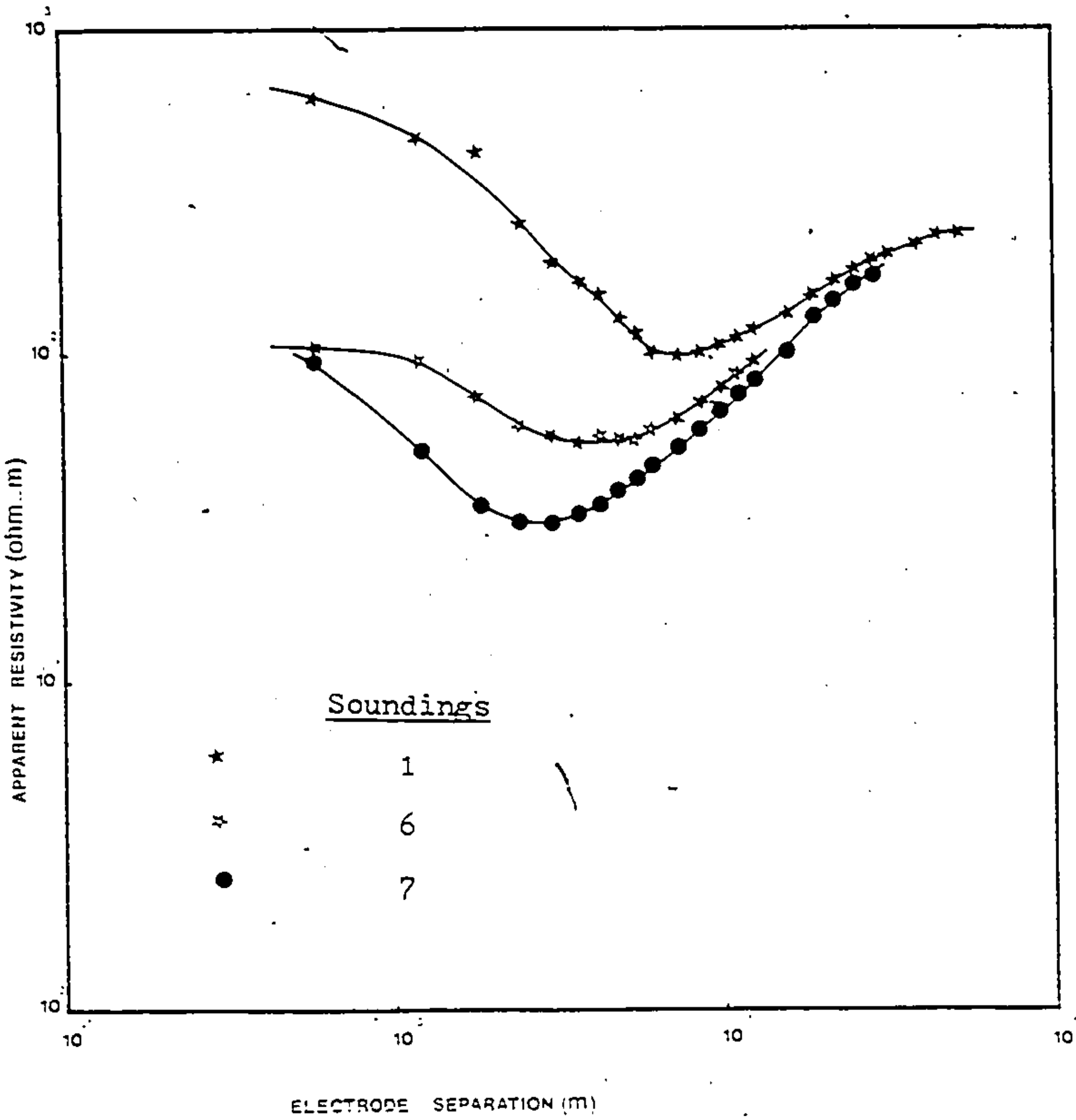
St.	a(m)	18.3	21.3	24.4	27.4	30.5	36.6	42.7	48.8
1	I	100	100	100	100	100	100	100	100
	SP	69.0	57.0	84.0	37.0	-54.0	75.0	-98.0	-63.0
	V	201.0	182.0	189.0	145.0	48.0	164.0	-14.0	11.0
	P_a	151.67	167.57	178.73	186.14	195.33	204.53	225.21	226.75
2	I	100	100	100	100	100	100	100	100
	SP	205.0	153.0	228.0	-11.0	-64.0	71.0	17.0	-132.0
	V	245.0	190.0	260.0	18.0	-35.0	97.0	40.0	-113.0
	P_a	45.96	49.60	49.02	49.98	55.53	59.75	61.66	58.22
3	I	100	100	100	100	100	100	100	100
	SP	-11.0	-36.0	-3.0	-6.0	-54.0	-66.0	-90.0	-70.0
	V	124.0	75.0	89.0	71.0	13.5	-18.5	-51.7	-39.0
	P_a	155.12	148.8	140.95	132.71	129.27	109.16	102.68	94.98
4	I	100	100	100	100	100	100	100	100
	SP	24.0	-16.0	104.0	137.0	77.0	-182.0	27.0	25.0
	V_a	90.0	44.0	161.0	191.0	128.5	-135.0	71.0	66.0
	P	75.84	80.43	87.33	93.07	98.63	108.01	117.97	125.63
5	I	100	100	100	100	100	100	100	100
	SP	-56.0	118.0	235.0	119.0	-12.0	-34.0	110.0	58.5
	V	51.0	221.0	337.0	219.0	82.0	55.0	193.0	136.0
	P_a	122.95	138.07	156.27	172.35	180.02	204.53	222.53	237.47

APPENDIX II-1 cont'd.

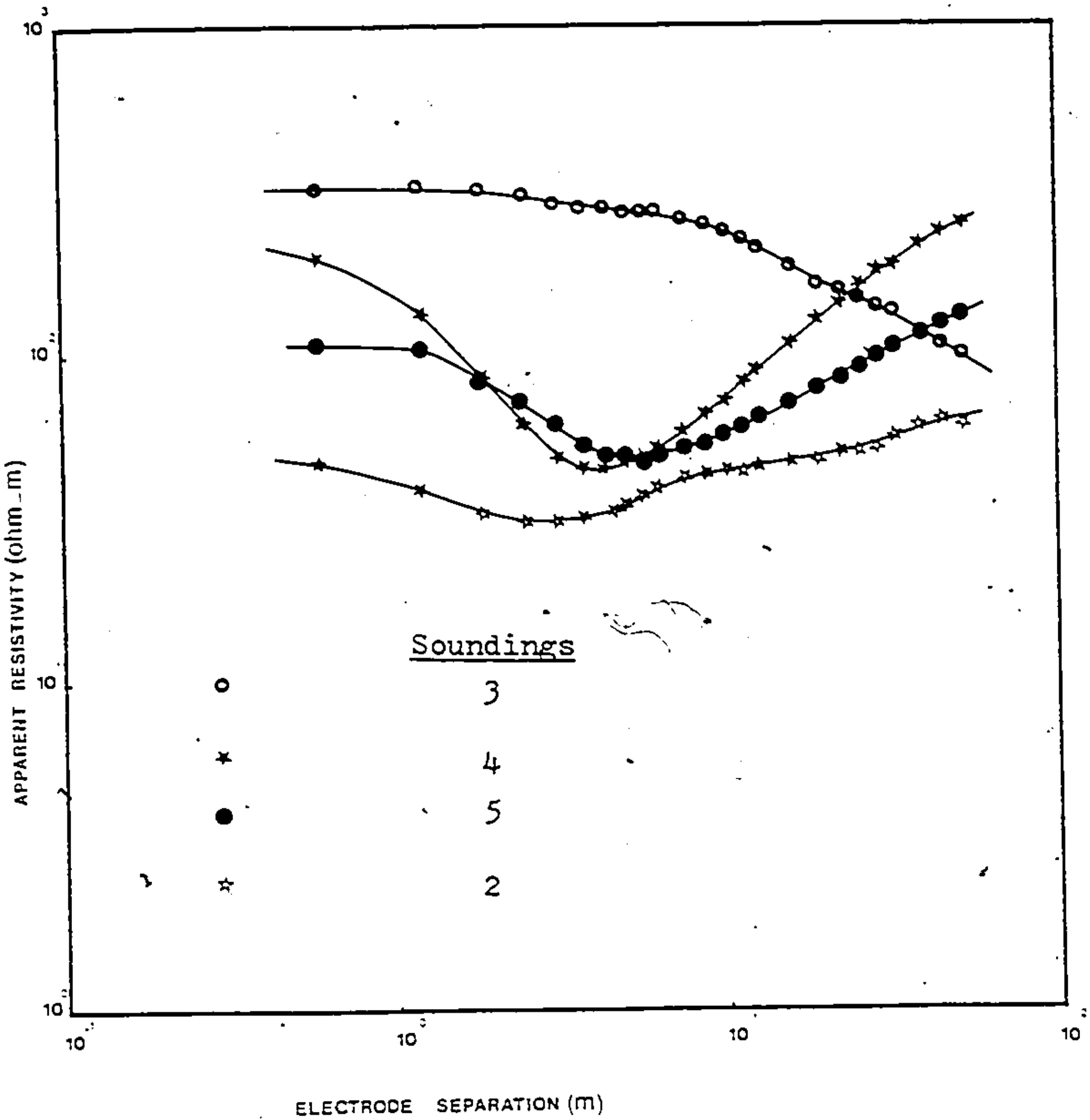
St.	a (m)	0.6	1.2	1.8	2.4	3.0	3.6	4.3	4.9	5.5	6.1	7.3
6	I	100	100	100	100	100	100	100	100	100	100	100
	SP	-80.0	-70.0	20.0	-9.0	140.0	100.0	32.0	-91.0	49.0	1.0	72.0
	V	2640.0	1183.0	655.0	381.0	432.0	333.0	242.0	35.0	207.0	155.0	211.0
	P_a	104.13	95.97	72.96	59.74	55.92	53.54	56.30	55.15	54.46	58.98	63.89
7	I	100	100	100	100	100	100	100	100	100	100	100
	SP	50.0	-222.0	59.0	-77.0	-2.0	-133.0	-11.0	24.0	-156.0	-60.0	-64.0
	V	2530.0	440.0	363.0	124.0	157.0	7.0	-119.0	148.0	-36.0	57.0	49.0
	P_a	94.94	50.70	34.93	30.79	30.45	32.17	34.85	37.99	41.36	44.81	51.94

St.	a (m)	8.5	9.7	11.0	12.2	15.2	18.3	21.3	24.4	27.4	30.5	36.6
6	I	100	100	100	100							
	SP	-1.0	-120.0	67.0	54.0							
	V	131.0	7.0	192.0	177.0							
	P_a	70.78	77.82	86.18	94.22							
7	I	100	100	100	100	100	100	100	100	70	90	
	SP	-34.0	164.0	54.0	32.0	-204.0	25.0	-225.0	-196.5	-300.0	-320.0	
	V	75.0	272.0	161.0	138.0	-101.0	125.0	-129.5	-104.0	-235.5	-241.5	
	P_a	58.45	66.18	73.77	81.20	98.63	114.90	128.02	141.71	158.81	168.10	

APPENDIX II-1 cont'd.



APPENDIX II-1 cont'd.



APPENDIX II-2 Results of Electrical Profiling Survey (Tables).

Station	a (m)	I (mA)	SP* (mV)	V (mV)	P_a (ohm-m)
1	3.05	100	105.0	2270.0	414.62
	6.10	100	-22.0	240.0	100.35
2	3.05	100	-56.0	2154.0	423.24
	6.10	100	21.0	253.0	88.86
3	3.05	50	-75.0	1162.0	473.80
	6.10	80	-4.0	199.0	97.19
4	3.05	100	90.0	1654.0	299.52
	6.10	100	78.0	474.0	151.68
5	3.05	80	-60.0	1210.0	304.02
	6.10	90	-154.0	170.0	137.89
6	3.05	100	76.0	1604.0	292.63
	6.10	100	99.0	347.0	94.99
7	3.05	70	-12.0	354.0	100.13
	6.10	50	-22.0	62.0	64.35
8	3.05	100	42.0	1376.0	255.48
	6.10	100	-68.0	137.0	78.52
9	3.05	50	160.0	2910.0	1053.31
	6.10	40	-54.0	290.0	329.40
10	3.05	60	1.0	3341.0	1066.08
	6.10	50	-34.0	360.0	301.82
11	3.05	60	-145.0	593.0	235.56
	6.10	50	48.0	173.0	95.75
12	3.05	100	14.0	585.0	109.35
	6.10	100	5.0	176.0	65.50
13	3.05	90	-40.0	1004.0	222.15
	6.10	70	-40.0	124.0	89.74

* SP value has been subtracted from V prior to calculating P_a

APPENDIX II-2 cont'd.

