PB84-198449

Geophysical Techniques for Sensing Buried Wastes and Waste Migration

Lockheed Engineering and Management
Services Co., Inc., Las Vegas, NV

Prepared for

Environmental Monitoring Systems Lab.
Las Vegas, NV

Jun 84

U.S. DEPARTMENT OF COMMERCE
National Technical Information Service
NTIS®

PB84-198449

EPA-600/7-84-064
June 1984

GEOPHYSICAL TECHNIQUES FOR SENSING BURIED WASTES AND WASTE MIGRATION

by

Richard C. Benson,
Robert A. Glaccum, Michael R. Noel
TECHNOS, Inc.
3333 N.W. 21st. Street
Miami, FL 33142

Subcontractors to Lockheed Engineering
and Management Services Company, Inc.
P.O. Box 15207
Las Vegas, Nevada 89114

Contract No. 68-03-3050

Project Officer
J. Jeffrey van Ee
Advanced Monitoring Systems Division
U. S. Environmental Protection Agency
Las Vegas, Nevada 89114

ENVIRONMENTAL MONITORING SYSTEMS LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
LAS VEGAS, NEVADA 89114

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA-600/7-84-064	2.	3. RECIPIENT'S ACCESSION NO. PB8 4 198449
4. TITLE AND SUBTITLE Geophysical Techniques for Sensing Buried Wastes and Waste Migration		5. REPORT DATE June 1984
		6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Richard C. Benson, Robert A. Glaccum, & Michael R. Noel		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS TECHNOS, Inc. 3333 N.W. 21st. Street Miami, FL 33142		10. PROGRAM ELEMENT NO. D109/Y105
		11. CONTRACT/GRANT NO. Contract 68-03-3050
12. SPONSORING AGENCY NAME AND ADDRESS U.S. Environmental Protection Agency Environmental Monitoring Systems Laboratory-Las Vegas P.O. Box 15027 Las Vegas, NV 89114		13. TYPE OF REPORT AND PERIOD COVERED Project Report/Project Summary
		14. SPONSORING AGENCY CODE EPA/600/07

15. SUPPLEMENTARY NOTES

16. ABSTRACT

Descriptions of the use of six geophysical techniques are presented to provide a broad understanding of the application of these techniques for sensing buried wastes and waste migration. Technical language and jargon are avoided as much as possible so that those with limited technical background can acquire a general understanding of current techniques and sufficient background to define project requirements, select professional support, and monitor and direct field programs.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group

18. DISTRIBUTION STATEMENT RELEASE TO THE PUBLIC	19. SECURITY CLASS (This Report) UNCLASSIFIED	21. NO. OF PAGES 255
	20. SECURITY CLASS (This page) UNCLASSIFIED	22. PRICE

EPA Form 2220-1 (Rev. 4-77) PREVIOUS EDITION IS OBSOLETE

ATTENTION

AS NOTED IN THE NTIS ANNOUNCEMENT, PORTIONS OF THIS REPORT ARE NOT LEGIBLE, HOWEVER, IT IS THE BEST REPRODUCTION AVAILABLE FROM THE COPY SENT TO NTIS.

NOTICE

The information in this document has been funded wholly or in part by the United States Environmental Protection Agency under contract number 68-03-3050 to Lockheed Engineering and Management Services Company, Inc., it has been subjected to the Agency's peer and administrative review, and it has been approved for publication. The contents reflect the views and policies of the Agency. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

ABSTRACT

Descriptions of the use of six geophysical techniques are presented to provide a broad understanding of their application to sensing buried wastes and waste migration. Technical language is avoided as much as possible so that those with limited technical background can acquire a general understanding of current techniques sufficient to define project requirements, select professional support, and monitor and direct field progrms.

Emphasis on cost-effective investigations at hazardous waste sites requires an integrated, phased approach: (1) preliminary site assessment involving the use of aerial photography, on-site inspections, and readily available information to approximate site boundaries and locations of waste concentrations, as well as probable site geology; (2) geophysical surveys to pinpoint buried wastes, estimate quantities, and delineate plumes of conductive contaminants in groundwater; and (3) confirmation of groundwater contamination through monitoring well networks designed on the basis of plumes and subsurface stratigraphy defined by the geophysical surveys.

The six geophysical techniques described include metal detection, magnetometry, ground penetrating radar, electromagnetics, resistivity, and seismic refraction. Metal detectors and magnetometers are useful in locating buried wastes. Ground penetrating radar can define the boundaries of buried tranches and other subsurface disturbances. Electromagnetic and resistivity methods can help define plumes of contaminants in groundwater. Resistivity and seismic techniques are useful in determining geological stratigraphy.

Simple metal detectors respond to changes in electrical conductivity caused by the presence of metallic objects, both ferrous and nonferrous. Magnetometers detect perturbations in the earth’s geomagnetic field caused by buried ferromagnetic objects such as drums, tools, or scrap metal. They sense ferrous objects at greater depths than metal detectors and can locate objects even in the presence of interferences created, for instance, by fences.

A ground-penetrating radar system radiates short-duration electromagnetic pulses into the ground from an antenna near the

surface. These pulses are reflected from interfaces in the earth (such as trench boundaries) and picked up by the receiver section of the antenna. Electromagnetic conductance measuring devices yield a signal proportional to the conductivity of the earth between the transmitter and receiver coils. Many contaminants will produce an increase or decrease over the background conductivity and thus can be detected and mapped. The resistivity method measures the electrical resistivity of the geohydrologic section which includes the soil, rock, and groundwater and provides a tool to evaluate contaminant plumes and locate buried wastes. Seismic refraction techniques can determine the thickness and depth of geologic layers and the travel time or velocity of seismic waves within the layers, thus revealing variations in site conditions.

This document was submitted by Technos, Inc., in fulfillment of Contract No. 68-03-3050 to Lockheed Engineering and Management Services Company, Inc., under the sponsorship of the U.S. Environmental Protection Agency. This report covers a period from August 1, 1981, to December 31, 1982, and work was completed as of December 31, 1982.

CONTENTS

FIGURES

FIGURES (Continued)

FIGURES (Continued)

FIGURES (Continued)

FIGURES (Continued)

FIGURES (Continued)

FIGURES (Continued)

FIGURES (Continued)

TABLES

ACKNOWLEDGEMENTS

This document was prepared by Technos, Inc., under Contract No. 62-03-3050 to Lockheed Engineering and Management Services Company, Inc., from the U.S. Environmental Protection Agency, Environmental Monitoring Systems Laboratory, Las Vegas, Nevada.

The document was written by Richard Benson, Robert Glaccum and Michael Noel of Technos, Inc.

A group of independent reviewers, experts in the field of remote-sensing geophysics, provided valuable input and guidance. The authors wish to express their thanks for the contributions from these reviewers:

Sheldon Breiner	GeoMetrics
Frank Frischknecht	U.S.G.S.-Denver
J.D. McNeill	Geonics
Gary Olhoeft	U.S.G.S. Denver
Phil Romig	Colorado School of Mines
Gerald Sandness	Battelle Laboratories
A.A. Zohdy	U.S.G.S.-Denver

Also acknowledged are the coordination efforts of Dr. Eric Walther, Lockheed Engineering and Management Services Company, Inc., project manager.

The assistance and cooperation extended by numerous other individuals who were contacted on matters related to this document is gratefully acknowledged.

All illustrations and tables were provided through the courtesy of Technos, Inc. except for Figures 7, 24, 28, 56, 60, 61 and 94, for which credit is given in the figure caption.

SECTION I

INTRODUCTION

Background

Traditional approaches to subsurface field investigations at hazardous waste sites (HWS) often have been inadequate. This is evidenced by the increased number of papers, conference topics, and research projects devoted to the problem, and by the tightening of ground water regulations. Traditionally, site investigation for contaminants has relied upon (1) drilling to obtain information on the natural setting, (2) monitor wells for gathering water samples, and (3) laboratory analysis of soil and water samples. This approach has evolved over many years, and is often regarded as the standard analytical approach. However, there are numerous pitfalls associated with this direct sampling approach, which can result in an incomplete or even erroneous understanding of site conditions.

In the designing of monitor well networks, the placement of wells has been done mainly by educated guesswork. The accuracy and effectiveness of such an approach is heavily dependent upon the assumption that subsurface conditions are uniform, and that regional trends hold true for the local setting. However, these assumptions are frequently invalid, resulting in non-representative locations for monitor well placement. If an attempt is made to improve accuracy by installing additional wells, the project may be thrown off schedule and costs will increase. Such delays are often unacceptable in rapid assessments required at HWS. At certain sites, there are also increased safety risks associated with drilling into unknown buried materials.

The accuracy of results can be affected hy other errors such as contamination introduced during drilling operations, well construction, and sampling or preservation procedures. These errors have been neglected for a number of years, but recently have been recognized as creating a major problem. Since the number of spatial samples is typically limited, at many sites no more than five monitor wells or clusters are drilled. If data from just one of the five wells or clusters contains a significant error, 20% of the total raw data is in error.

Some measurements are difficult or impossible to obtain hy conventional methods. For example, since the detection of contaminant movement through the unsaturated zone, and the determination of detailed local flow patterns and directions are both difficult, solutions are often derived by conjecture. The investigator's inability to make some of the desired measurements, and the enhanced possibility of error, as well as the potential for increased risk, lost time and high direct costs, often result in low levels of confidence in traditional methods of field investigations.

Figure 1 shows a hypothetical curve representing the level of information developed for a HWS investigation versus the effort involved. Many investigations result in an unexpectedly low level of accuracy. However, this need not always be the case. There are two ways for investigators to obtain results with optimal levels of accuracy: they can add more money, time, sample stations, etc., or they can adopt an integrated systems approach. The latter is safer and more cost-effective and this document describes the techniques used in such an approach.

During the past decade, extensive development in remote-sensing geophysical equipment, portable field instrumentation, field methods, analytical techniques and related computer processing has resulted in a striking improvement in our capability to assess hazardous waste sites. Further, many of these improved methods allow measurement of parameters in the field and rapid site characterization, sometimes with continuous data acquisition at traverse speeds up to several miles per hour.

Some of these geophysical methods offer a direct means of detecting contaminant plumes and flow directions in both the saturated and unsaturated zones. Others offer a way to obtain detailed information about subsurface soil and rock conditions. This capability to rapidly characterize subsurface conditions without disturbing the site (much like nondestructive testing used in many production facilities and test laboratories) offers the benefits of lower cost and less risk, and provides better overall understanding of complex site conditions.

Once a spatial characterization of the site is made by these methods, an optimal direct sampling plan may be designed to:

- Minimize the number of drilling sites;
- Locate drilling and monitor wells at representative sites;
- Reduce risk associated with drilling into unknowns;
- Reduce overall project time and costs;
- Provide improved accuracy and confidence levels.

In brief, geophysical methods provide a means of rapid reconnaissance to characterize the site; drilling and monitor wells are then used to provide specific quantitative data from discrete stations, which have been located so as to be representative of site conditions. The drilling and monitor wells are no longer used for expensive hit-or-miss reconnaissance sampling. In sum, the systems approach using geophysical methods utilizes cost-effective means for improving our understanding of site conditions (Figure 1).

Geophysics has already been successfully applied to many HWS investigations. Notable examples include Love Canal in New York, Valley of the Drums in Kentucky, and the 58th Street Landfill in Florida. At these sites, and numerous others throughout the country, geophysics has been used to define plumes, locate buried drums, detect boundaries of burial trenches, and determine geological settings. The synergistic features of an integrated systems approach combining traditional and contemporary geophysical methods have resulted in enhanced quality, safety, and cost-effectiveness in investigations at numerous HWS.

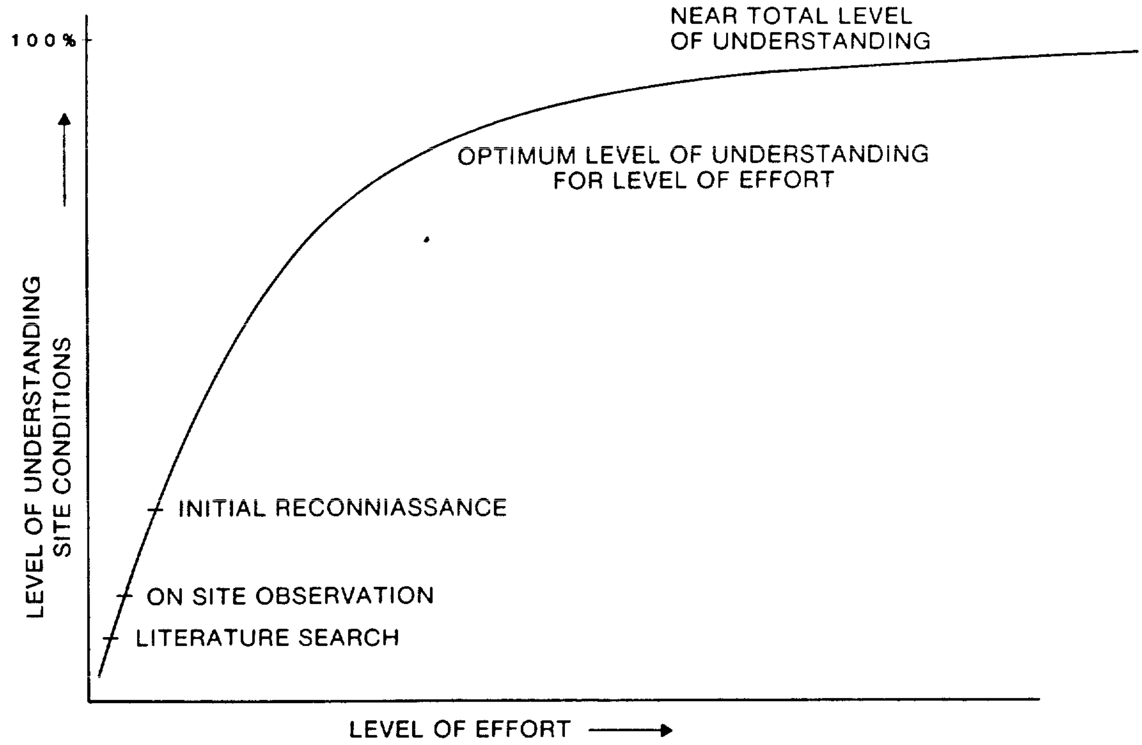


Figure 1. Level of understanding versus level of effort for hazardous waste site investigation.

Objective of this Document

This document is primarily intended for management and administrative personnel responsible for investigation and assessment of hazardous waste sites. Although it is not intended as a "how to" book, it does provide a basic understanding of the technology and some field procedures For those who may be involved in making recommendations or assisting with such field activities. It has been assumed that the reader's technical background in the fields discussed in this document may be limited. Accordingly, use of detailed theory and formulas has been minimized. Technical language has been avoided as much as possible. In some cases, the more technically-qualified reader may recognize some imprecision; the authors recognize this possibility but have opted to favor the general reader in an effort to achieve better communication. The document should provide the reader with a general understanding of current techniques, together with sufficient background to allow him to proceed to define project requirements, select professional support, and monitor and direct field programs.

The scope of this document has been limited to the description and use of six geophysical techniques. They are:

- Ground Penetrating Radar
- Electromagnetic
- Resistivity
- Seismic Refraction
- Metal Detection
- Magnetometry

These six techniques were selected because they are regularly used and have been proven effective for hazardous waste site assessments. Within each of the six techniques, discussion has been further limited to equipment and methodology meeting the same criteria. The application of geophysics to hazardous waste site assessments is a relatively new field (less than 5 years old). There are only a few qualified practitioners, and a limited number of proven methods, equipment, etc., regularly in use. With some types of geophysical equipment, there may be only one manufacturer supplying the entire field. The methods discussed offer a capability for in-situ measurements, and often complement each other technically. Table 1 shows some possible applications of each of these methods to HWS assessments.

The primary tasks to which these methods can be applied include:

- Mapping of natural geohydrologic features;
- Mapping of conductive leachates and contaminant plumes (landfill leachates, acids, bases);

- Location and boundary definition of buried trenches;
- Location and definition of buried metallic objects (drums, pipes, tanks).

Organization

The document is organized as follows: Section II focuses on factors that influence the planning and execution of a HWS assessment. Section III contains an overview of some of the limitations of traditional approaches, together with an introduction to concepts of applying geophysical techniques for HWS evaluations. Sections IV through IX discuss use of six remote-sensing geophysical techniques in particular, and Sections X and XI summarize capabilities and limitations of the six methods, concluding with a presentation of case studies.

TABLE 1. APPLICATIIONS OF GEOPHYSICAL METHODS TO HAZARDOUS WASTE SITES

APPLICATION	RADAR	ELECTROMAGNETICS	RESISTIVITY	SEISMIC	METAL DETECTOR	MAGNETOMETER
Mapping of Geohydrologic Features	1	1	1	1	-	-
Mapping of Conductive Leachates and Contaminant Plumes (ex. Landfills, Acids, Bases)	2	1	1	-	-	-
Locations and Boundary Definition of Buried Trenches with Metal	1	1	2	2	2	2
Location and Boundary Definition of Buried Trenches without Metal	1	1	2	2	-	-
Location and Definition of Buried Metallic Objects (ex. Drums, Ordinance)	2	2	-	-	1	1

1. Primary method - Indicates the most effective method
2. Secondary Method - Indicates an alternate approach

SECTION II

THE FIELD INVESTIGATION

Background

A proper evaluation of a hazardous waste site must include consideration of a large number of variables, many of them unknown and potentially interacting in a complex manner. A site investigation program must define conditions to the necessary level of accuracy, and meet project schedule and cost constraints.

This section presents some of the variables that the project manager may encounter and address in his project plan. It is important to appreciate the magnitude and scope of various factors in planning, field investigation and final analysis. Because the field investigation may not provide all of the answers in a particular site assessment, it is necessary to have a good understanding of the variables in order to evaluate available data, identify missing information and evaluate its relative significance to the project.

Objectives

Figure 2 shows some of the many factors which may influence the planning and execution of a HWS assessment. The three primary objectives usually involved in subsurface investigations at HWS are shown in the center of the figure and include:

- o Location of buried waste materials, including the resolution of quantity and type;
- o Determination of the presence of plumes and the direction, rate of movement, and distribution of contaminants;
- o Characterization of the natural geohydrologic conditions, and manmade factors which will influence these conditions.

Location of Buried Materials--includes establishing the boundaries of trenches, as well as their depth and volume. The investigator will wish to assess the contents of a trench or burial site. For example, he may ask these questions: Were the materials bulk-dumped or containerized? Are there drums present? Where are the drums located within the site, and how many are there? Knowledge of the precise boundaries of burial sites is

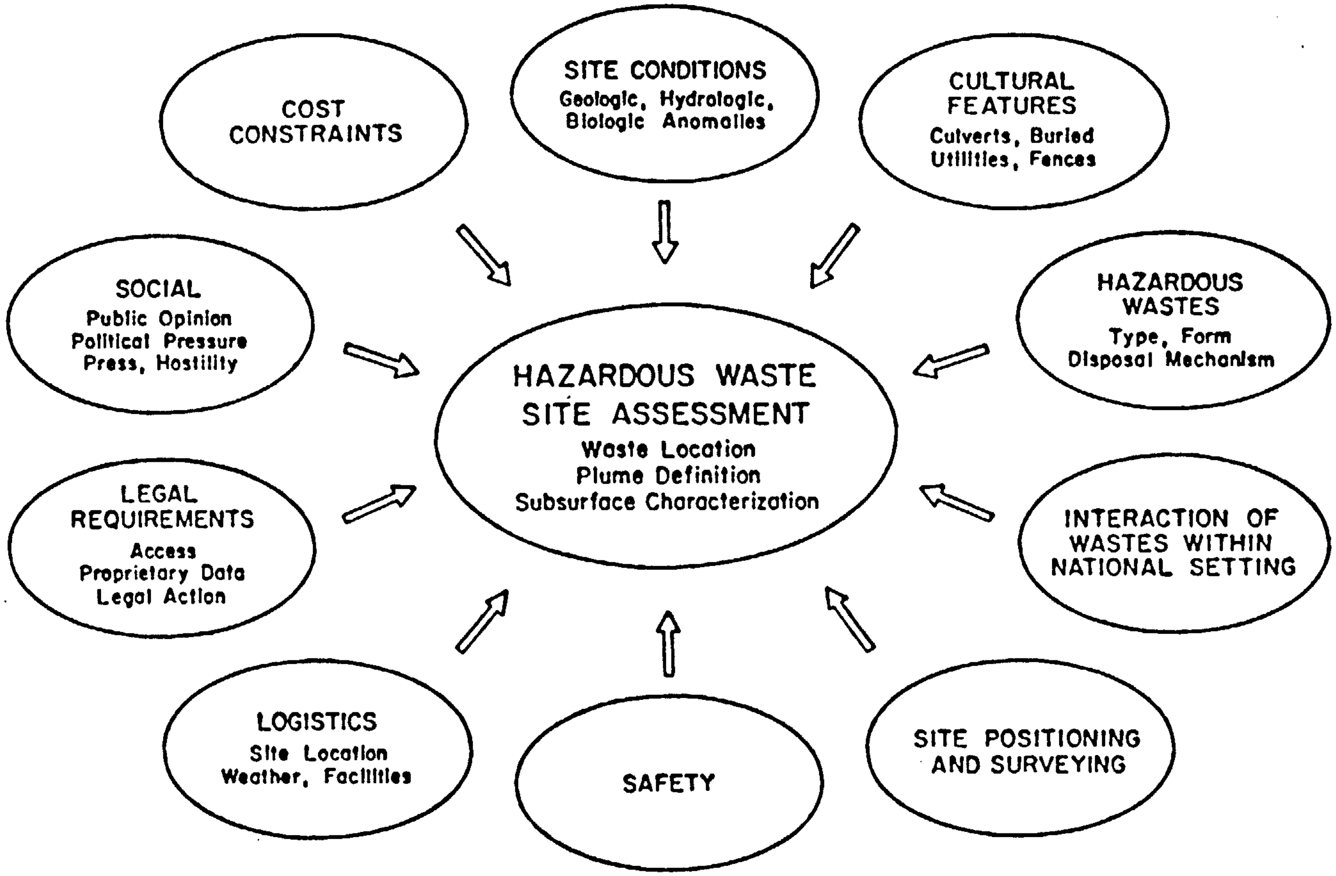


Figure 2. Factors affecting the subsurface investigation plan.

important for safety considerations, as well as for quantifying the contents for remedial action planning. For example, placement of a monitor well in a trench may puncture containers within the burial site resulting in explosion, fire, or release of toxic fumes. An existing seal between the trench contents and the surrounding soils or rock may also be breached. Drilling in areas with soluble rocks such as limestone, could lead to rapid movement of the contaminants into underlying aquifers.