14	3.05	100	-50.0	596.0	123.72
	6.10	100	28.0	192.0	62.81
15	3.05	100	3.0	201.0	37.92
	6.10	100	9.0	99.0	34.47
16	3.05	100	10.0	224.0	40.98
	6.10	100	-18.0	68.0	32.94
17	3.05	100	-22.0	224.0	47.11
	6.10	100	-60.0	49.0	41.75
18	3.05	100	2.0	326.0	62.05
	6.10	100	38.0	165.0	48.64
19	3.05	100	-23.0	423.0	85.41
	6.10	100	74.0	218.0	55.15
20	3.05	100	-60.0	383.0	84.84
	6.10	100	-26.0	138.0	62.81
21	3.05	100	-52.0	657.0	135.78
	6.10	100	-83.0	168.0	96.14
22	3.05	100	42.0	502.0	88.09
	6.10	100	-48.0	105.0	58.60
23	3.05	100	-3.0	393.0	75.84
	6.10	100	-30.0	126.0	59.75
24	3.05	100	-17.0	317.0	63.96
	6.10	100	-62.0	76.0	52.86
25	3.05	100	-20.0	2270.0	438.56
	6.10	100	255.0	660.0	155.12
26	3.05	100	90.0	3200.0	595.60
	6.10	100	160.0	1520.0	520.91
27	3.05	100	44.0	1205.0	222.34
	6.10	100	-2.0	494.0	189.98
28	1.80	100	18.0	595.0	66.30
	3.05	100	-252.0	100.0	67.41
29	1.80	100	10.0	3600.0	412.51
	3.05	100	-53.0	1346.0	267.92

APPENDIX II-2 cont'd.

30	1.80	100	-90.0	2910.0	344.72
	3.05	100	-127.0	1094.0	233.84
31	1.80	100	140.0	7300.0	822.73
	3.05	100	-60.0	2700.0	532.40
32	1.80	100	111.0	792.0	78.25
	3.05	100	-66.0	489.0	106.29
33	1.80	100	9.0	257.0	28.50
	3.05	100	125.0	295.0	32.56
34	1.80	100	55.0	487.0	49.64
	3.05	100	7.0	146.0	26.62
35	1.80	100	-174.0	-32.0	16.32
	3.05	100	295.0	473.0	34.09
36	1.80	100	-167.0	176.0	39.41
	3.05	100	62.0	252.0	36.39
37	1.80	100	-60.0	450.0	58.60
	3.05	100	140.0	413.0	52.28
38	1.80				
	3.05	100	-111.0	490.0	115.10
39	1.80	100	20.0	287.0	30.68
	3.05	100	-4.0	140.0	27.58
40	1.80	100	-40.0	146.0	21.37
	3.05	100	-54.0	46.0	19.15
41	1.80	90	-10.0	1138.0	146.57
	3.05	80	-93.0	501.0	142.20
42	1.80	100	40.0	3070.0	348.17
	3.05	100	160.0	2280.0	406.00
43	1.80	100	-127.0	892.0	117.09
	3.05	100	112.0	622.0	97.67
44	1.80	100	-50.0	3700.0	430.90
	3.05	100	-78.0	1581.0	317.72
45	1.80	100	4.0	390.0	44.35
	3.05	100	-21.0	201.0	42.51

APPENDIX II-2 cont'd.

46	1.80	100	81.0	218.0	15.74
	3.05	100	80.0	157.0	14.75
47	1.80	100	61.0	170.0	12.52
	3.05	100	92.0	218.0	24.13
48	1.80	100	-79.0	6[illegible]0.0	86.06
	3.05	100	-87.0	1[illegible]0.0	37.73
49	1.80	70	-170.0	3400.0	586.02
	3.05	100	-41.0	350.0	74.88
50	1.80	80	-69.0	212.0	40.36
	3.05	100	60.0	288.0	43.66
51	1.80	100	-10.0	1160.0	134.44
	3.05	70	-114.0	9.0	33.65
52	1.80	100	-166.0	262.0	49.18
	3.05	100	-176.0	87.0	50.37
53	1.80	100	-6.0	301.0	35.28
	3.05	100	82.0	278.0	37.54
54	1.80				
	3.05	100	-37.0	242.0	53.43
55	1.80	100	-10.0	420.0	49.41
	3.05	100	19.0	277.0	49.41
56	1.80				
	3.05	80	57.0	219.0	38.78
57	1.80				
	3.05	100	-38.0	136.0	33.32
58	1.8				
	3.05	100	-21.0	163.0	35.24
59	1.80	60	-55.0	402	87.52
	3.05	100	86.0	328.0	46.34
60	1.80				
	3.05	50	-23.0	213.0	90.39
61	3.05	100	77.0	538.0	88.29
	6.10	100	40.0	225.0	70.86

APPENDIX II-2 cont'd.

62	3.05	100	-94.0	622.0	137.12
	6.10				
63	3.05	60	-8.0	185.0	61.60
	6.10				
64	3.05	100	-41.0	495.0	102.65
	6.10	100	-179.0	-21.0	60.52
65	3.05	100	94.0	601.0	97.10
	6.10	100	124.0	247.0	47.11
66	3.05	100	-100.0	1935.0	389.73
	6.10				
67	1.80	100	-140.0	664.0	92.38
	3.05	100	-1.0	401.0	76.99
68	1.80	100	65.0	1107.0	119.73
	3.05	100	55.0	692.0	121.99
69	3.05	100	-41.0	242.0	54.20
	6.10	100	8.0	131.0	47.11
70	3.05	100	9.0	523.0	98.44
	6.10	100	-27.0	133.0	61.28
71	3.05	100	145.0	658.0	98.24
	6.10	100	135.0	327.0	73.54
72	3.05	100	-32.0	508.0	103.42
	6.10	100	38.0	192.0	58.98
73	3.05	70	10,0	4500.0	1228.41
	6.10	80	-46.0	1930.0	946.07
74	3.05	100	30.0	5460.0	1039.91
	6.10	100	100.0	2700.0	995.86
75	3.05	100	20.0	7700.0	1470.8
	6.10	90	90.0	3370.0	1395.91
76	3.05	60	50.0	3720.0	1171.41
	6.10	60	24.0	1502.0	943.51
77	3.05	50	-10.0	2860.0	1099.28
	6.10	50	-3.0	692.0	532.40

APPENDIX II-2 cont'd.

78	3.05	100	-13.0	1930.0	372.11
	6.10	100	-11.0	845.0	327.87
79	3.05	100	6.0	1132.0	215.64
	6.10	100	49.0	422.0	142.87
80	3.05	100	43.0	1863.0	348.55
	6.10	100	-33.0	932.0	369.62
81	3.05	100	83.0	1453.0	262.37
	6.10	100	-18.0	960.0	374.60
82	3.05	100	3.0	1139.0	217.56
	6.10	100	1.0	613.0	234.41
83	3.05	100	90.0	2390.0	440.48
	6.10	100	-12.0	940.0	364.64
84	3.05	100	40.0	3100.0	586.03
	6.10	100	-55.0	930.0	377.28
85	3.05	100	180.0	2200.0	386.85
	6.10	100	188.0	651.0	177.34
86	3.05	100	110.0	2490.0	455.80
	6.10	100	95.0	1058.0	368.85
87	3.05	100	40.0	1420.0	264.29
	6.10	100	-122.0	377.0	191.13
88	3.05	100	130.0	2720.0	496.01
	6.10	100	-30.0	890.0	352.38
89	3.05	100	90.0	3700.0	691.36
	6.10	100	80.0	1190.0	425.16
90	3.05	100	70.0	3070.0	574.53
	6.10	100	16.0	986.0	371.53
91	3.05	100	90.0	3640.0	679.87
	6.10	100	12.0	1070.0	405.24
92	3.05	80	80.0	3630.0	849.83
	6.10	100	45.0	1630.0	607.09
93	3.05	100	30.0	4760.0	905.85
	6.10	90	-27.0	1580.0	683.91

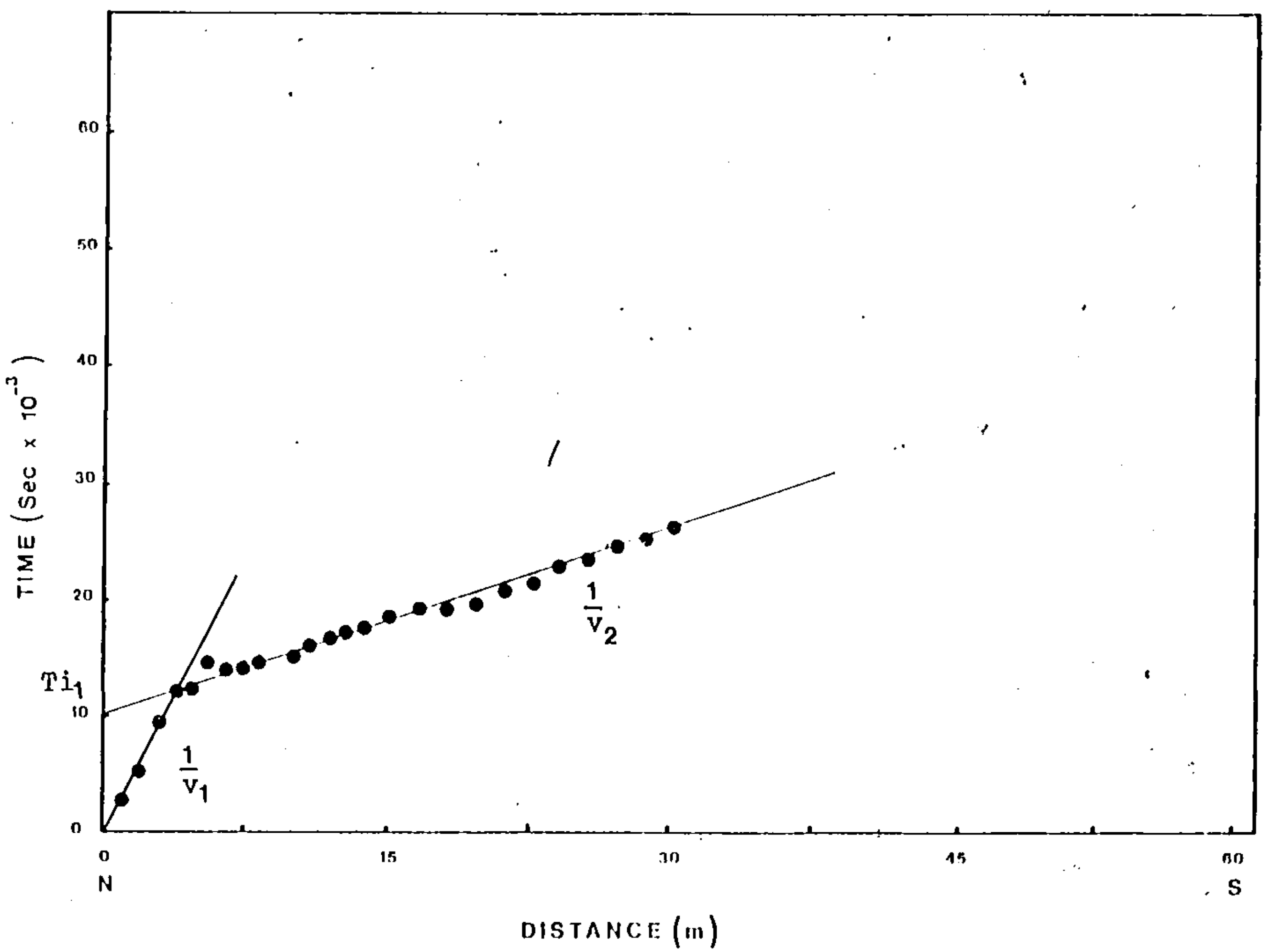
APPENDIX II-2 cont'd.

94	3.05	100	120.0	3630.0	672.21
	6.10	100	115.0	1884.0	677.57
95	3.05	100	110.0	4230.0	789.03
	6.10	100	32.0	1810.0	681.02
96	3.05	100	30.0	3300.0	626.24
	6.10	100	-22.0	1550.0	602.11
97	3.05	100	100.0	2760.0	509.42
	6.10	100	93.0	1405.0	502.53
98	1.80	100	-123.0	132.0	29.30
	3.05	100	-50.0	95.0	27.77
99	1.80	100	87.0	1436.0	153.86
	3.05	100	65.0	436.0	71.05
100	1.80	100	160.0	2450.0	263.14
	3.05	100	18.0	983.0	184.81
101	1.80	100	-53.0	988.0	119.62
	3.05	100	-3.0	351.0	67.79
102	1.80	100	63.0	686.0	71.59
103	1.80	100	-51.0	657.0	81.35
104	1.80	100	-63.0	629.0	79.51
105	1.80	100	11.0	711.0	80.43
106	1.80	100	12.0	722.0	81.58
107	1.80	100	22.0	405.0	44.01
108	1.80	100	-21.0	364.0	44.24
109	1.80	100	61.0	1024.0	110.65
110	1.80	100	-70.0	454.0	60.21
111	1.80	100	-122.0	1515.0	188.10

APPENDIX II-3 Results of Seismic Refraction Survey (Tables and Plots).