Determination of the Presence of Contaminant Plumes--and their flow direction and movement rate is commonly required. Often the first question is whether leakage from the HWS is occurring. If the existence of a plume is confirmed, it will be necessary to establish its direction and extent. But if there are only a few monitor wells, the data they provide may not be truly representative of site conditions, and thus may lead to incorrect conclusions. A typical example: If the local ground water flow does not coincide with the regional flow, the monitor wells may be incorrectly placed, and may fail to indicate the presence of an existing plume. Geophysical monitoring of plume location and dynamics may avoid these problems.

Characterization of Subsurface Conditions--is usually a major portion of the field investigation. At most sites, the local soil and rock types, the depth of the water table, and the direction of ground water flow will strongly influence movement of contaminants; therefore, these factors must be well defined, as must the potential of the contaminants to be retarded by soils. Natural anomalies within the geohydrologic section must be taken into consideration, as well as surface drainage, sewers, and buried utilities, all of which can affect both surface and ground water flow around a HWS.

Factors to be Considered

The ten factors shown in the perimeter of Figure 2 may impact on a specific site assessment. The following disussion reviews some of these variables.

1) Natural Site Conditions
   - Surface features can be easily observed; they include the natural setting, vegetation, topography, geomorphology, physiography, and cultural development;
   - Subsurface features including soils, rock, hydrologic, chemical and biologic conditions cannot be seen; therefore these subsurface conditions are difficult to evaluate.

If subsurface conditions were as uniform as layer cake, the assessment would be relatively straightforward. However, in most field situations, this will not he the case. For example, a small change of a few percent in sand/clay content can change hydraulic permeability by a factor of 10. Therefore, the site investigator must be alert to small variations which will cause significant but unsuspected errors. The subtle changes in subsurface conditions are by far the most difficult to detect.

Daily or seasonal effects of temperature and precipitation will influence contaminant stability and migration. Areas of ground water recharge are important because contaminants may easily enter a ground water system. Subtle variations in permeability will permit preferential ground water flow directions and rates unsupported hy regional conditions, surface observations or limited borings.

Assessment of natural site conditions requires that the site be considered at various dimensional scales (Figure 3). While a specific waste site may be only an acre in size, its contamination may be spread over many tens of acres. Its impact upon the surrounding area can depend upon its regional setting, including geology, vegetation, population, water supply, rivers, lakes, and seasonal factors. Insight into the character of the local setting can be derived from knowledge of the broader regional picture, therefore it is commonly necessary to plan the investigation to include an area considerably greater than the HWS itself. This will provide an overview, which will enable the local site conditions to be more rapidly and accurately evaluated. (Contaminant transport by ground water and the geohydrologic factors controlling it do not stop at property lines.)

An analogy can he drawn to the use of a camera's telescopic zoom lens to zoom in from an overall view to a close-up of the finer details. Omitting the broad overview can result in a number of critical gaps in information about the setting. Here are some examples:

Figure 4 shows a hazardous waste site situated over an old buried stream channel. In many cases such channels act as preferential pathways for movement of contaminants because of their increased permeability. Understanding that a regional area contains buried stream channels, and knowing where they may he located, will be a significant aid in assessing the local situation.

Figure 5 shows a hazardous waste site in a soil overlying a massive hard rock, such as granite. Within the massive rock itself, little if any water flow occurs. However, these rocks are often fractured, increasing the overall permeability of the bulk rock. To maximize the yield of potable water, wells are drilled to intersect such fractures. The same fractures may also become conduits for contaminants to move into the bedrock and ground water system. The investigator must be aware of the regional geologic setting, the secondary porosity of the granite due to fracturing, and the extraction of drinking water from these localized fractures. The directions of major fracture trends may also be known by local drillers or geologists.

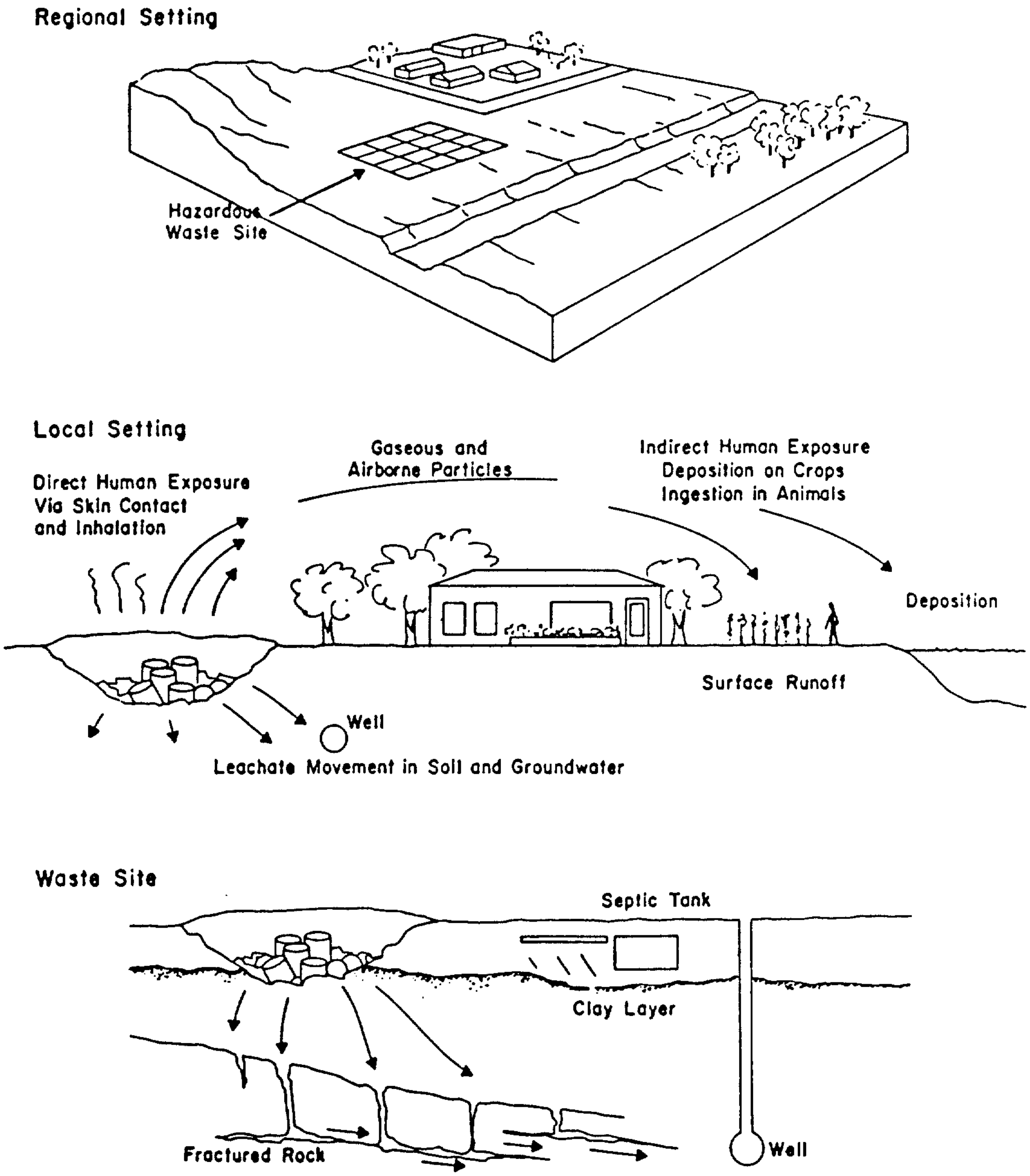


Figure 3. Regional, local and detail aspects of a hazardous waste site may all play a role in site investigation.

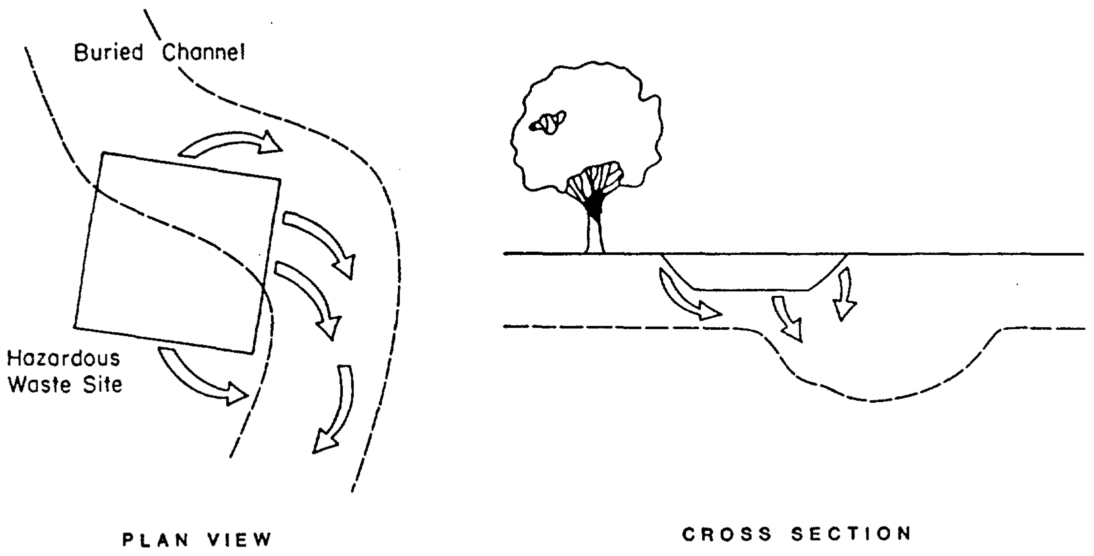


Figure 4. Buried stream channel may direct hazardous waste flow.

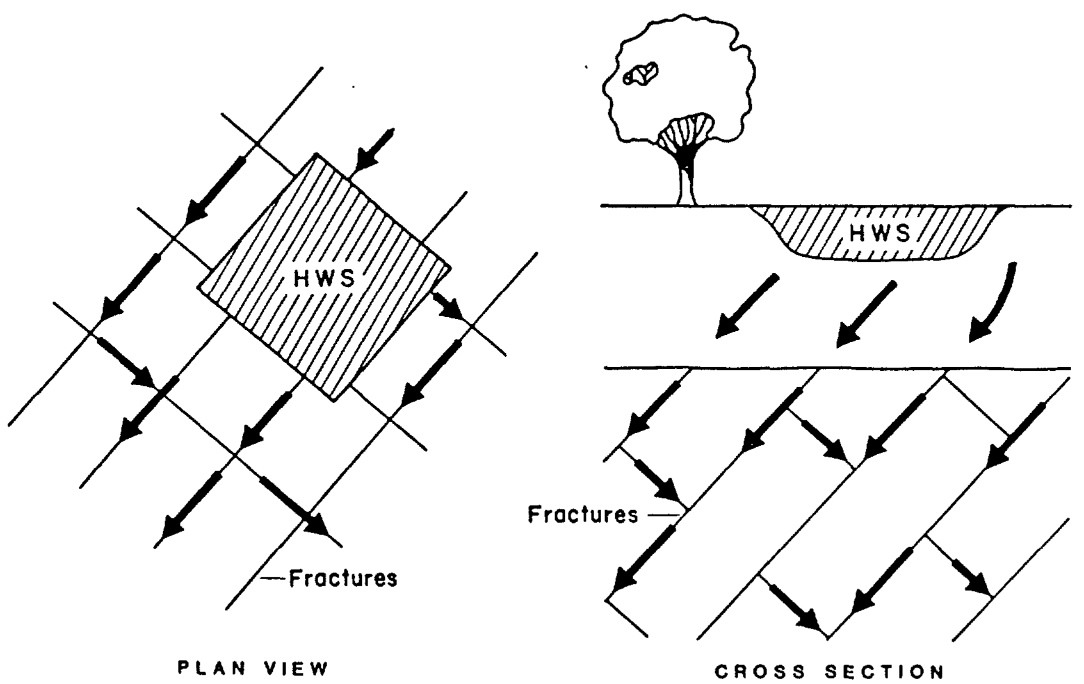


Figure 5. Fractured rock can direct hazardous waste flow.

Figure 6 illustrates the influence that the presence of dissolved limestone (karst) may have on a HWS. Soluble rocks such as limestone and slowly dissolved by natural waters. Caves and surface collapse result from this dissolution and associated erosion. Waterfilled caverns are often part of the ground water system under such conditions. In addition to these major water conduits, the existence of many smaller fractures leads to increased permeability. These site conditions are referred to as karst, and susceptible areas are well-known on a regional basis. Rapid and direct communication may occur between the HWS and local and regional ground water at such a site. Figure 7 shows the regional ground water at such a site. Figure 7 shows the distribution of soluble rock area in the United States. According to Davies of the U.S. Geological Society Survey, 15% of the United States has limestone or other soluble rock at or near the surface. If other forms of activity (pseudo-karst) and mining activites are included, up to 54% of the U.S. area is included.

2) Cultural Features

Cultural development and modifications can also affect the HWS. Paved areas and drainage systems concentrate surface waters. Trenches for buried pipes, sewer lines, telephone cables, and other utilities are often back-filled with materials which are more loosely packed, or more permeable than the natural soil and rock. These pathways are potential conduits for the rapid movement of contaminants, which have been observed following such pathways. The existence of canals and the pumping of ground water may influence migration of contaminants over the surface and into ground water. In addition, leaks from many pipes or tanks are sources of pollution.

3) Hazardous Waste: Types, Forms, and Methods of Disposal

The Resource Conservation and Recovery Act (RCRA) defines a hazardous waste as that which can cause substantial damage to health or environment when improperly managed. The definition of hazardous wastes includes four characteristics:

- o Ignitability
- o Corrosivity
- o Reactivity
- o Toxicity

To determine if wastes may cause or potentially cause "substantial" hazard to human health or the environment, other factors can be considered:

- o degree of toxicity
- o concentrations
- o potential to migrate into the environment
- o potential to bioaccumulate
- o possibility of improper management

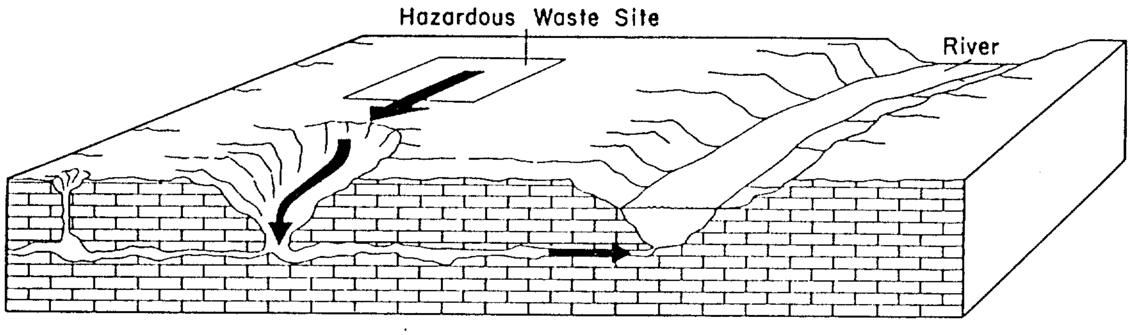


Figure 6. Cross section of karst area showing potential for rapid transport of ground water contamination to nearby stream.

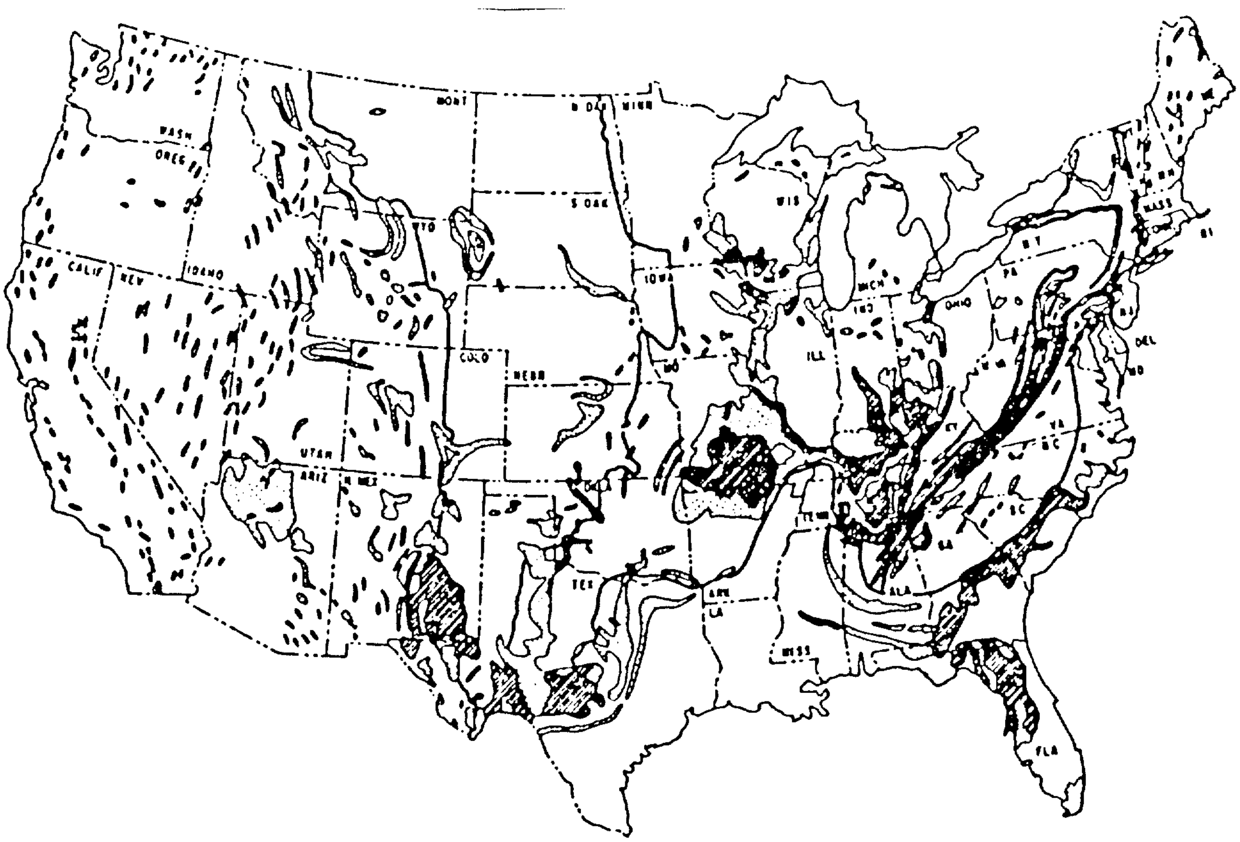


Figure 7. Distribution of karst areas in the U.S. (Ref. Davies USGS).

- o quantities of the waste
- o historic records of human health and environmental damage

The site investigator must be prepared for and deal with virtually any material and condition. These materials may be hydrocarbons, organic complexes, herbicides, pesticides, toxic gases, heavy metals, explosives, fly ash, sludge, specific or complex industrial processing wastes, or radioactive substances. They may be in the form of gases, liquids, powders, sludges, and solids--alone or mixed with general debris.

Waste materials may be buried or found as surface or subsurface leaks and spills. They may leak or evaporate from impoundments, or may simply be left abandoned on the surface. In some cases, materials have been disposed of in rivers or estuaries. Some will mix readily with water and some will not. Many components at a HWS will migrate rapidly through the unsaturated and saturated zones. Others will move more slowly and can be attenuated by various chemical and biological mechanisms during transport. Denser contaminants will sink more rapidly due to their weight, while hydrocarbons, which are lighter, will float on water.

The type of hazardous waste, its method of disposal, and its behavior in the environment are quite varied. The investigator must be aware of these factors when considering his technical approach, so that he may select an optimal combination of technologies.

4) Interaction of Wastes and the Natural Setting

Many contaminants will move by advection along with ground water flow and become dispersed by mechanical dispersion and molecular diffusion. These processes cause spreading of the contaminant, not only along the line of flow but also transverse to the flow path. It is possible for some contaminants (conservative parameters) to travel for long distances and to spread out over large areas as a result of these processes. One such plume had migrated more than 8 miles in 35 years and had contaminated the ground water in over 10 square miles.

Regional and local ground water flow will often differ due to influences of pumping, presence of canals, lakes and impoundments, and runoff, as well as local changes in soil and rock permeability. Flow rates are commonly estimated based on soil or rock permeabilities shown in reference literature or from laboratory tests; however, these usually indicate lower permeability than is observed in the field. Furthermore, permeabilities are commonly referenced to water as the pore fluid, whereas permeabilities based upon specific chemicals are often found to differ significantly. Some chemicals have been observed to migrate up to 10 times faster than ground water. In addition to influencing flow rates, certain chemicals may react directly with the natural soil or clay liner materials to increase their permeability, as for example by desiccation cracking of these materials. Accordingly, it is important to know not only the type of contaminant, but also the kinds of materials within which the contaminant is contained or is migrating.

Physical and chemical characteristics of soil and rock, and biologic factors will significantly influence the transport and attenuation of many hazardous materials. Some contaminants will be retarded or attenuated as they move into the soil or with the ground water. Materials such as heavy metals and PCB's are often readily attenuated by absorption or adsorption. If these materials pass through clays or natural organics (mucks, peats), they are attenuated more than by passing through clean sand. Clean fine sands will provide greater attenuation than will more permeable materials, such as coarse sands or highly permeable limestone. This increased attenuation can signficantly retard the extent of contamination.

Low pH materials (acids) will be neutralized by the car– bonates of natural limestone and by the buffering effect of sea water. A chemically reducing environment will tend to immobilize or retard the movement of heavy metals, while an acid environment will allow metals to move more freely. In many cases bacterial action will significantly reduce hydrocarbon fuel oil concen- trations.

The many ways in which contaminants can interact, be absorbed or released from the soils, and migrate through the unsaturated and saturated zones will influence the technical approach selected for subsurface investigation.

5) Site Surveying and Positioning

It is critical to any field work that the investigator be able to position himself and the data with adequate accuracy. Further, it is important that other investigators be able to return to any location with the desired level of accuracy, so that data obtained from various investigations may be compared. On the other hand, it makes no sense to spend time and money on plotting a survey grid with a high degree of accuracy if such accuracy is unnecessary.

The level of precision and accuracy necessary will depend on whether general reconnaissance or detailed work is in order, and how the information is to be subsequently used. In some cases, plus or minus 10 feet will be more than adequate; in others, a tolerance of a few inches will be required. In some cases only a random walk search with no pre-search survey grid laid in may be needed to look for buried drums. If a trench with drums is detected, its boundary may then be surveyed and mapped.