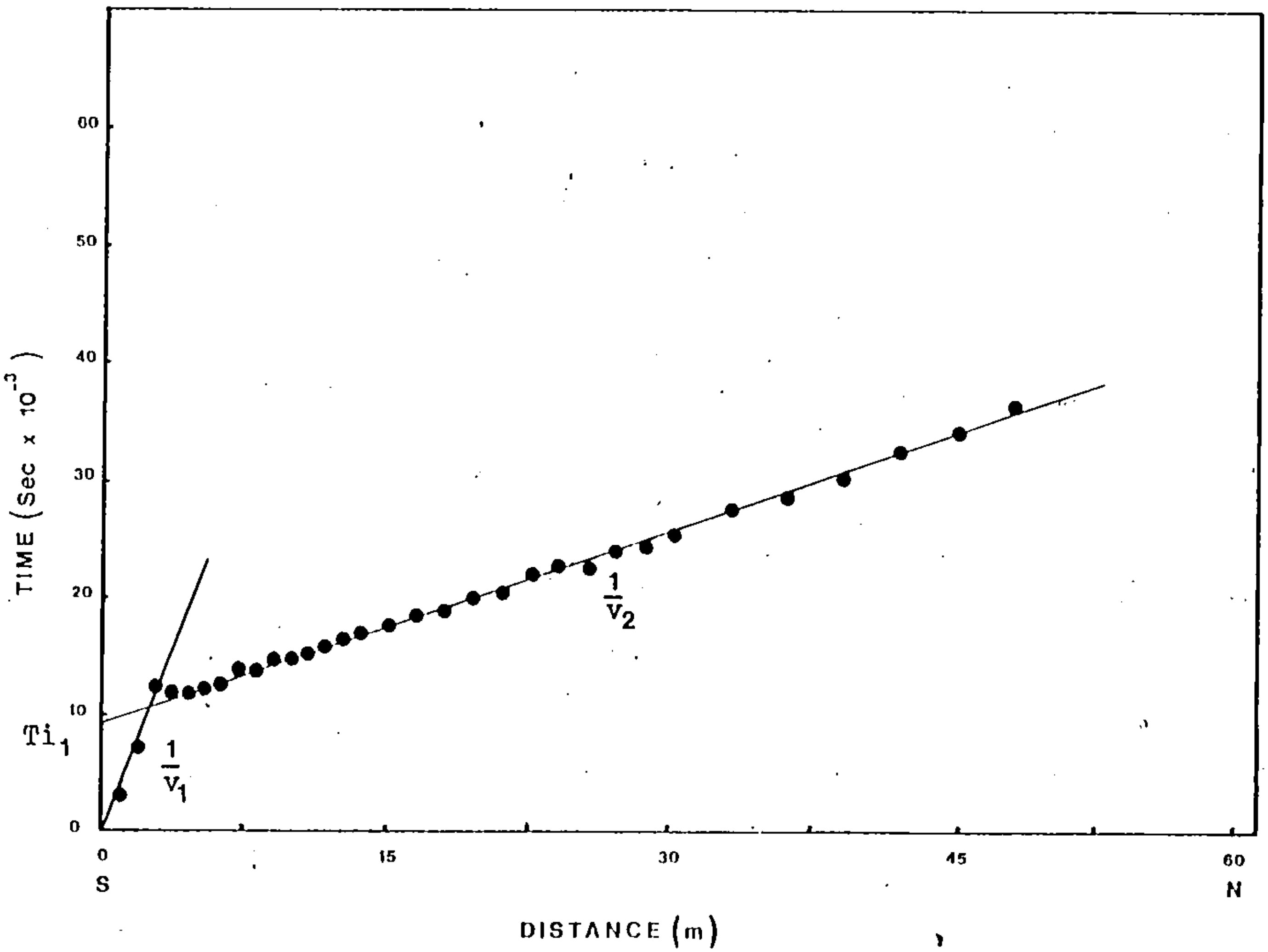
Distance (X) (m)	Time ($s \times 10^{-3}$)		Distance (X) (m)	Time ($s \times 10^{-3}$)	
	Seismic St.1	Seismic St.4		Seismic St.1	Seismic St.4
0.9	2.60	2.97	16.8	19.43	18.69
1.8	5.12	7.03	18.3	19.24	19.00
2.7	9.20	12.47	19.8	19.68	20.38
3.6	12.00	11.88	21.3	21.17	20.69
4.6	12.43	11.58	22.9	21.90	22.20
5.5	14.80	12.34	24.4	23.34	22.95
6.4	14.21	12.71	25.9	23.71	22.85
7.3	14.31	13.90	27.4	25.07	24.33
8.2	14.55	13.64	28.9	25.51	24.75
9.1	15.31	14.77	30.5	26.60	25.84
10.1	15.05	14.90	33.5		28.03
11.0	16.26	15.25	36.6		29.00
11.9	17.02	15.65	39.6		30.70
12.8	17.51	16.53	42.7		32.96
13.7	17.90	17.02	45.7		34.83
15.2	18.63	17.85	48.8		37.18

APPENDIX II-3 cont'd.



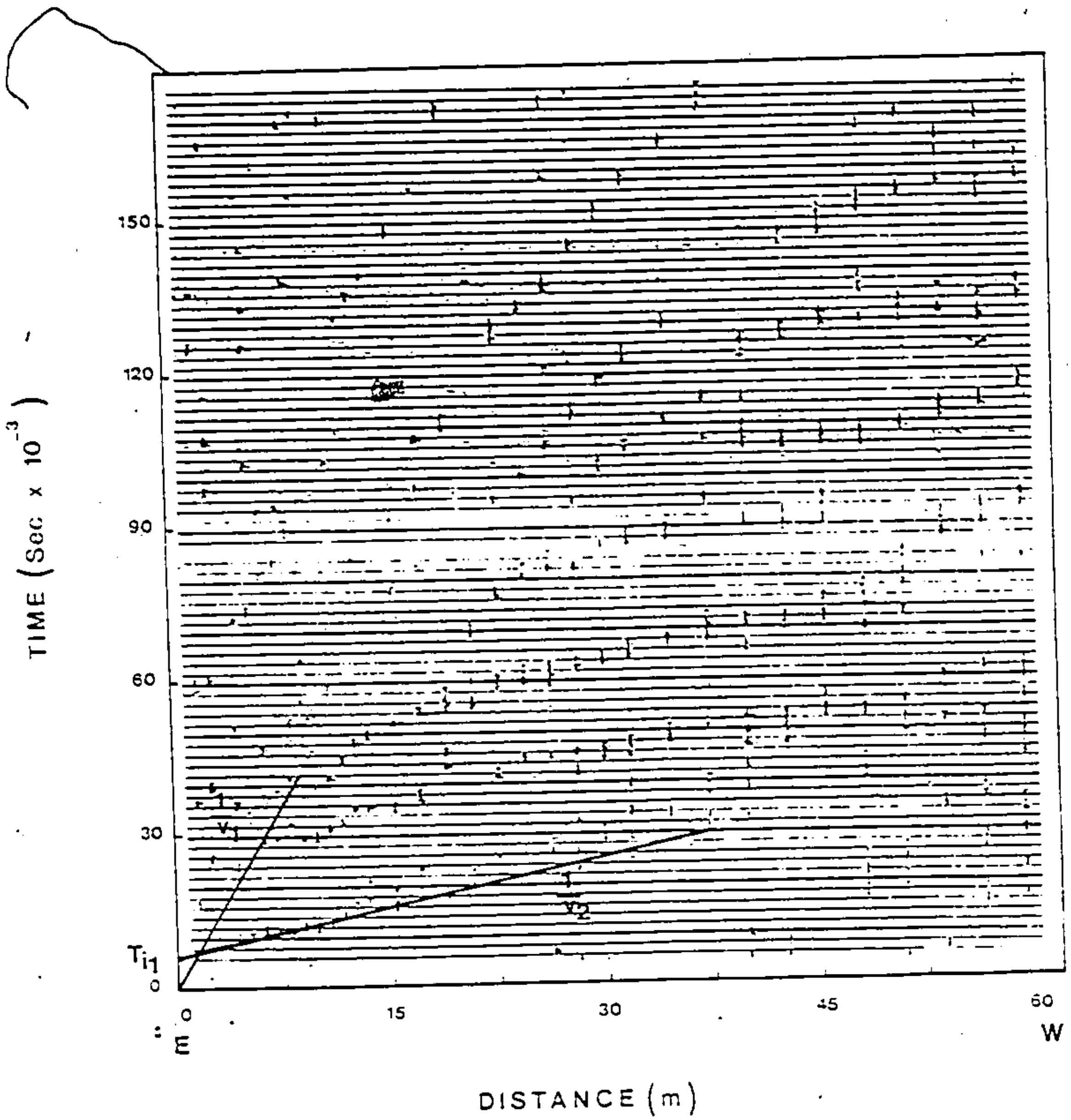
Time-distance curve(Seismic Profile 1)

APPENDIX II-3 cont'd.



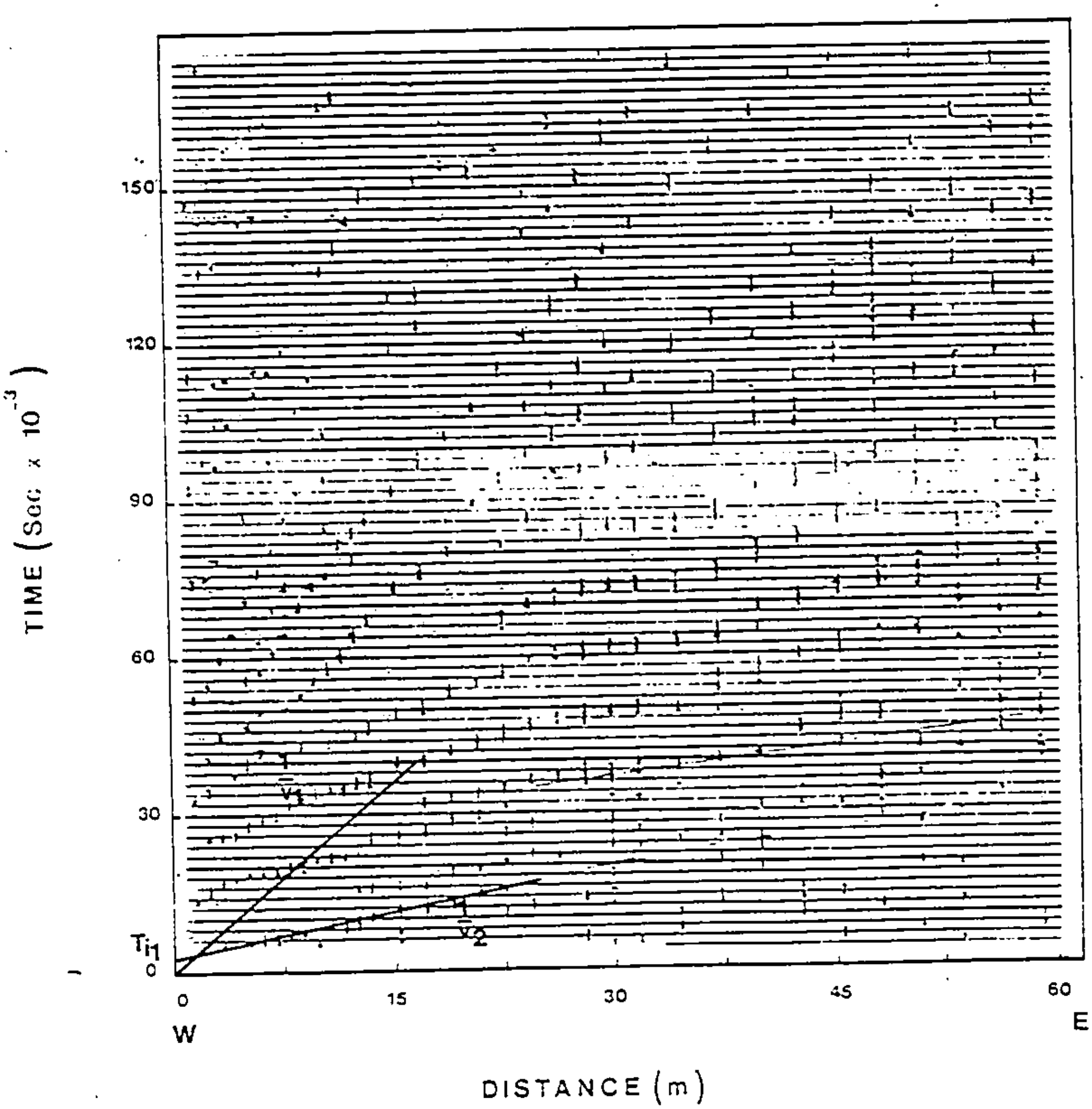
Time-distance curve(Seismic Profile 4)

APPENDIX II-3 cont'd.



Time-distance curve (seismic Profile 5)

APPENDIX II-3 cont'd.



Time-distance curve (Seismic Profile 7)

APPENDIX II-4 Electrical Conductivity Measurements.

Site	Conductivity (µS/cm) at 25°C	Date Day	Month	Year
1	811	03	10	1982
2	755			
3	722			
4	598			
5	1240			
6	1040	"	"	"
7	867			
8	620			
9	871			
10	1101			
11	819	"	"	"
12	1066			
13	564			
14	1268			
15	609			
16	905			
17	495	"	"	"
18	1407	05	11	1982
19	990	03	10	"
20	683	"	"	"
21	750	"	"	"
	725	05	11	"
22	1473	03	10	"
23	1549			
24	2268			
	1449			
25	1410	"	"	"

APPENDIX II-4 cont'd.

26	445	03	10	1982
	414			
	516			
27	604			
	578			
	556			
28	584	"	"	"
	549			
	550			
29	576	"	"	"
	534			
	565			
	527			
30	1288	"	"	"
	615	05	11	1982
	596	03	10	"
31	387			
	550			
32	658			
	799			
	589	"	"	"
33	608			
	593			
34	446			
	388			
35	835	"	"	"
36	385			
	393			
37	398			
	397			
38	1201	05	11	1982
39	1368	"	"	"

APPENDIX II-4 cont'd.

40	2505	05	11	1982
41	2474			
42	5931			
43	429			
44	378	"	"	"
45	408			
46	413			
47	435	"	"	"

APPENDIX II-5 Selected borehole logs for the Essex County Landfill No. 2.

Well	Elevation (m.a.s.l.)	Log (thickness in m)	Reference
BH-6	-------	Compact light brown fine to medium sand with some silt 1.7, compact to dense broyn sand with occasional fine to medium gravel 1.0, hard grey silty clay with some sand and occasional gravel 2.6.	Golder Associates (1969b)
BH-7	-------	Compact light brown fine to medium sand with some silt and occasional gravel 1.4, dense brown sand with some silt 1.0, very stiff grey silty clay with some sand and occasional gravel 0.9.	Golder Associates (1969b)
BH-8	-------	Loose to compact fine to medium sand with some silt 1.5, very loose light brown sand and gravel 2.1, compact to dense brown sand with some silt 1.2, hard grey silty clay 0.7.	Golder Associates (1969b)

APPENDIX II-5 cont'd.

Well	Elevation	Log (thickness in m)	Reference
Shallow-well 1*	--------	Dense sand 2.4, hard silty clay 2.2.	De Calume, personal communication
21-2278	213.4	Yellow medium sand 0.9, gravel 5.8, grey clay 29.9, quick sand 9.7, white and red limestone** 47.3.	Ontario Ministry of Environment(OME), 1977
21-2279	213.4	Yellow medium sand 0.9, gravel 5.8, grey clay 14.6, gravel 1.6, hardpan 8.5, quick sand 15.5, white to brown limestone 21.7.	OME, 1977
21-2281	213.4	Top soil 0.9, grey gravel 5.8, grey clay 13.1, hardpan 1.2, gravel 1.9.	OME, 1977
21-2282	213.4	Medium sand and clay 47.5, brown and white limestone 43.9.	OME, 1977

* Location of the well is shown in Figure 16.

** Sanford (1969) indicated that the bedrock at Essex County Landfill No. 2 is dolomite.

APPENDIX II-5 cont'd.

Well	Elevation (m.a.s.l.)	Log (thickness in m)	Reference
21-2283	213.4	Medium sand and gravel 6.4, fine sand and clay 12.8, medium sand and gravel 2.1.	OME, 1977
21-3321	204.2	Brown medium sand 9.7, grey clay 7.1, brown medium sand and gravel 1.5, gravel 4.6, medium sand 0.6.	OME, 1977
21-3646	198.1	Sand 3.6, grey clay 14.7, sand 1.5, clay 1.5, sand 18.6, gravel 1.2, grey limestone 0.9, gravel and fine sand 1.3.	OME, 1977.
21-3914	213.4	Top soil 0.6, sand 4.0, clay 6.0, black sand and gravel 36.3, grey to brown limestone 33.9.	OME, 1977

APPENDIX II-6 Results of Levelling Survey.

Site	Elevation (m.a.s.l.)	Site	Elevation (m.a.s.l.)
1	206.8	25	216.9
2	210.6	26	218.0
3	213.8	27	218.1
4	214.5	28	218.4
5	216.7	29	219.9
6	217.9	30	220.6
7	219.2	31	220.7
8	219.6	32	220.4
9	220.7	33	211.4
10	217.0	34	211.8
11	216.1	35	212.4
12	213.0	36	213.5
13	212.6	37	213.2
14	211.3	38	213.0
15	212.5	39	212.5
16	212.5	40	212.2
17	212.6	41	211.1
18	212.9	42	206.0
19	213.3	43	208.6
20	214.2	44	208.0
21	214.7	45	207.0
22	215.4	46	207.6
23	212.8	47	206.5
24	215.8		

APPENDIX III

WINDSOR WEST END LANDFILL

APPENDIX III-1 Results of Electrical Sounding Survey

APPENDIX III-2 Results of Electrical Profiling Survey

APPENDIX III-3 Results of Seismic Refraction Survey

APPENDIX III-4 Electrical Conductivity Measurements

APPENDIX III-5 Selected Borehole Logs

APPENDIX III-1 Results of Electrical Sounding Survey (Tables and Plots).

St.	a(m)	0.6	1.2	1.8	2.4	3.0	3.6	4.3	4.9
1	I	100	100	100	100	100	100	100	100
	SP*	-70.0	-80.0	-18.0	-10.0	20.0	-10.0	-5.0	1.0
	V	4150.0	1850.0	877.0	447.0	305.0	172.0	134.0	106.0
	P_a	161.54	147.82	102.84	70.00	54.58	41.82	37.26	32.17
2	I	100	100	100	100	100	100	100	100
	SP	-10.0	17.0	16.0	30.0	-1.0	80.0	26.0	72.0
	V	845.0	288.0	147.0	125.0	76.4	145.3	82.6	124.3
	P_a	32.73	20.75	15.05	14.55	14.82	15.00	15.17	16.02
3	I	100	100	100	100	100	100	100	100
	SP	-30.0	-40.0	-60.0	-4.0	-8.0	-5.0	-2.0	-7.8
	V	9460.0	2800.0	970.0	463.0	201.0	109.0	78.3	52.6
	P_a	361.04	217.53	117.89	71.53	40.02	26.19	21.53	18.51
4	I	100	100	100	100	100	100	100	100
	SP	40.0	-82.0	25.0	130.0	100.0	94.0	-79.0	22.0
	V	1134.0	165.0	129.0	188.0	143.0	130.0	-48.4	50.1
	P_a	41.88	18.92	11.95	8.88	8.23	8.41	8.26	8.60
5	I	100	100	100	100	100	100	100	100
	SP	171.0	-67.0	-96.0	-80.0	-65.0	22.6	65.0	-43.0
	V	812.0	285.0	155.0	119.0	93.0	151.2	163.0	36.4
	P_a	24.54	26.96	28.84	30.48	30.26	29.55	26.27	24.33

* SP value has been subtracted from V prior to caculating P_a

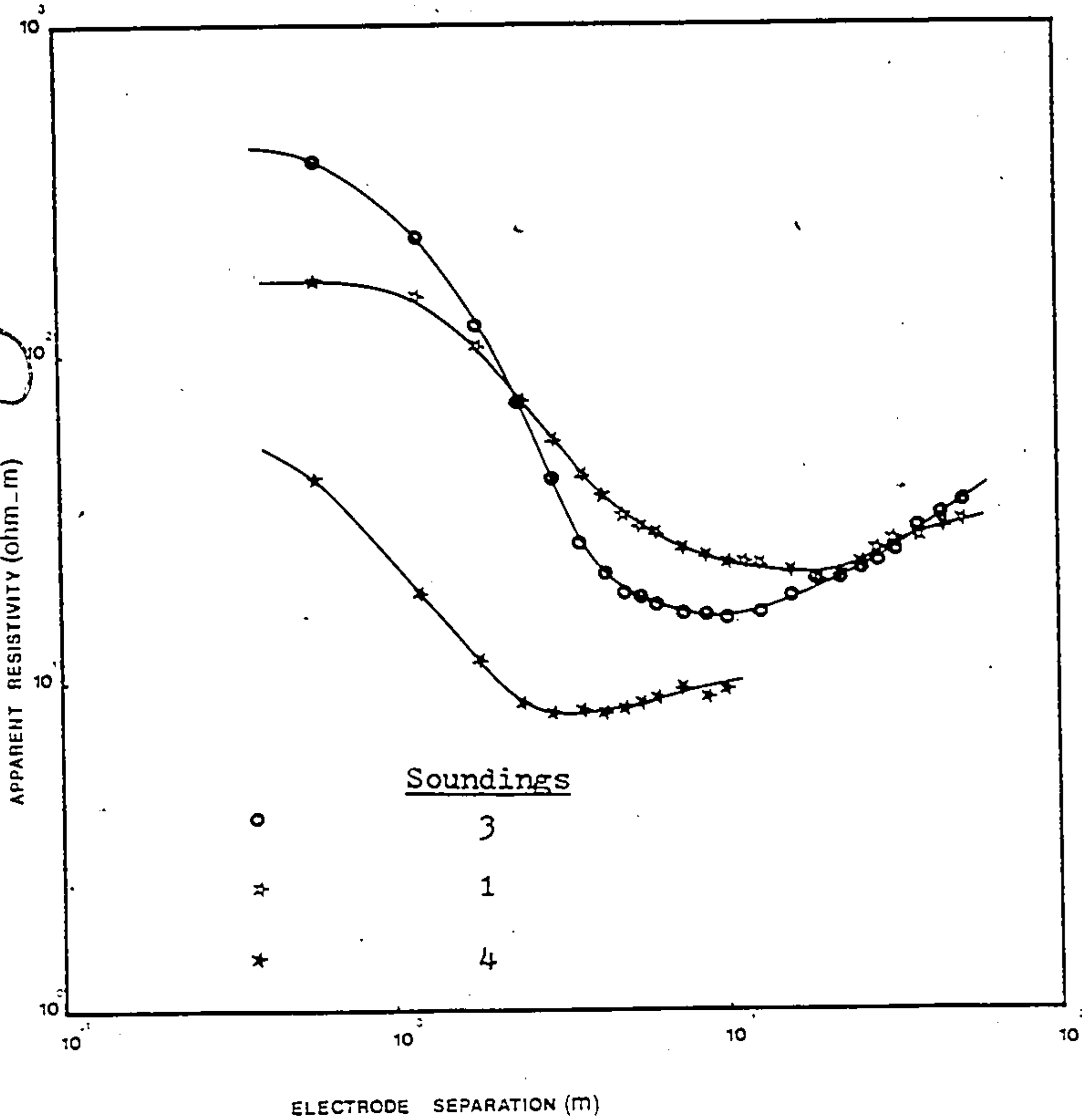
APPENDIX III-1 cont'd.

St.	a(m)	5.5	6.1	7.3	8.5	9.7	11.0	12.2	15.2
1	I	100	100	100	100	100	100	100	100
	SP	30.5	-0.5	-20.5	-20.5	-11.0	7.0	17.0	29.0
	V	116.0	73.2	35.3	24.0	27.0	41.0	47.0	52.0
	P_a	29.47	28.23	25.64	23.86	23.28	23.44	22.98	22.02
2	I	100	100	100	100	100	100	100	100
	SP	80.0	60.2	107.2	182.0	51.0	120.0	60.5	-13.0
	V	126.7	102.2	143.8	213.0	78.8	144.6	82.5	5.0
	P_a	16.09	16.09	16.82	16.62	17.03	16.96	16.85	17.23
3	I	100	100	100	100	100	100	100	100
	SP	4.0	16.5	29.0	62.0	1.0	43.0	35.7	11.5
	V	57.1	60.7	63.7	92.2	26.5	67.5	57.1	30.5
	P_a	18.30	16.93	15.95	16.19	15.59	16.89	16.39	18.19
4	I	100	100	100	100	100			
	SP	64.0	150.0	79.5	94.0	223.0			
	V	90.2	174.0	101.0	111.4	239.0			
	P_a	9.03	9.19	9.88	9.33	9.80			
5	I	100	100	100	100	100	100	100	100
	SP	-63.4	-112.0	-131.5	46.6	253.0	-49.3	-31.0	-332.0
	V	-3.8	-62.7	-94.3	75.9	278.0	-27.7	-10.3	-316.0
	P_a	20.54	18.88	17.09	15.71	15.32	14.89	15.86	15.32