When survey grids are required, they may be laid down relative to some on-site reference points, and may be paced off, or located by tape measure. If it is required that the data then be located by tape measure and reference points, a professional and survey crew should be engaged.

6) Safety Aspects

HWS operations require that suitable health and safety precautions be met. The site must be initially characterized so that a suitable health/safety plan can be implemented. Continuous atmospheric monitoring may be required if digging, drilling, or drum sampling activity is taking place. Decontamination of both materials and personnel must be considered in on-site operations. Special training, equipment and standards must be utilized for field activities. Crews dressed in heavy, hot protective clothing will certainly work at decreased efficiency. Therefore, increased time and costs of site surveys will result from increased levels of safety requirements.

Another safety problem to be considered is the risk of drilling at a HWS without prior site characterization. As the number of drilled holes increases, the probabilty of accidentally hitting a target such as a buried drum of hazardous waste also rises. The methods discussed in this document may be used before drilling or backhoe work to characterize the site and minimize the likelihood of accidents and liability.

7) Logistics

A HWS may be located in a heavily-populated area (Love Canal, New York) or in a pasture many miles from the nearest town (Denney Farm Site, Missouri). Support facilities and their access are important to HWS investigations. The program should identify facilities such as airports, hotels and restaurants, as well as safety support such as hospitals, fire and police facilities. Water for drinking and decontamination purposes may have to be brought to the site by tank truck and special disposal arrangements, for wash-down water and other disposables, must be made.

Weather conditions will obviously affect personnel comfort and efficiency and may also influence technical work. If possible, field work should be scheduled in periods of good weather; if not, allowances should be made for unusual weather conditions, particularly if respirators, self-contained breathing apparatus (SCBA), or cumbersome protective clothing must be worn.

Site access is often a critical aspect of field work. Steep slopes, heavy vegetation or wet ground can inhibit movement of both personnel and equipment. Working access is sometimes required not only at the immediate site but also in the surrounding area, for tracing off-site contamination, or obtaining background reference data.

8) Legal

Suitable personnel ID's, procedures, and common courtesy are called for in dealing with people. In matters which will involve legal proceedings, the site investigator should consult with the project legal staff before beginning the job. While initial reconnaissance work may require only routine documentation, subsequent investigations may require extensive documentation for legal purposes. If the site investigation data are to be used in court, attention to proper documentation, traceability of samples, calibration and analysis will be important. There may be legal obstacles impeding site access, due to liability considerations and/or legal actions in process.

9) Social

Social and political aspects of HWS investigations are worthy of attention. Will local residents, special interest groups, agencies or industries be hostile in any way to the presence of a field team? Is a "low profile" of activities required to avoid unnecessarily alarming people? Are press statements necessary and should a specific person be assigned this responsibility? Will private citizens come in contact with the HWS operation? What safety measures may be required for nearby residents or passersby?

10) Economics

It is essential to develop a technical plan and budget which are compatible and which meet the objectives. However, some flexibility should be incorporated into both the technical program and the budget, because the complexity of HWS assessments will not generally allow a detailed technical plan, and unforeseen variations are bound to occur.

Summary

It should be apparent that the HWS investigation is a complex problem because of the many variables involved. Generally the simple first-order approximations of site conditions will be addressed first and then information will be upgraded as budgets and time permit. The skills, tools and effort brought to bear should be focused to bring about a rapid convergence of information and results, to avoid (or at least minimize) some of the pitfalls of the traditional approach. Practically speaking, one cannot expect to obtain results that are 100% accurate; the investigator must understand the possible effects of the variables involved and he must be able to judge when he is close enough to the project objectives.

SECTION III

EVALUATION OF SUBSURFACE CONDITIONS

Background

In any subsurface assessment, the investigator hopes to find a simple "layer cake" system of uniform, flat-lying soil and rock strata (Figure 8). In the real world, however, conditions are not so simple. Major variations in the soil and rock profiles occur in both horizontal and vertical directions (Figures 9 and 10). These spatial variations can range from macroscopic to microscopic, and they all can affect HWS conditions.

Subsurface variations are controlled by the stratigraphy and structure of the geologic deposits and formations. Although the individual geologic formations may be homogeneous, an entire section may be heterogeneous because of differences in hydraulic permeability between layers. Structural features such as joints, fractures, folds and faults also influence the direction and speed of water movement within the bedrock. Even mineral composition or grain size substantially influence water seepage, and therefore the movement of contaminants. This geologic heterogeneity can have a profound effect on the interrelationship between regional and local ground water flow systems.

Both natural and man-induced factors can affect subsurface conditions. Increased precipitation will lead to greater leachate production from landfills, provide rapid transport of contaminants by surface water, and may also provide a benefit by diluting contaminants. Hydrocarbons or other light materials will float on top of ground water, in the form of a surface lens. In shallow water table conditions, elevation of the water table by heavy rainfall may cause the movement of an otherwise immobile contaminant. Man-induced fluctuations include pumping of ground water for agricultural, industrial. or drinking purposes. Nearby pumping will often influence the direction and rate of local ground water and contaminant flow. Accurate measurement of subsurface conditions becomes more difficult as both natural and man-induced variables increase site complexity.

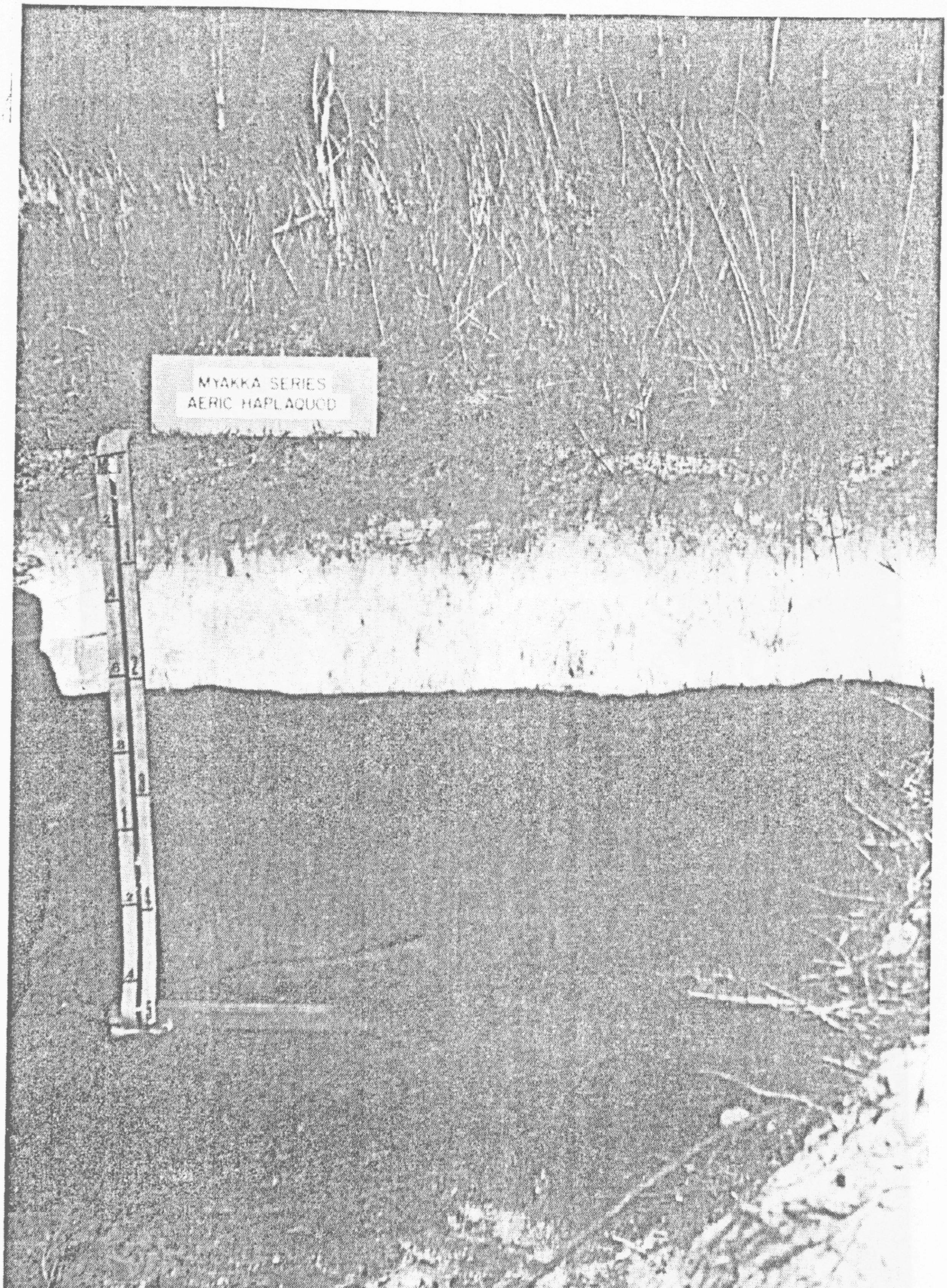


Figure 8. Uniform "layer cake" soils.

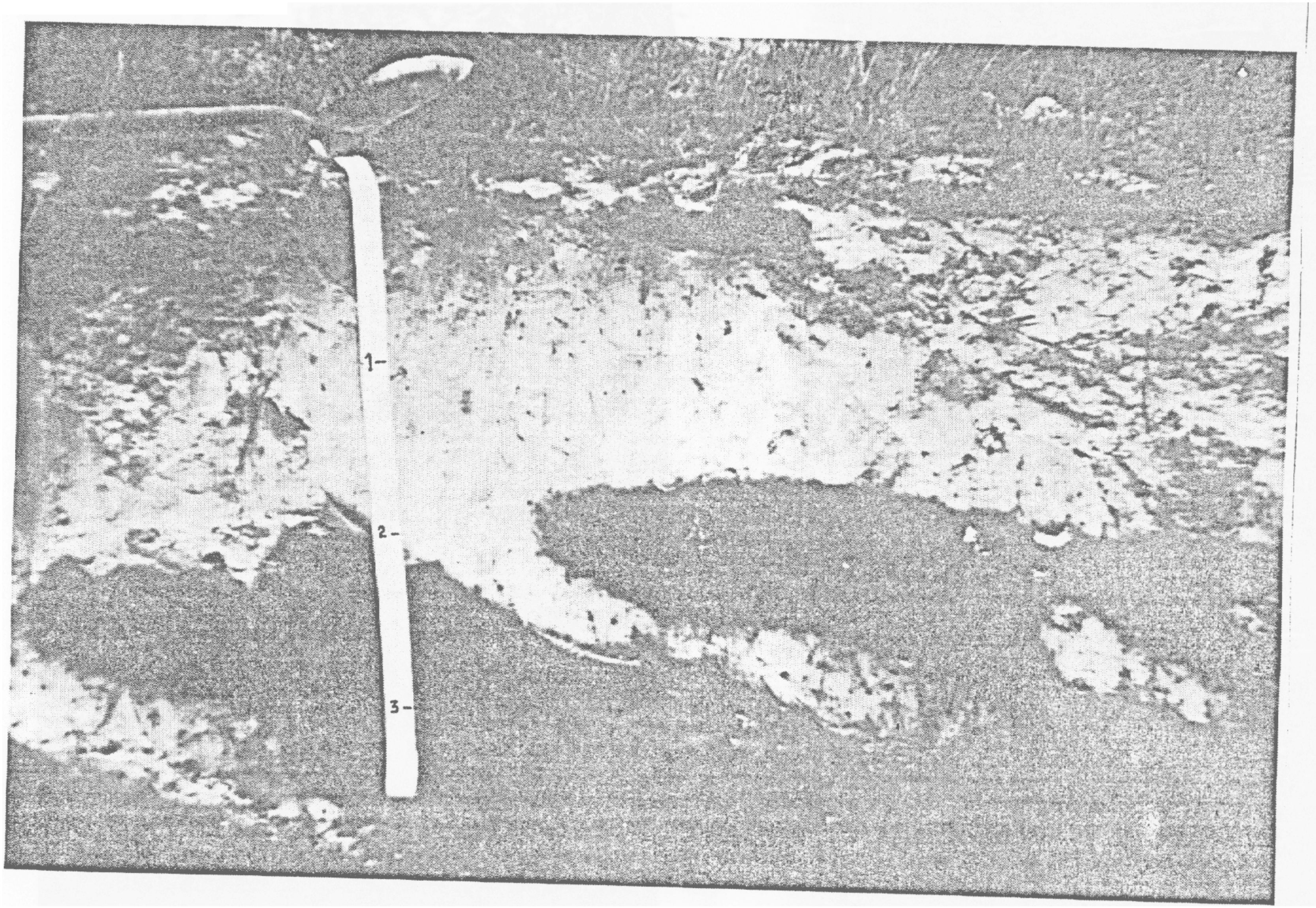


Figure 9. A complex soil horizon.