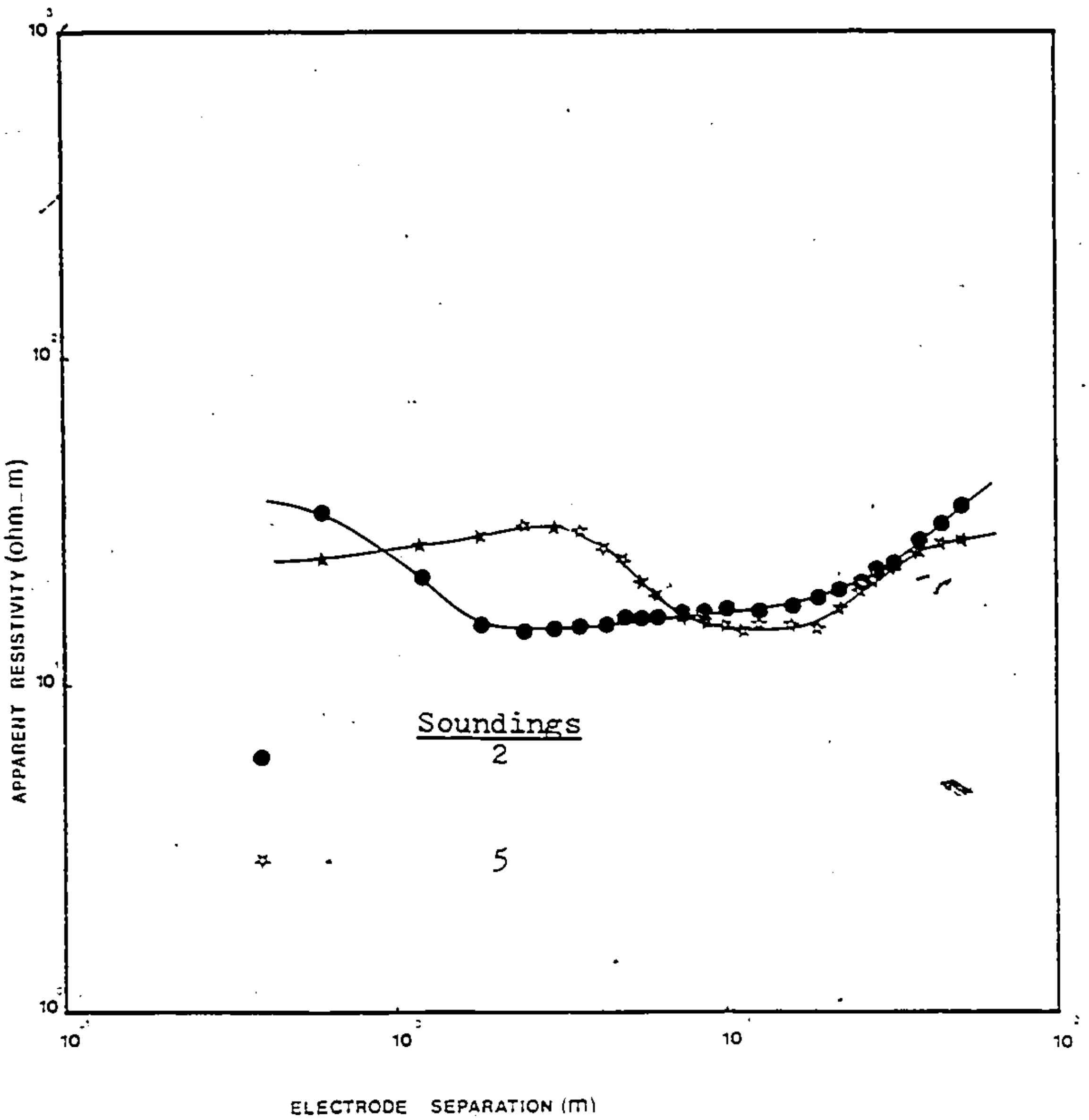
APPENDIX III-1 cont'd.

St.	a(m)	18.3	21.3	24.4	27.4	30.5	36.6	42.7	48.8
1	I	100	100	100	100	100	100	100	100
	SP	8.6	28.5	-23.0	100.0	171.0	174.0	237.0	312.0
	V	26.3	44.3	-8.0	115.0	185.0	186.0	248.0	322.0
	P_a	20.33	21.18	22.97	25.85	26.81	27.57	29.49	30.64
2	I	100	100	100	100	100	100	100	100
	SP	140.5	180.0	190.0	223.0	121.0	82.0	171.8	142.0
	V	156.4	194.6	203.0	236.0	133.0	94.0	183.0	153.0
	P_a	18.27	19.57	19.91	22.40	22.98	27.57	30.03	34.56
3	I	100	100	100	100	100	100	100	100
	SP	32.0	-76.5	-115.0	-211.0	-176.5	23.0	-103.0	-5.0
	V	49.7	-61.5	-101.0	-225.0	-163.0	33.4	-91.0	6.5
	P_a	20.33	20.11	21.45	23.26	24.89	28.72	32.17	35.33
4	I								
	SP								
	V								
	P_a								
5	I	100	100	100	100	100	100	100	100
	SP	-343.0	62.0	1.9	-44.0	64.0	-383.0	-460.0	-194.0
	V	-330.0	75.0	14.4	-32.0	76.0	-372.0	-450.0	-185.0
	P_a	14.94	17.42	19.15	20.68	22.98	25.28	26.81	29.58

APPENDIX III-1 cont'd.



APPENDIX III-1 cont'd.



APPENDIX III-2 Results of Electrical Profiling Survey (Tables).

Station	a (m)	I (mA)	SP* (mV)	V (mV)	P_a (ohm-m)
1	3.05	100	21.0	244.0	42.71
	4.60	100	2.0	136.0	38.49
2	3.05	100	-30.5	92.0	23.46
	4.60	100	89.0	171.0	23.55
3	3.05	100	-15.5	64.0	15.22
	4.60	100	37.0	98.0	17.52
4	3.05	100	-50.0	38.0	16.85
	4.60	100	-10.0	52.0	17.81
5	3.05	100	47.0	158.0	21.25
	4.60	100	-43.0	21.0	18.38
6	3.05	100	-195.0	-84.0	21.25
	4.60	100	13.0	81.0	19.53
7	3.05	100	53.0	231.0	34.09
	4.60	100	44.0	156.0	32.17
8	3.05	100	-16.0	132.0	28.34
	4.60	100	10.0	110.0	28.73
9	3.05	100	-120.0	37.0	30.06
	4.6	100	-60.0	40.0	28.73
10	3.05	100	49.0	213.0	31.40
	4.60	100	-24.0	91.0	33.03
11	3.05	100	-1.0	146.0	28.15
	4.60	100	-17.0	74.0	26.14
12	3.05	100	-155.0	85.0	45.96
	4.60	100	70.0	145.0	21.54
13	3.05	100	98.0	578.0	91.92
	4.60	100	25.0	227.0	58.03

* SP value has been subtracted from V prior to calculating P_a

APPENDIX III-2 cont'd.

14	3.05	100	-43.0	287.0	63.20
	4.60	100	-102.0	-29.0	20.97
15	3.05	100	185.0	550.0	69.90
	4.60	100	-11.0	128.0	39.93
16	3.05	100	5.0	420.0	79.48
	4.60	100	77.0	253.0	50.56
17	3.05	100	175.0	302.0	24.32
	4.60	100	-30.0	38.0	19.53
18	3.05	100	32.0	216.0	35.24
	4.60	100	90.0	192.0	29.30
19	3.05	100	8.0	140.0	25.28
	4.60	100	91.0	183.0	26.43
20	3.05	100	5.0	115.0	21.07
	4.60	100	113.0	193.0	22.98
21	3.05	100	-5.0	946.0	182.12
	4.60	100	-15.0	298.0	91.43
22	3.05				
	4.60	100	-24.0	499.0	150.24
23	3.05	100	40.0	2710.0	511.34
	4.60	100	-4.0	946.0	272.90
24	3.05	100	24.0	982.0	183.47
	4.60	100	-60.0	81.0	40.50
25	3.05	100	49.0	1535.0	284.59
	4.60	100	6.0	406.0	114.90
26	3.05	70	117.0	606.0	133.78
	4.60	100	-45.0	215.0	74.69
27	3.05				
	4.60	100	272.5	-48.5	64.37
28	3.05	80	-11.0	356.0	87.86
	4.60	100	-5.5	150.5	44.81
29	3.05				
	4.60	100	115.0	226.0	31.89

APPENDIX III-2 cont'd.

30	3.05	100	40.0	233.0	36.96
	4.60	100	-82.0	13.0	27.29
31	3.05				
	4.60	100	-15.0	38.5	15.37
32	3.05	90	19.0	142.7	26.32
	4.60	100	-18.0	40.0	16.66
33	3.05				
	4.60	100	165.0	215.0	14.36
34	3.05	100	67.0	142.5	14.46
	4.60	100	-105.0	-55.0	14.36
35	3.05				
	4.60	100	-31.0	12.5	12.50
36	3.05	100	-3.5	57.3	11.64
	4.60	100	92.0	128.0	10.34
37	3.05				
	4.60	100	228.0	205.0	6.61
38	3.05	100	16.0	75.0	11.30
	4.60	100	130.0	162.0	9.19
39	3.05				
	4.60	100	-91.0	-67.5	6.75
40	3.05	100	74.0	138.0	12.26
	4.60	100	12.0	48.5	10.48
41	3.05	100	-121.0	-76.5	8.52
	4.60	100	-82.5	-53.5	8.33
42	3.05	100	64.0	322.0	49.41
	4.60	100	40.0	124.0	24.13
43	3.05	70	40.0	1240.0	328.30
	4.60	70	22.5	170.0	60.53
44	3.05				
	4.60	100	141.0	276.0	38.78
45	3.05	100	-61.0	158.0	41.94
	4.60	100	5.0	137.0	37.92

APPENDIX III-2 cont'd.

46	3.05	100	1.0	164.0	31.22
	4.60	100	-35.0	82.5	33.75
47	3.05	100	22.0	212.0	36.39
	4.60	100	-18.4	60.0	22.52
48	3.05				
	4.60	100	-11.0	198.0	60.04
49	3.05				
	4.60	100	10.0	180.0	48.83
50	3.05				
	4.60	100	37.0	120.0	23.84
51	3.05				
	4.60	100	70.0	151.0	23.27
52	3.05				
	4.60	100	73.0	206.0	38.21
53	3.05				
	4.60	100	-48.0	470.0	148.80
54	3.05				
	4.60	100	-90.0	286.0	108.01
55	3.05				
	4.60	100	-88.0	110.0	56.88
56	3.05				
	4.60	100	-11.0	4.0	4.31
57	3.05	100	-51.0	-8.0	8.23
	4.60	100	-43.0	-10.0	9.48
58	3.05	100	103.0	148.0	8.62
	4.60	100	-53.0	-23.0	8.62
59	3.05	100	-116.0	-107.0	1.72
	4.60	100	-14.0	5.5	2.44
60	3.05	100	-26.0	37.0	12.06
	4.60	100	6.0	48.0	12.06
61	3.05	100	16.5	23.5	1.34
	4.60	100	-84.5	-79.0	1.58

APPENDIX III-2 cont'd.

62	3.05	100	-1.0	32.0	6.32
	4.60	100	-50.0	-25.0	7.18
63	3.05	100	113.0	179.0	12.64
	4.60	100	40.0	85.0	12.93
64	3.05	100	-16.0	516.0	101.88
	4.60	100	-30.0	127.0	45.10
65	3.05	100	40.0	155.0	22.02
	4.60	100	55.0	127.0	20.68
66	3.05				
	4.60	100	-49.0	-30.0	5.46
67	3.05	100	35.0	167.0	25.28
	4.60	100	-37.0	47.0	24.13
68	3.05	100	35.0	140.0	20.11
	4.60	100	68.0	133.0	18.67
69	3.05	100	-7.0	238.0	46.92
	4.60	100	-7.0	116.0	35.33
70	3.05	100	55.0	241.0	35.62
	4.60	100	-12.0	95.0	30.74
71	3.05	100	74.0	259.0	35.43
	4.60	100	-96.0	-7.0	25.57
72	3.05	100	-21.0	168.0	36.19
	4.60	100	30.0	131.0	29.01
73	3.05	100	25.0	140.0	22.02
	4.60	100	85.0	154.0	19.82
74	3.05	100	45.0	152.0	20.49
	4.60	100	124.0	187.0	18.10
75	3.05	100	134.5	262.5	24.51
	4.60	100	135.0	217.0	23.55
76	3.05	100	-28.5	94.5	23.55
	4.60	100	-26.5	52.5	22.69
77	3.05	100	-65.0	428.0	94.41
	4.60	100	-211.0	62.0	78.42

APPENDIX III-2 cont'd.

78	3.05	100	-503.0	-345.0	30.26
	4.60	100	-126.0	-34.0	26.43
79	3.05	100	64.0	201.0	26.24
	4.60	100	-9.0	53.0	17.81
80	3.05	100	-36.0	82.0	22.60
	4.60	100	-23.0	37.0	17.23
81	3.05	100	40.0	111.0	13.60
	4.60	100	-11.0	39.0	14.36
82	3.05	100	84.0	138.0	10.34
	4.60	100	-66.0	-26.0	11.49
83	3.05	100	-43.0	4.0	9.00
	4.60	100	-73.0	-37.0	10.34
84	3.05	100	259.0	320.0	11.68
	4.60	100	11.0	57.0	13.21
85	3.05	100	-36.0	40.0	14.55
	4.60	100	-70.0	-21.0	14.07
86	3.05	100	46.0	136.0	17.24
	4.60	100	12.0	72.0	17.23
87	3.05	100	-23.0	78.0	19.34
	4.60	100	-53.0	7.0	17.23
88	3.05				
	4.60	100	82.0	139.5	16.52
89	3.05	100	-17.0	72.0	17.04
	4.60	100	15.0	68.0	15.22
90	3.05	100	-9.0	89.0	18.77
	4.60	100	-20.0	39.0	16.95
91	3.05	100	45.0	152.0	20.49
	4.60	100	-73.0	-15.5	16.52
92	3.05	100	-97.0	-21.0	14.55
	4.60	100	-14.0	43.0	16.37
93	3.05	100	-19.0	69.0	16.85
	4.60	100	-41.0	19.5	17.38

94	3.05	100	14.0	98.0	16.09
	4.60	100	-31.0	25.0	16.09
95	3.05	100	-12.0	99.0	21.25
	4.60	100	8.0	67.0	16.95
96	3.05	80	39.0	180.0	33.75
	4.60	100	103.0	182.0	22.69
97	3.05				
	4.60	100	11.0	72.4	17.64
98	3.05				
	4.60	80	17.0	124.0	38.42
99	3.05	100	10.0	178.0	32.17
	4.60	100	31.0	111.0	22.98
100	3.05	100	5.0	625.0	118.74
	4.60	100	12.0	219.0	59.46
101	3.05	100	32.0	370.0	64.73
	4.60	100	17.0	134.0	33.61
102	3.05	100	62.0	206.0	27.57
	4.60	100	140.0	224.0	24.13
103	3.05	100	-19.5	681.5	134.25
	4.60	100	1.0	172.0	49.12
104	3.05	100	38.0	209.0	32.75
	4.60	100	36.0	142.0	30.45
105	3.05	100	-30.0	79.0	20.87
	4.6	100	19.0	85.0	18.96
106	3.05				
	4.60	100	7.0	79.0	20.68
107	3.05	100	-24.0	157.0	34.66
	4.60	100	-110.0	-38.0	20.68
108	3.05	100	113.0	274.0	30.83
	4.60	100	121.0	210.0	25.26
109	3.05	100	1.0	407.0	77.75
	4.60	100	-37.0	85.0	35.04

APPENDIX III-2 cont'd.

110	3.05	100	-10.0	104.0	21.83
	4.60	100	87.0	157.0	20.10
111	3.05	100	43.0	220.0	33.89
	4.60	100	42.0	121.0	22.69
112	3.05	100	25.0	184.0	30.44
	4.60	100	-32.0	43.0	21.54
113	3.05	100	20.0	193.0	33.13
	4.60	100	43.5	118.5	21.54
114	3.05				
	4.60	100	-123.0	-29.0	27.00
115	3.05	100	21.0	219.0	37.92
	4.60	100	120.0	215.0	27.29
116	3.05	100	69.0	301.0	44.43
	4.60	100	19.0	100.0	23.27
117	3.05	100	-15.0	61.0	14.55
	4.60	100	67.0	114.0	13.50
118	3.05	100	60.0	146.0	16.47
	4.60	100	23.0	75.0	14.94
119	3.05	100	24.0	141.0	22.41
	4.60	100	33.0	91.0	16.66
120	3.05	100	92.0	183.0	17.43
	4.60	100	60.0	112.0	14.94
121	3.05	100	3.0	158.0	29.68
	4.60	100	65.0	139.0	21.26
122	3.05	100	-14.0	171.0	35.43
	4.60	100	11.5	84.0	20.83
123	3.05	100	-14.0	1091.0	211.62
	4.60	100	27.0	324.0	85.32
124	3.05	100	34.0	434.0	76.60
	4.60	100	109.0	209.0	28.73
125	3.05	100	8.0	222.0	40.98
	4.60	100	33.0	108.0	21.54

APPENDIX III-2 cont'd.

126	3.05	100	-7.0	1666.0	320.40
	4.60	100	50.0	391.0	97.96
127	3.05	100	44.0	248.0	39.07
	4.60	100	47.0	124.0	22.12
128	3.05	100	37.0	251.0	40.98
	4.60	100	21.0	106.0	24.42
129	3.05	100	-24.0	131.0	29.68
	4.60	100	38.0	96.0	16.66
130	3.05	100	22.0	258.0	45.20
	4.60	100	-84.0	-7.0	22.12
131	3.05	100	60.0	192.0	25.28
	4.60	100	-10.0	47.0	16.37
132	3.05	100	27.0	220.0	36.96
	4.60	100	47.0	116.0	19.82
133	3.05	100	38.0	285.0	47.30
	4.60	100	-25.0	57.0	23.55
134	3.05	100	15.0	263.0	47.49
	4.60	100	-9.0	71.0	22.98
135	3.05	100	-11.0	223.0	44.81
	4.60	100	-19.5	57.0	21.97
136	3.05	100	31.0	171.0	26.81
	4.60	100	-29.0	41.0	20.11
137	3.05	100	-16.0	127.0	27.39
	4.60	100	-11.0	61.0	20.68
138	3.05	100	-21.0	143.0	31.41
	4.60	100	-10.0	65.4	21.66
139	3.05	100	28.5	420.0	74.98
	4.60	100	3.0	124.0	34.76
140	3.05	100	-3.0	208.0	40.41
	4.60	100	14.5	112.0	28.01

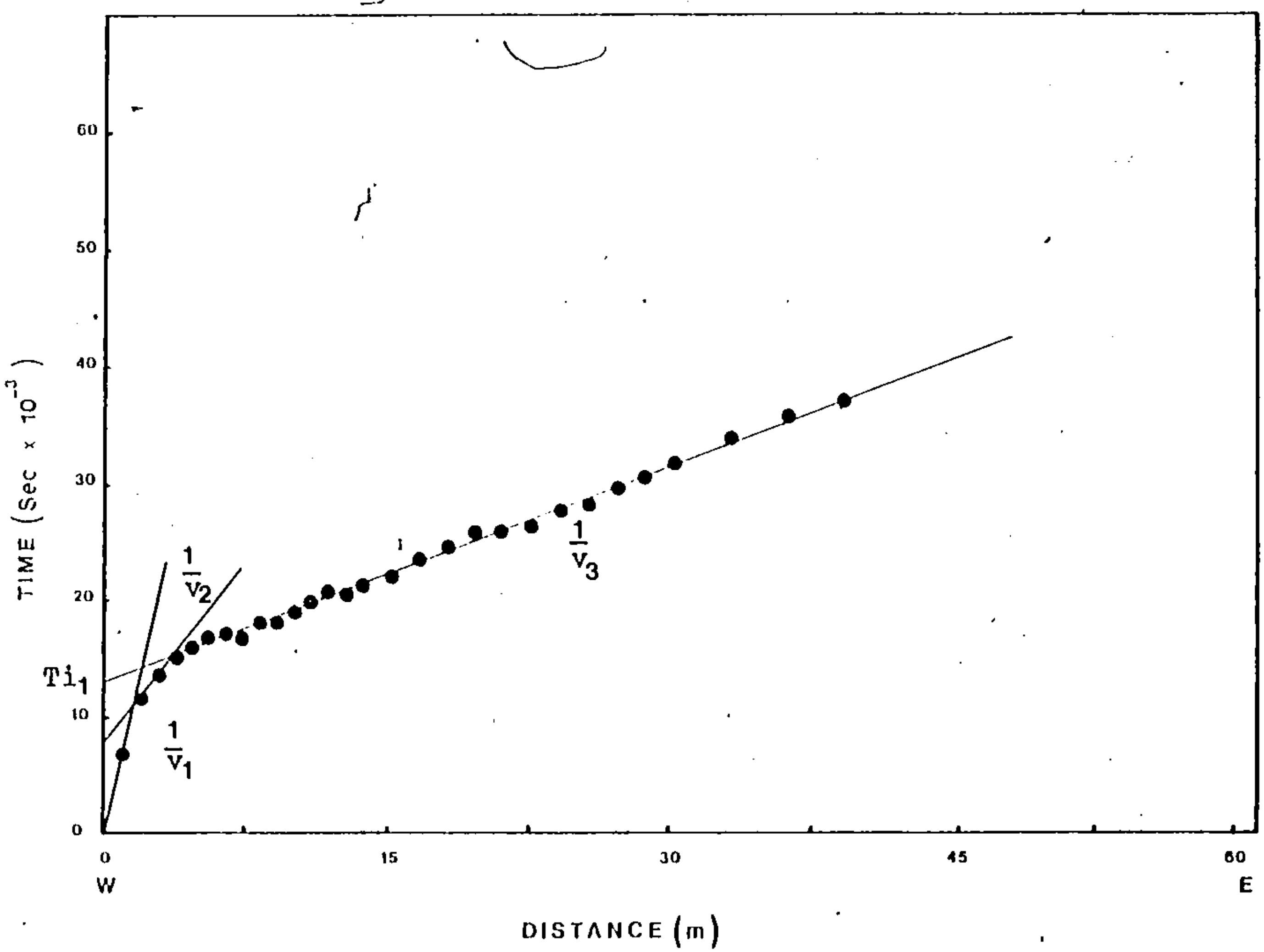
APPENDIX III-3 Results of Seismic Refraction Survey (Tables and Plots).

Distance(X) (m)	Time (s x 10^{-3})				
	Seismic St. 1	Seismic St. 2	Seismic St. 3	Seismic St. 4	Seismic St. 5
0.9	6.81	5.82	8.34	3.48	7.78
1.8	11.80	14.04	13.30	8.75	15.23
2.7	14.05	13.50	12.25	13.88	19.00
3.6	15.33	13.99	15.77	14.04	20.79
4.6	16.10	15.95	16.46	16.01	22.64
5.5	17.00	15.88	17.37	15.43	24.13
6.4	17.24	15.87	17.71	15.06	23.62
7.3	16.51	17.42	18.17	16.37	25.18
8.2	18.07	16.19	18.55	17.15	26.12
9.1	17.95	17.90	19.99	17.33	26.48
10.1	18.92	18.88	20.53	18.22	27.12
11.0	19.94	19.01	21.78	18.82	26.83
11.9	20.80	18.78	22.46	19.54	28.00
12.8	20.61	19.21	21.25	20.48	28.04
13.7	21.43	22.14	22.95	21.05	28.89
15.2	22.08	22.76	22.68	22.21	30.00
16.8	23.89	22.07	24.45	23.01	32.01
18.3	24.43	23.14	25.13	25.32	32.50
19.8	26.01	26.12	25.84	24.68	33.31
21.3	26.00	25.62	27.65	27.00	34.82

APPENDIX III-3 cont'd.

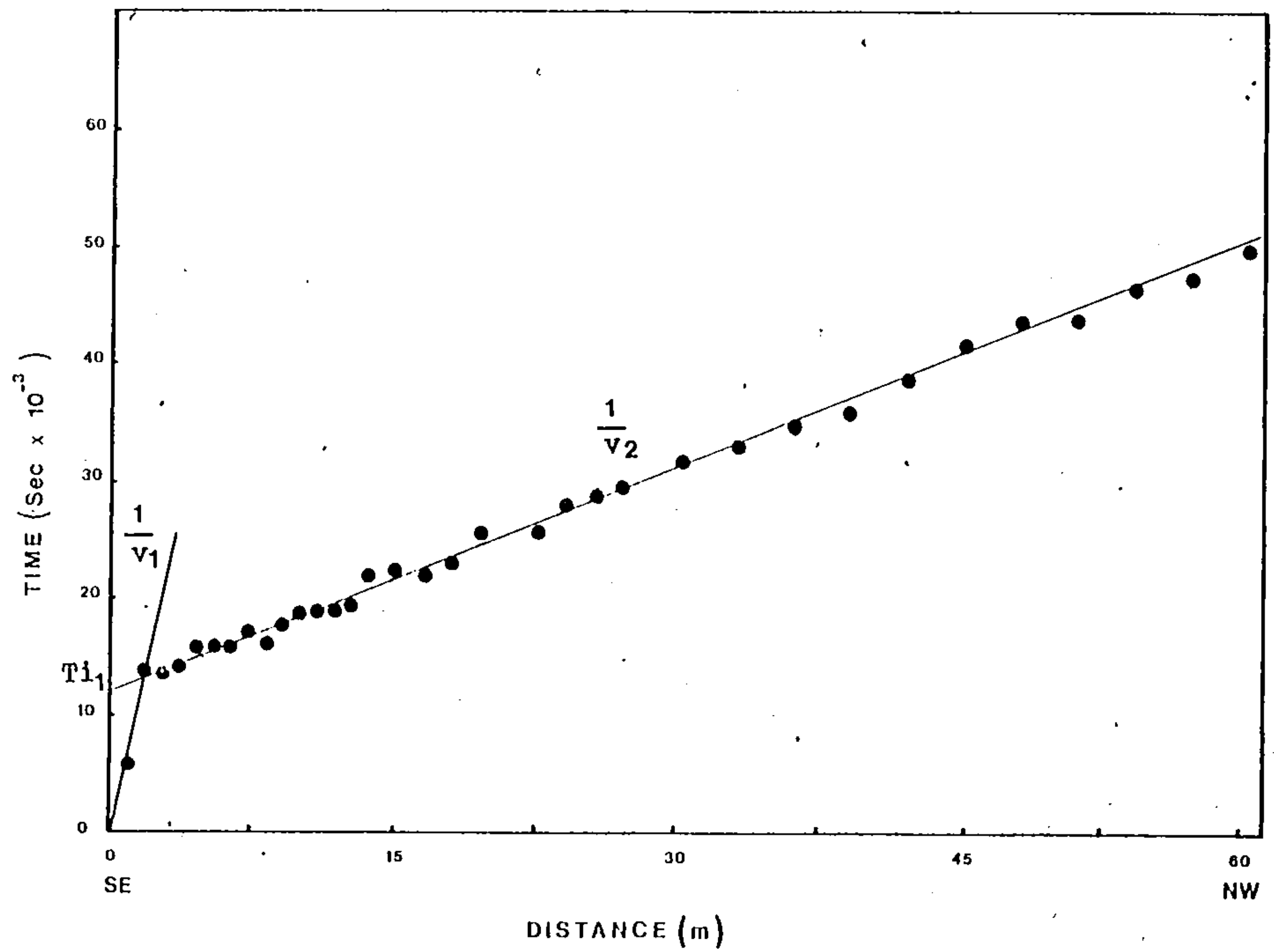
22.9	26.32	25.86	28.70	27.53	36.05
24.4	27.89	28.36	29.28	28.54	36.90
25.9	28.31	28.97	30.82	29.53	37.54
27.4	29.88	29.95	32.60	30.38	38.70
28.9	30.90	30.88	32.71	31.40	40.00
30.5	32.05	32.34	34.80	32.24	40.73
33.5	34.40	33.31	36.40		43.30
36.6	36.24	35.30	37.13		45.53
39.6	37.50	36.20	38.17		46.50
42.7		39.17	42.11		47.85
45.7		42.53	43.13		51.22
48.8		44.76	45.81		52.77
51.8		44.73	46.97		
54.9		47.58	49.70		
57.9		48.63	50.21		
61.0		50.63	51.50		

APPENDIX III-3 cont'd.