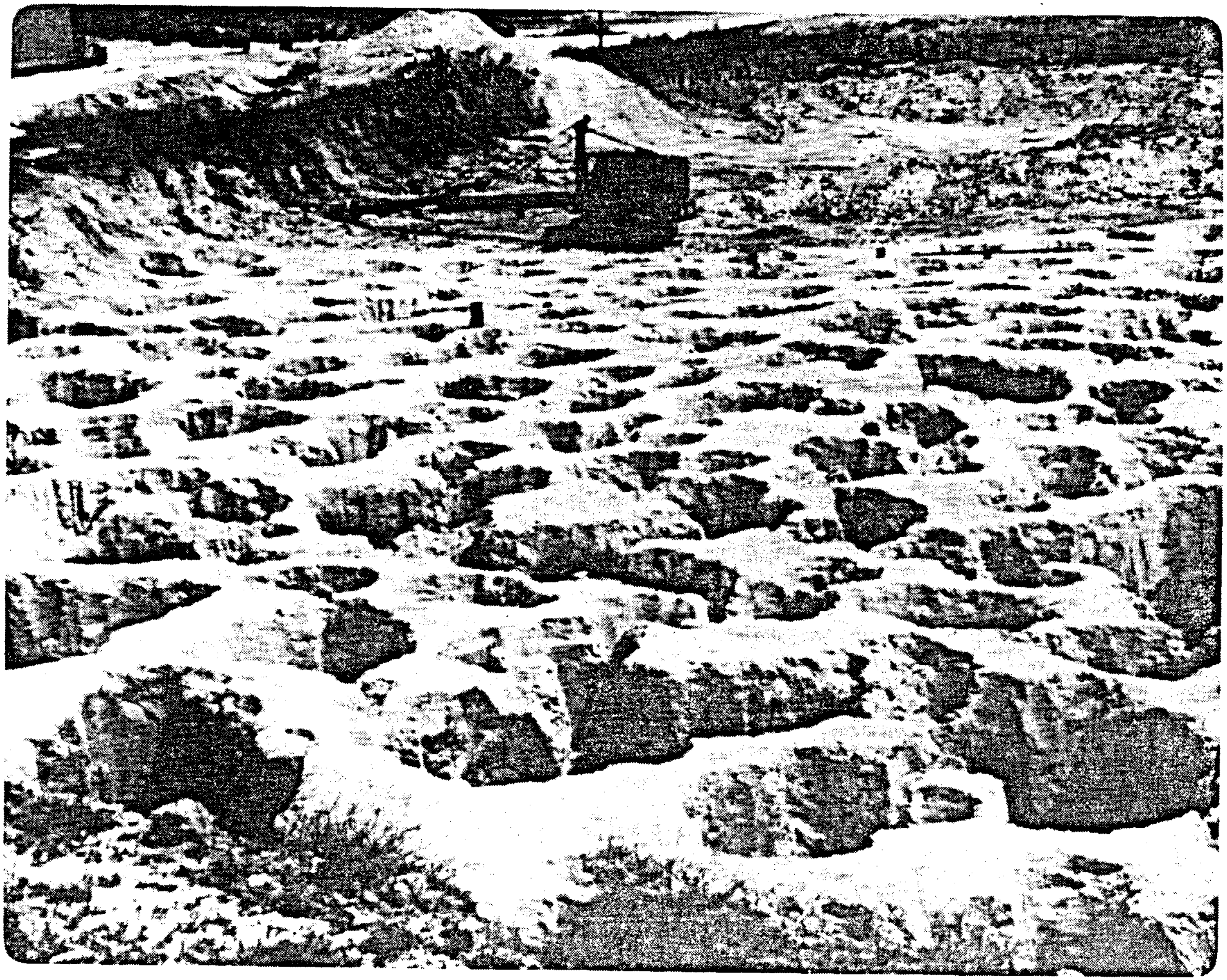


Figure 10. Solution-eroded limestone. The overburden has been removed from the limestone so it can be mined.

Limitations and Requirements of Spatial Sampling

In monitoring a HWS, the new Resource Conservation and Recovery Act (RCRA) standards require the installation of at least one upgradient well and three downgradient wells to monitor ground water contamination (Figure 11). No reference is made to well locations or their relation to uniformity of site conditions.

The soil sample obtained from drilling, or the water sample from a monitor well, is representative only of the immediate surroundings from which it came, as shown in Figure 12. If the subsurface geologic and hydrologic parameters are highly variable, serious omissions and errors often result from the interpretation of a limited number of sampling points. Clearly, in order to reach a high level of accuracy, a statistically valid sampling program must be implemented which anticipates the possibility of site variability.

An insight to the number of discrete samples that are required for site definition can be obtained by considering detection probability curves. Figure 13 shows a burial site which is 1/10 of the total site area. (The size and location of the target area are usually unknown.) Based upon detection probability calculations, the number of samples or borings required to achieve various detection probabilities at this site is shown in Figure 14. More than ten holes are required for a uniform grid search pattern and more than 40 are needed for a random search pattern, in order to achieve a probability of detection approaching 100%. If an error is made in estimating the target size, and it is in fact smaller than assumed, a much lower detection probability will result. A series of "misses" in a drilling program will obviously lead to an erroneous conclusion as to the presence or absence of a target.

With a smaller target, such as with a fracture system a few inches in width, the As/At ratio (site to target area ratio) increases significantly, and assessment by drilling becomes almost impossible. Typical As/At ratios at various hazardous waste sites may range from less than 10 to more than 1,000. As this ratio increases, the search problem can rapidly become comparable to "looking for a needle in a haystack".

The above example discusses only the problem of hitting the target, which requires only one contact; it does not address the problem of definition of the target's shape. Additional sampling will be required to establish the spatial extent of the target and to define its perimeter. As the shape of the site becomes more complex, or if it is made up of several smaller sites, or if the project requirements dictate that detailed boundaries be established, the number of borings needed will increase greatly. It is obvious that to achieve a good statistical evaluation of complex site conditions would require test holes to be placed in a close-order grid, which would reduce the site to "Swiss cheese".

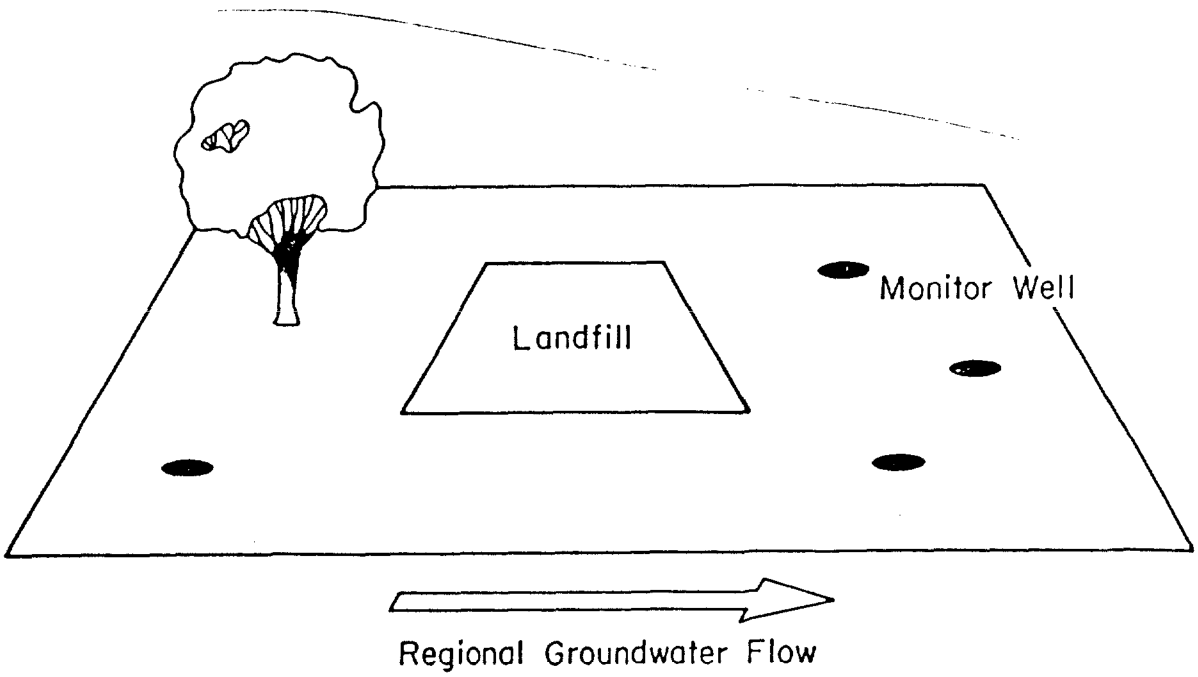


Figure 11. Four monitoring wells are the minimum required by RCRA.

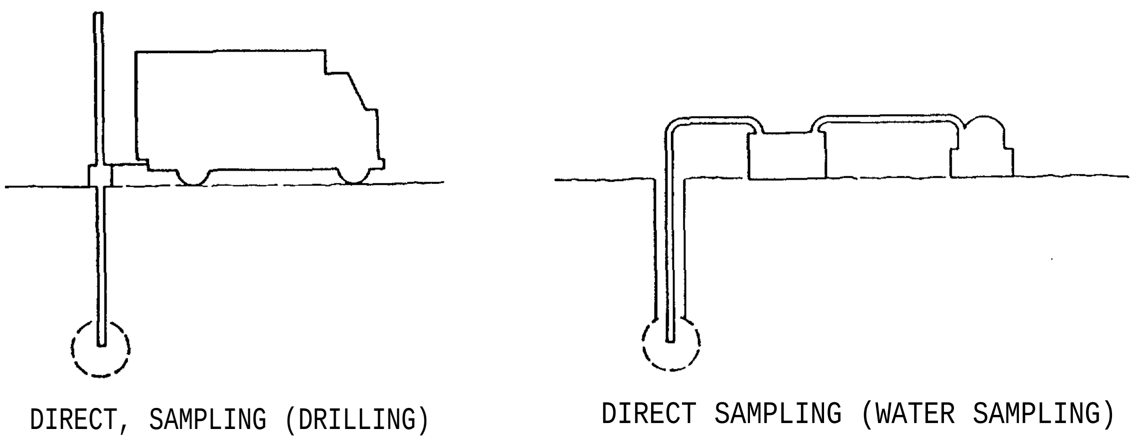


Figure 12. Sample from drilling and monitor wells is only representative of the immediate area.

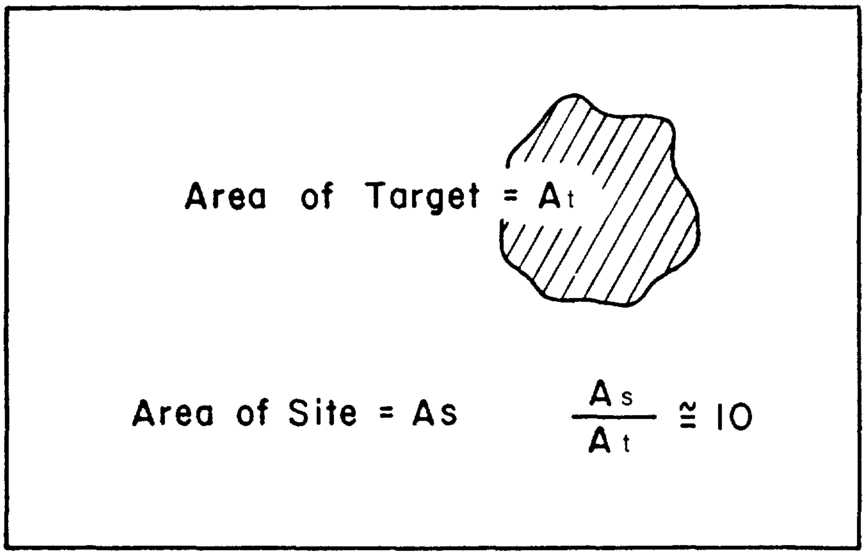


Figure 13. Ratio of overall site area to target area is often large. Target area may represent a plume or burial site. Smaller targets become more difficult to find.

Other Errors Associated with Monitor Wells

In addition to the potential errors introduced from placement and the number of borings, samples and monitor wells, factors such as poor quality monitor well construction, improper sampling or preservation of samples, and imprecise analytical methods may lead to other errors in site assessment. Improperly sealed well screen intervals may produce unrepresentative samples, and create cross-contamination problems. Even with properly installed wells, the collection of representative water samples is not easily accomplished. Furthermore, the water chemistry within the monitor well will often change with time making the result time-dependent. Depending upon the type of sampling device used and the extent of well development, the chemical parameter measured can present a distorted view of site conditions. The effort to collect a representative ground water sample is futile if the chemical composition changes between the time of collection and the time of analysis, due to improper sample preservation and storage.

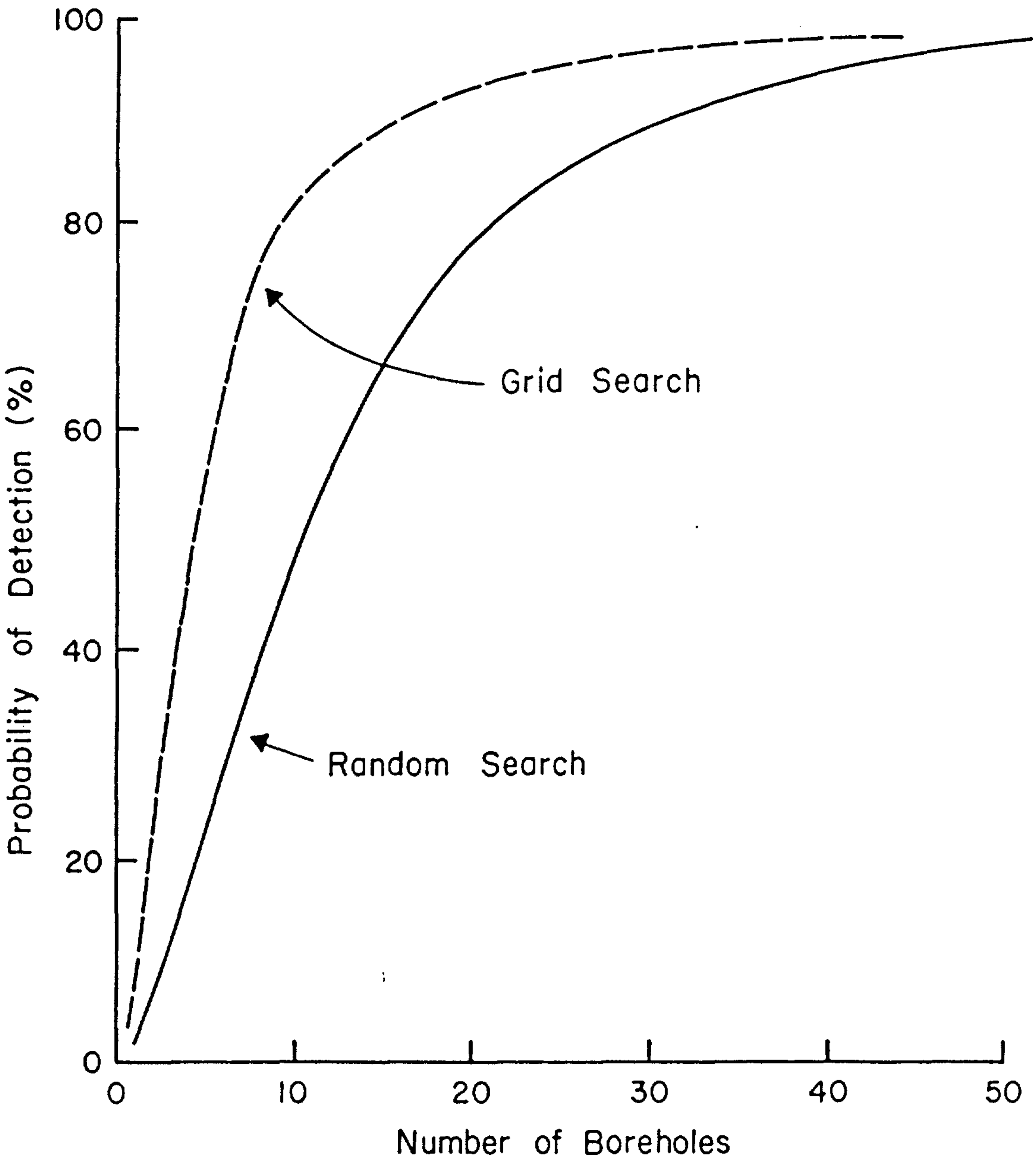


Figure 14. Probability of detecting a target using a rectangular grid and randomly located borings. Data for A_s/A_t Ratio of 10.

Errors associated with the location and sampling of monitor wells are not well understood and are commonly ignored, and the resulting interpretations and calculations are based upon assumptions of ideal conditions. While the resulting calculations may appear convincing, if they are based upon conditions which are not representative, they can lead to significant errors.

Safety and Risk Factors

An important factor in HWS assessment is the risk associated with drilling for monitor wells and exploratory holes in unknown conditions at hazardous waste sites. As the number of holes needed to define a problem area increases, so does the possibility of penetrating buried containers or trenches, and exposing field crews to toxic fumes and liquids. In extreme cases, the detonation of explosive materials and fire may result. In addition, there is the risk of cross-contamination which can result from a drill penetrating a natural or man-made seal. The hole may then act as a seepage route, possibly releasing contaminants into more permeable soil horizons or fractured rock, and ultimately into contact with ground water.

An Alternative Approach--Geophysical Methods

The previous discussion has been centered around the traditional approach to characterizing subsurface conditions by drilling and soil sampling, monitor wells, and water sample analysis. The general philosophy of the discussion applies to any direct sampling discrete measurements. In making such measurements, it has been pointed out, a statistically significant number of samples must be obtained to assure a reasonable level of definition and accuracy The deficiencies of using the traditional approach alone have recently been identified in technical seminars and literature. What is needed is a means to optimize the approach to site assessment, to maximize the benefits obtained in exchange for invested dollars, while reaching a reasonable level of technical accuracy. More cost-effective reconnaissance techniques are needed, which provide rapid, continuous spatial coverage, and reduce the risk of contamination and other hazards associated with conventional drilling programs alone. Using remote-sensing geophysical methods in an integrated systems approach is a proven way of achieving these objectives. Such an approach does not eliminate drilling and monitor wells--nor can it hope to compensate for poorly constructed wells--but it does provide us with an improved understanding of site conditions, and helps us to place monitor wells in the right locations to be representative of site conditions.

What is Remote Sensing and Geophysics?

Our eyes are remote-sensing devices; they produce images of the spatial variations of electromagnetic energy within-the visible portion of the spectrum. The term remote sensing is usually associated with aerial photography or complex computer images derived from Landsat satellites. However, there are many other types of remote sensing.

Some forms of remote sensing produce a representative measurement, rather than an image. Temperature, for example, may be measured directly by a common thermometer or by a remote infrared sensor. Geophysical measurements are remote–sensing methods, because by their nature they respond to changes in physical and/or chemical parameters at a distance.

Geophysical measurement systems cover an extremely wide range of techniques, applied to such fields as space exploration, earthquake monitoring, and mineral exploration. One of the more familiar geophysical methods is the seismic reflection technique used by all major oil companies for selecting sites for exploratory oil wells. An "acoustic" signal is generated near the surface, and travels thousands of feet into the subsurface. Reflections of these signals are returned from various rock interfaces and are recorded to produce a geologic profile or cross section of the area. An examination of this cross section then reveals to the trained geologist the most promising locations to drill for oil and gas.

Direct and Indirect Measurements

A soil or rock sample from a drill rig may be examined visually and analytically for physical and chemical properties. If, for example, the drilling log locates rock at a depth of 10 feet below the surface, it has determined the depth to top of rock at that specific location. Such an observation is a direct observation or measurement. Many other strategies are available for determining depth to rock by less direct means. For example, a probe could be driven into the ground and the force or number of hammer blows could be measured. When we hit the rock, we might expect that the measurement of force or blow counts would increase, indicating the top of the rock. Such a determination would be an indirect measurement of the top of the rock. We have actually measured force or blow count, and have used it as an indicator of contact with the rock. A geophysical method would accomplish the same goal by measurement of some physical or electrical property difference between the soil and rock.

The measurements made by the seismic refraction method, for example, will yield an indirect measurement of depth to bedrock, which is based on a number of measurements and subsequent calculations. However, the seismic method also provides us with the seismic wave velocity of the rock (travel. time) which is in fact a direct measurement. Thus the geophysical methods can provide both indirect and direct measurement of subsurface properties.

The terms "direct measurement" and "indirect measurement" used in this document are open to some interpretation. The use of these terms is not intended to be definitive, but merely a convenient device to distinguish between two broad categories of measurements.

In-Situ Measurements

Some change or degradation in sample properties occurs when a sample is removed from its natural setting. In-situ measurements provide a means of in-place, non–destructive measurement and sometimes offer a more reliable mode of measurement than methods which require removal of a sample. Geophysical techniques provide the capabilities for such in–situ measurement of various physical and electrical properties under certain conditions. Besides these benefits, they provide a means of characterizing site conditions so that the danger of drilling into unforeseen hazards may be avoided.