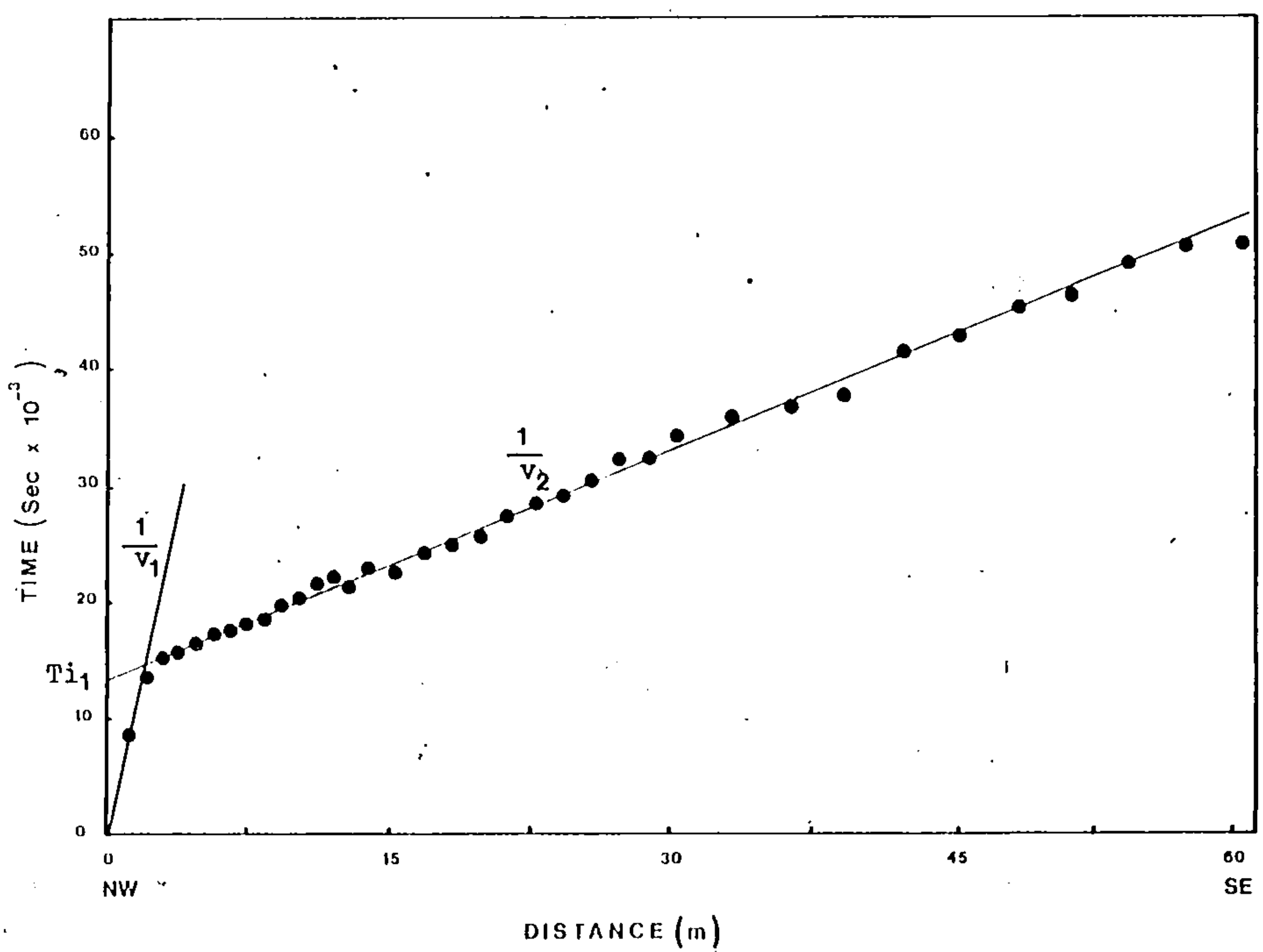
Time-distance curve (Seismic Profile 1)

APPENDIX III-3 cont'd.



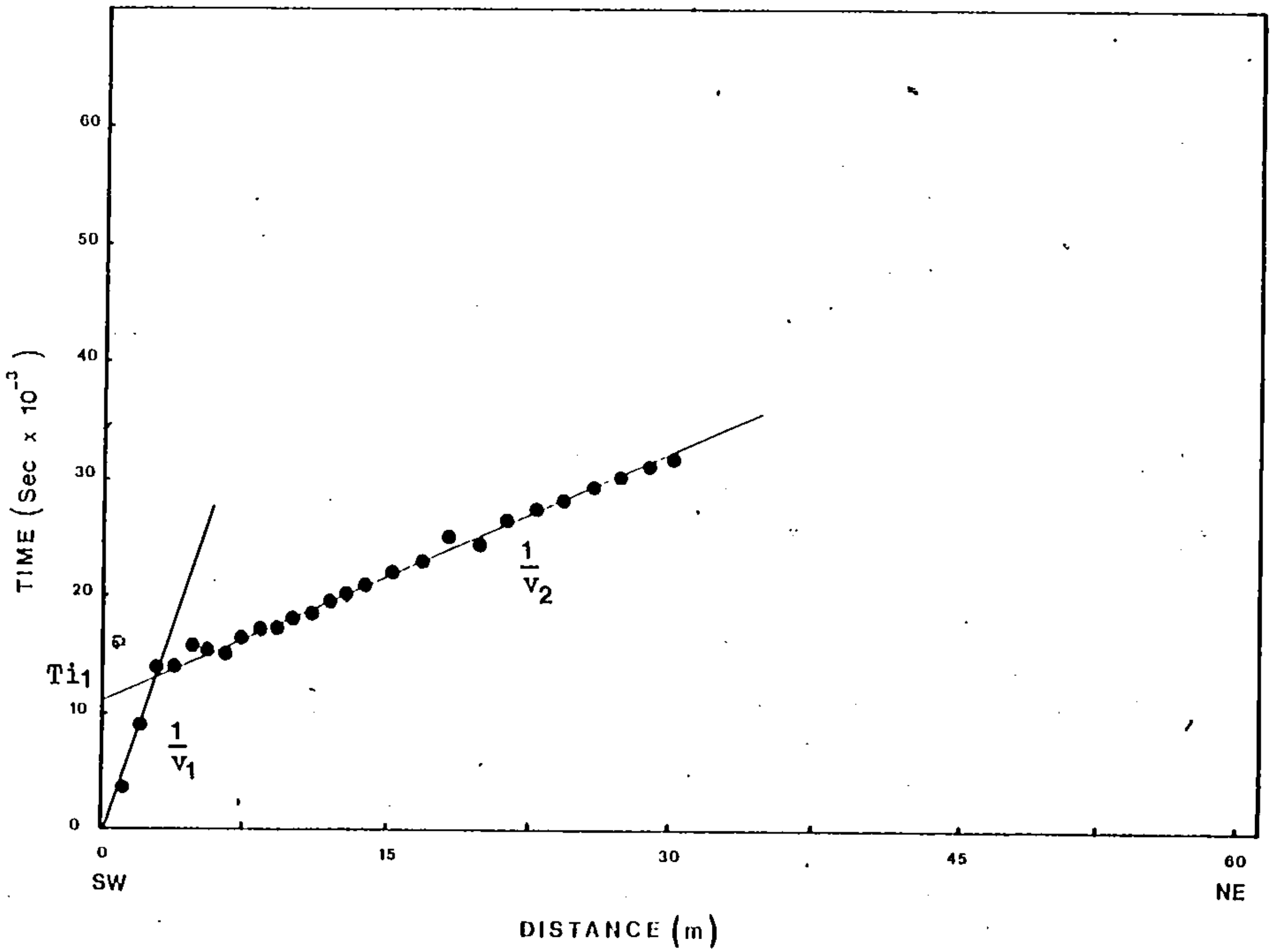
Time-distance curve (Seismic Profile 2)

APPENDIX III-3 cont'd.



Time-distance curve (Seismic Profile 3)

APPENDIX III-3 cont'd.

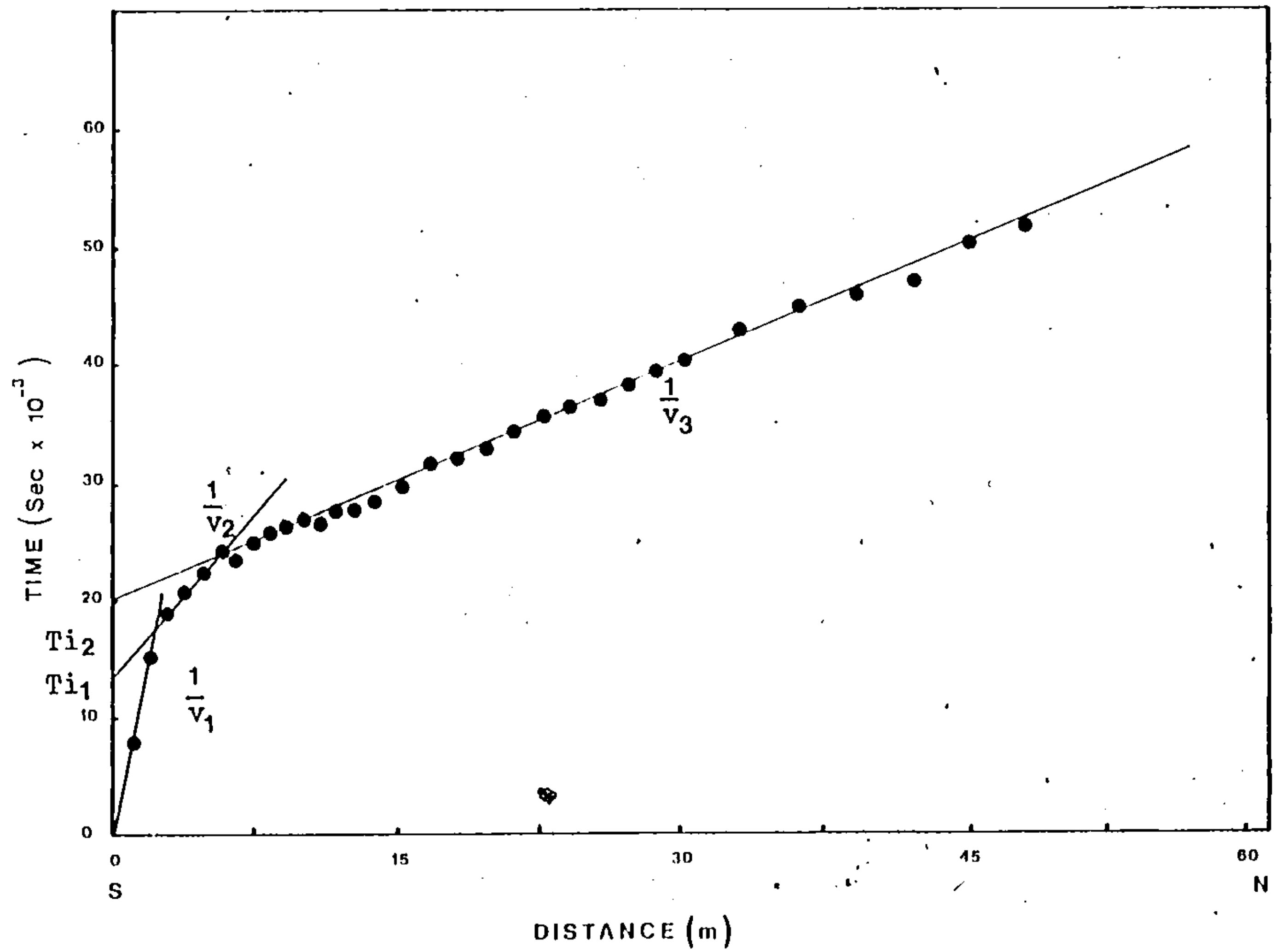


Time-distance curve (Seismic Profile 4)

APPENDIX III-4 Electrical Conductivity Measurements.

Site	Conductivity(µS/cm) at 25°C	Date Day	Month	Year
1	1012	08	11	1982
2	1232			
3	1102			
4	1093			
5	1301	"	"	"
6	2310			
7	3613			
8	903			
9	1677	"	"	"
10	1550	09	"	"
11	1541	"	"	"
12	1258	08	"	"
13	3001	"	"	"
14	2989	09	"	"
15	1255	08	"	"
16	1223			
17	1185			
18	859			
19	649	"	"	"
20	648			
21	872			
22	933	"	"	"
23	411			
24	2535			
25	1345			
26	970	"	"	"

APPENDIX III-3 cont'd.



Time-distance curve (Seismic Profile 5)

APPENDIX III-5 Selected borehole logs for the Windsor West End Landfill.

Well	Elevation (m.a.s.l.)	Log (thickness in m)	Reference
21-2947	182.9	Yellow sand 1.2, yellow clay 6.4, blue clay 19.2, blue clay and gravel 3.1, grey limestone 3.0.	Ontario Ministry of Environment (1977)
BH-3	212.0	Top soil 0.1, compact brown fine to medium sand with some silt 2.9, firm to soft grey clayey silt to silty clay 3.4.	Golder associates (1970)
BH-21	178.5	Top soil 0.1, compact light brown coarse to medium sand 1.0, stiff to very stiff clayey silt to silty clay 2.o, stiff to very firm grey silty clay with some sand and occasional fine to medium gravel 12.1.	Golder Associates (1969c)
BH-22	178.6	Top soil 0.1, compact brown medium to coarse sand 1.4, very stiff to stiff clayey silt to silty clay 2.1, stiff to firm grey silty clay with some sand and occasional fine to medium gravel 11.3.	Golder Associates (1969c)

APPENDIX III-5 cont'd.

Well	Elevation (m.a.s.l.)	Log (thickness in m)	Reference
BH-23	178.9	Top soil and fill 0.6, loose brown coarse to medium sand 0.3, stiff to very stiff clayey silt to silty clay 1.5, very stiff to stiff grey silty clay with some sand and occasional fine to medium gravel 11.9.	Golder Associates (1969c)
BH-24	180.5	Silty sand (fill) 1.7, loose medium to coarse sand 1.7, stiff grey brown clayey silt 0.6, stiff grey silty clay with some sand and occasional fine to medium gravel 12.8.	Golder Associates (1969c)
BH-25	179.8	Fill 0.4, top soil 0.3, loose brown sand 0.3, stiff to very stiff silty clay to clayey silt 2.2, stiff grey silty clay with some sand and occasional fine to medium gravel 11.6.	Golder Associates (1969c)
BH-26	179.9	Silty sand fill 1.7, very stiff to stiff silty clay with some sand and	Golder Associates (1969c)

APPENDIX III-5 cont'd.

Well	Elevation (m.a.s.l.)	*Log* (thickness in m)	Reference
		occasional fine to medium *gravel* 13.1.	
BH-27	179.9	Loose brown sand with some silt (organic fill) 1.8, very stiff to stiff *grey* silty clay with some sand and occasional fine to medium gravel 12.7.	Golder Associates (1969c)
BH-28	180.4	Top soil 0.3, compact light brown medium to fine sand 1.5, stiff to very stiff clayey silt to silty clay 2.2, very stiff silty clay with some sand and occasional fine *gravel* 11.8.	Golder Associates (1969c)
BH-29	178.3	Top soil 0.4, compact brown coarse to medium clayey silt 2.2, stiff to firm silty clay with sand and occasional fine to medium *gravel* 11.1.	Golder Associates (1969c)

APPENDIX III-5 cont'd.

Well	Elevation (m.a.s.l.)	Log (thickness in m)	Reference
BH-33	181.6	Top soil 0.3, compact yellow medium to coarse sand 2.3, stiff grey clayey silt 3.6, very stiff to stiff silty clay with some sand and occasional fine to medium gravel 13.2.	Golder Associates (1969c)
BH-34	181.5	Top soil 0.3, grey silty sand (fill) 0.4, loose grey brown medium to coarse sand 1.4, stiff grey brown clayey silt 1.5, very stiff to stiff grey silty clay with some sand and occasional fine to medium gravel 12.4.	Golder Associates (1969c)
BH-35	181.8	Top soil 0.3, loose brown coarse to medium sand 1.2, very stiff to stiff silty clay with some sand and occasional fine to medium gravel 14.3.	Golder Associates (1969c)
BH-OW1	178.0	Top soil 0.1, light brown fine sand 0.9, light brown medium sand 0.4, silt 0.1, clayey silt 0.1.	Guiton (1978)

APPENDIX III-5 cont'd.

Well	Elevation (m.a.s.l.)	Log (thickness in m)	Reference
BH-OW3	180.0	Top soil 0.3, light brown fine sand 1.0, silt 0.05, light brown fine sand 0.8, clayey silt 0.1.	Guiton (1978)
BH-OW4	179.7	Top soil 0.1, yellow fine sand 0.5, light brown medium sand 0.2, silt 0.1, light brown fine sand 1.4, clayey silt 0.1.	Guiton (1978)
BH-OW5	178.5	Top soil 0.1, light brown fine sand 0.8, silt 0.2, grey medium sand 0.6, grey coarse sand 0.3, clayey silt 0.3.	Guiton (1978)
BH-OW6	178.3	Top soil 0.1, brown medium sand 0.9, silt 0.3, grey medium sand 0.1, grey medium to coarse sand 0.2, clayey silt 0.1.	Guiton (1978)
BH-OW7	178.4	Top soil 0.3, light brown medium sand 0.8, grey coarse sand 0.1, clayey silt 0.5.	Guiton (1978)

APPENDIX III-5 cont'd.

Well	Elevation (m.a.s.l.)	Log (thickness in m)	Reference
BH-OW10	179.3	Top soil 0.4, light brown fine sand 0.9, clayey silt 0.3.	Guiton (1978)
BH-RW1	178.3	Top soil 0.3, light brown fine sand 0.4, yellow fine sand 0.5, grey medium to coarse sand 0.05, silt silt 0.05, clayey silt 0.2.	Guiton (1978)

APPENDIX IV

INSTRUMENTATION

The Bison Signal Enhancement Hammer Seismograph, Model 1570C

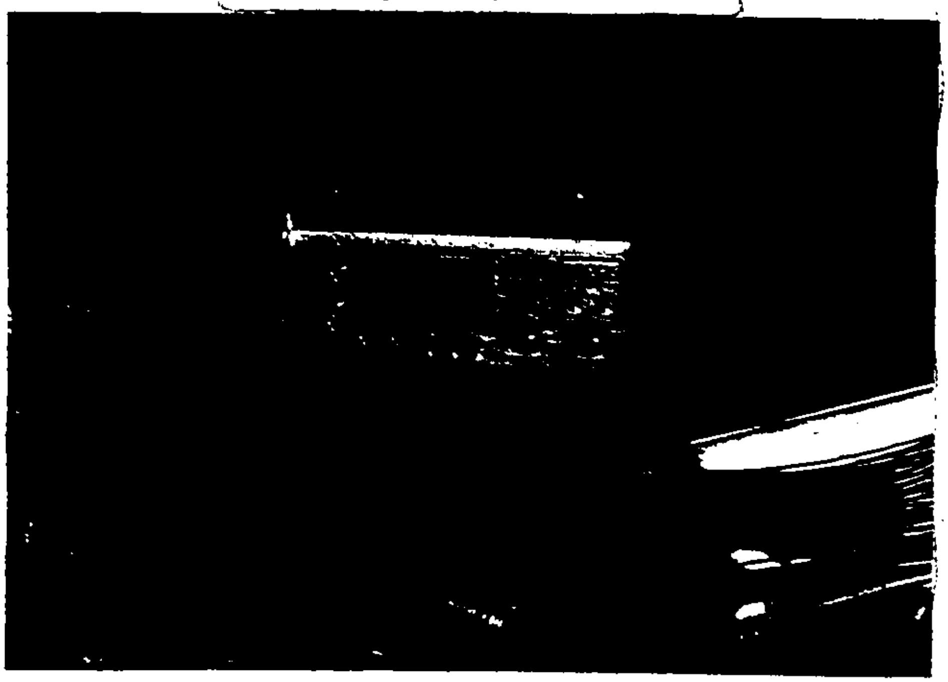
The Huntec FS-3 Seismograph

The Soiltest R-50 Resistivity Meter

The Barnstead Conductivity Bridge Model PM-70CB

APPENDIX IV cont'd.

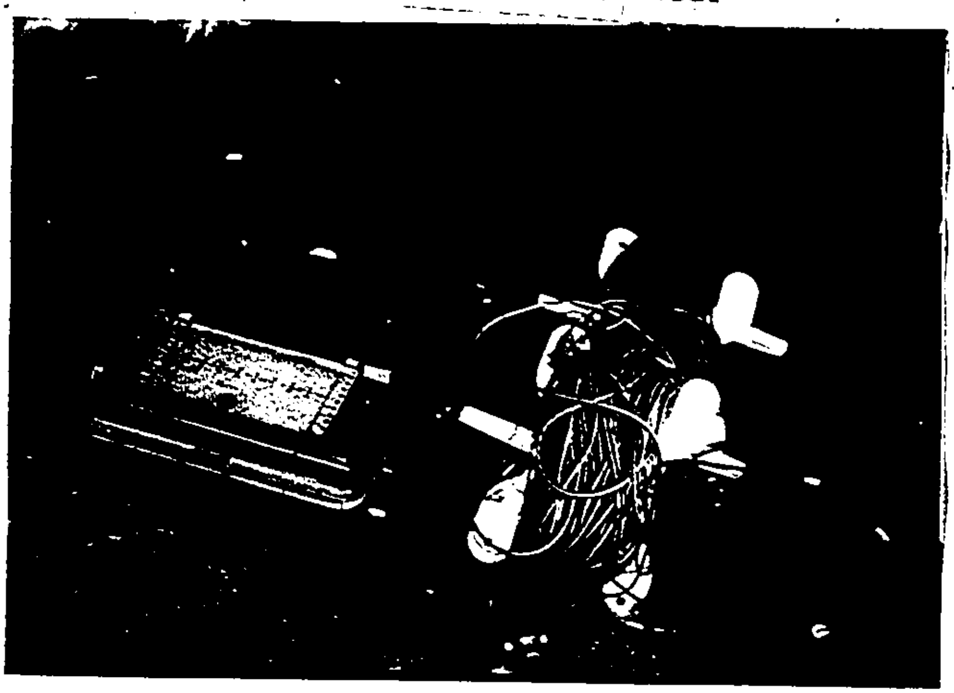
COLOURED PICTURES
Images en couleur



The Bison Signal Enhancement Hammer Seismograph, Model 1570C.

APPENDIX IV cont'd.

COLOURED PICTURES
Images en couleur



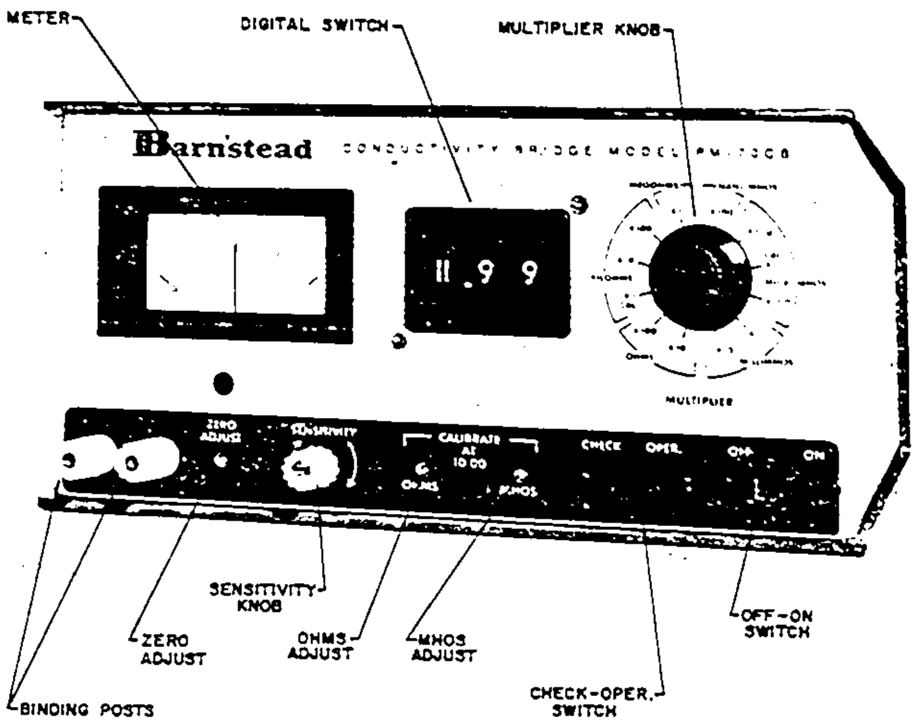
The Huntec FS-3 Seismograph.

APPENDIX IV cont'd.

COLOURED PICTURES
Images en couleur

The Soiltest R-50 Resistivity Meter.

APPENDIX IV cont'd.



The Barnstead Conductivity Bridge Model PM-70CB.

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