Spatial Measurements

It has been previously established that when the number of borings or monitor wells is limited, results may not be representative of site conditions, and that in many cases, to examine site details adequately would have made "Swiss cheese" of the site. In general, data obtained from borings or monitor wells comes from discrete depths. Unlike such discrete sampling, which yields only limited spatial and volumetric information, geophysical methods measure a much larger volume of the subsurface, thereby increasing the volume sampled for a given measurement (Figure 15). This larger volume integrates any variations within the sample, and provides an "average picture" of subsurface conditions.

This aspect of geophysical measurement has both advantages and disadvantages. One advantage is that a larger volume of the subsurface is sampled with each measurement; a disadvantage is that if a feature or anomaly is small, it may not be detected in this larger volume. In practice then, there is a trade-off between the two methods: on the one hand, the possibility of obtaining better resolution through the use of direct sampling by drilling (a large number of samples is required); on the other, the more representative results provided by indirect sampling with geophysics. When combined in an optimal manner, the two methods complement one another to produce a highly accurate subsurface investigation. By using geophysical methods for locating anomalous and non-anomalous zones then converging on the critical areas with direct sampling, the survey can proceed rapidly to completion.

Most traditional geophysical techniques assess subsurface conditions by station measurements; however, some contemporary techniques can measure subsurface parameters continuously along survey lines (Figure 16). While theoretically the number of station measurements could be increased to achieve a density sufficient to yield the resolution of continuous measurements, to do so would be impractical in many cases for technical and economic reasons.

Although the continuous methods referred to in this document are typically limited to a depth of 15 meters or less, they are still to be preferred when applicable, as they enable site coverage to approach 100%. In addition, they offer significant benefits when applied to sites which are highly variable because they provide a continuity of subsurface information which is not practically obtainable from station measurements. Continuous geophysical methods can be applied at traverse speeds of 1 to 5 mph, resulting in a cost-effective approach for relatively shallow survey work. In order to illustrate the benefits of continuous measurements, a comparison of station measurements and continuous measurements is discussed below.

The lower data set in Figure 17 reveals the highly variable nature of a site as recorded by a continuous spatial measurement technique. The upper data plot shows the loss of information and misleading interpretations that can result from a limited number of station samples and interpolating between sample points. As can be seen, a limited number of measurements can result in distorted data. By increasing the number of station measurements, greater resolution and accuracy is attained.

Sampling of spatially varying data may be accurately accomplished by discrete as well as continuous measurements. If the size of the smallest feature in the data that will be of interest can be established, a survey can be designed to obtain adequate data from discrete station measurements. To accomplish this requires that an estimate be made before the survey is carried out. If our estimate is in error, our data will also be in error. To minimize the possibility of making such errors, to achieve maximum resolution, and to minimize project costs, continuous methods should be employed whenever possible, particularly when a small sample interval is required or site conditions are suspected of being highly variable.

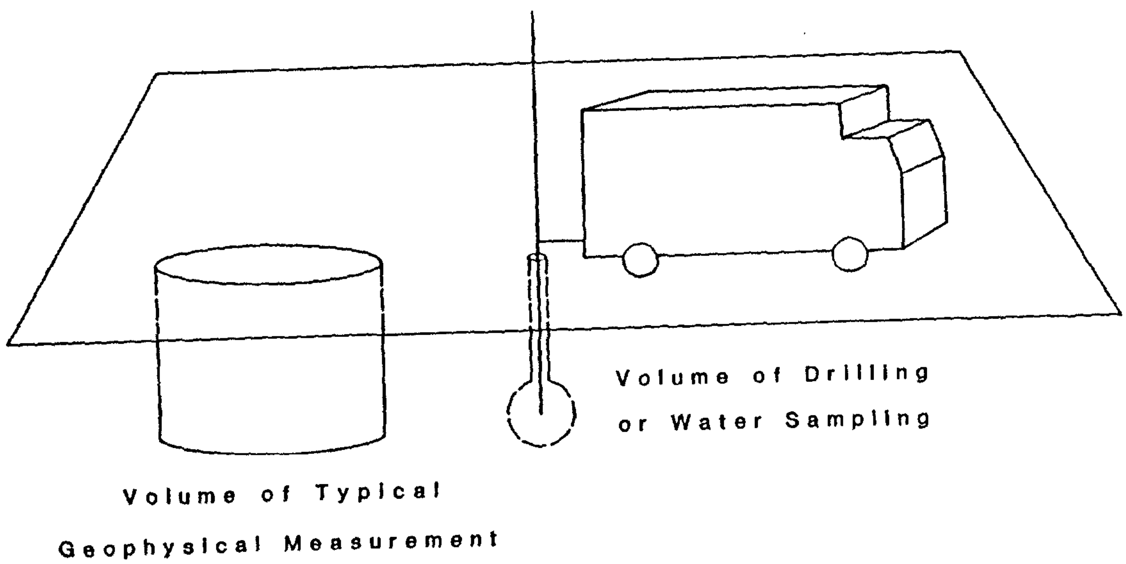


Figure 15. Simplified comparison of the volume sampled by geophysical and drilling methods.

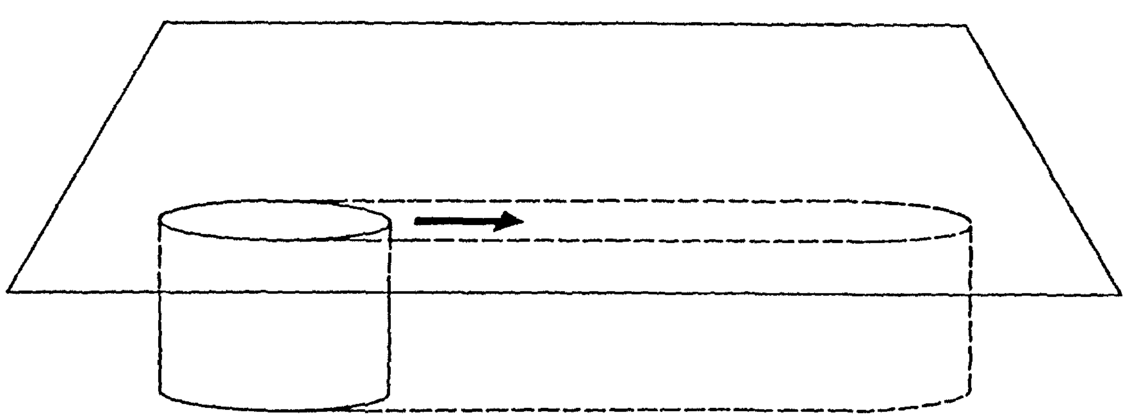


Figure 16. Simplified example of the volume sampled by continuous geophysical measurement.

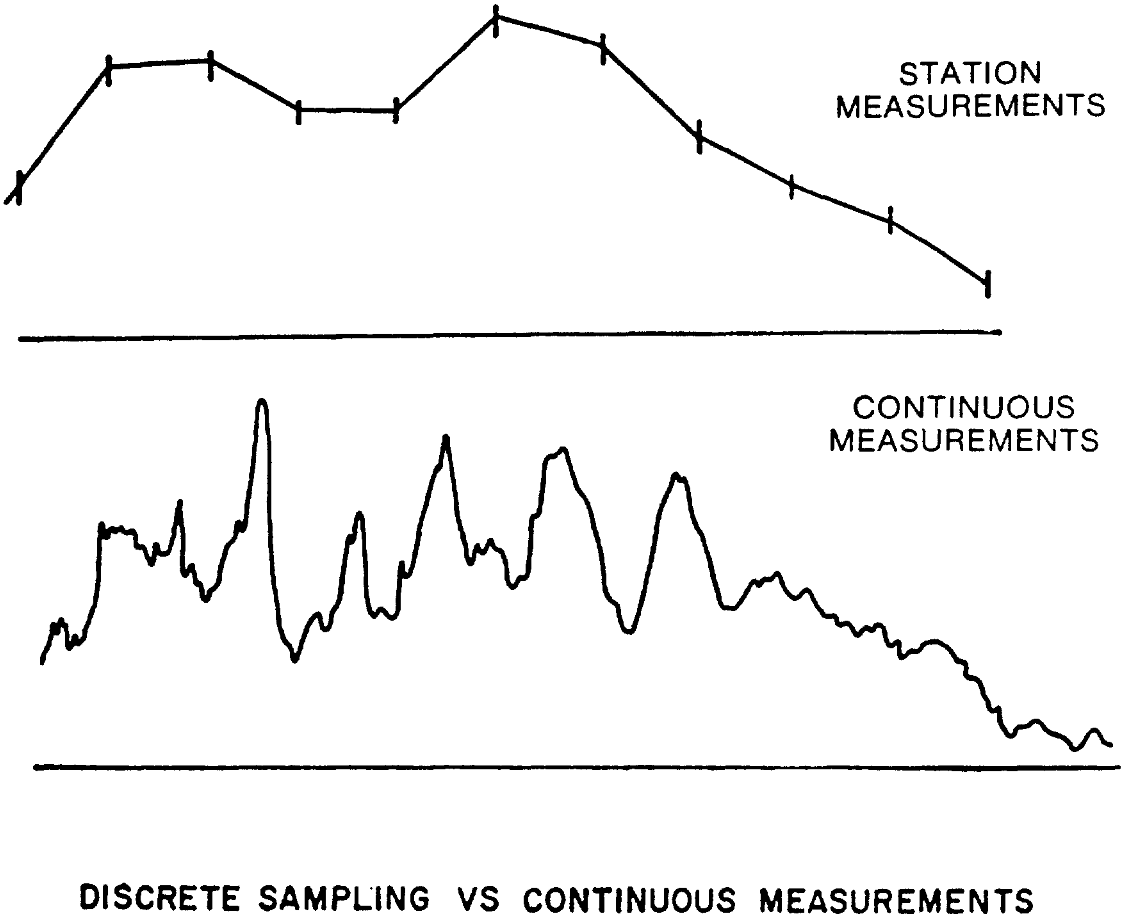


Figure 17. Continuous measurement will provide greater resolution than limited station measurements.

By running closely-spaced parallel survey lines with a continuous method, changes in subsurface parameters (electrical conductivity, for example) can be mapped, with the high-resolution response showing subtle details of site conditions. Results may be presented in the form of 3-dimensional figures or isopleth maps (Figures 18 & 19). With detailed data of this type, the confidence level in site assessment is high because the results are “continuous” and they show details which would be missed by other approaches. Attempting to obtain this level of data detail by drilling would have been unrealistic.

The data in Figures 18 & 19 are for the same site, and not only show where an anomaly occurs, but may also provide some idea of its size. With this information, the investigator can converge rapidly upon unusual conditions and proceed to drill and sample at discrete points in a logical manner independent of drilling grids or statistical methods. Often, no more than 3 to 6 direct samplings are needed to obtain a high-accuracy assessment of a HWS, once it has been characterized by such geophysical data.

Airborne, Surface, and Downhole Methods

Three possible ways of using the remote-sensing methods are illustrated in Figure 20:

- Airborne or satellite remote sensing clearly has merits, in terms of spatial coverage per unit time and cost, but relatively poor resolution of local details. It provides little, if any, subsurface data other than that which is derived by interpretation.

- Surface methods yield less spatial coverage per unit time but can significantly improve resolution while providing subsurface information. A three-dimensional "picture" can often be generated using special measurement techniques. An inherent limitation of all surface geophysical methods is that their resolution (ability to detect a small feature) decreases with depth.

- Downhole or hole-to-hole methods (lowering various sensors

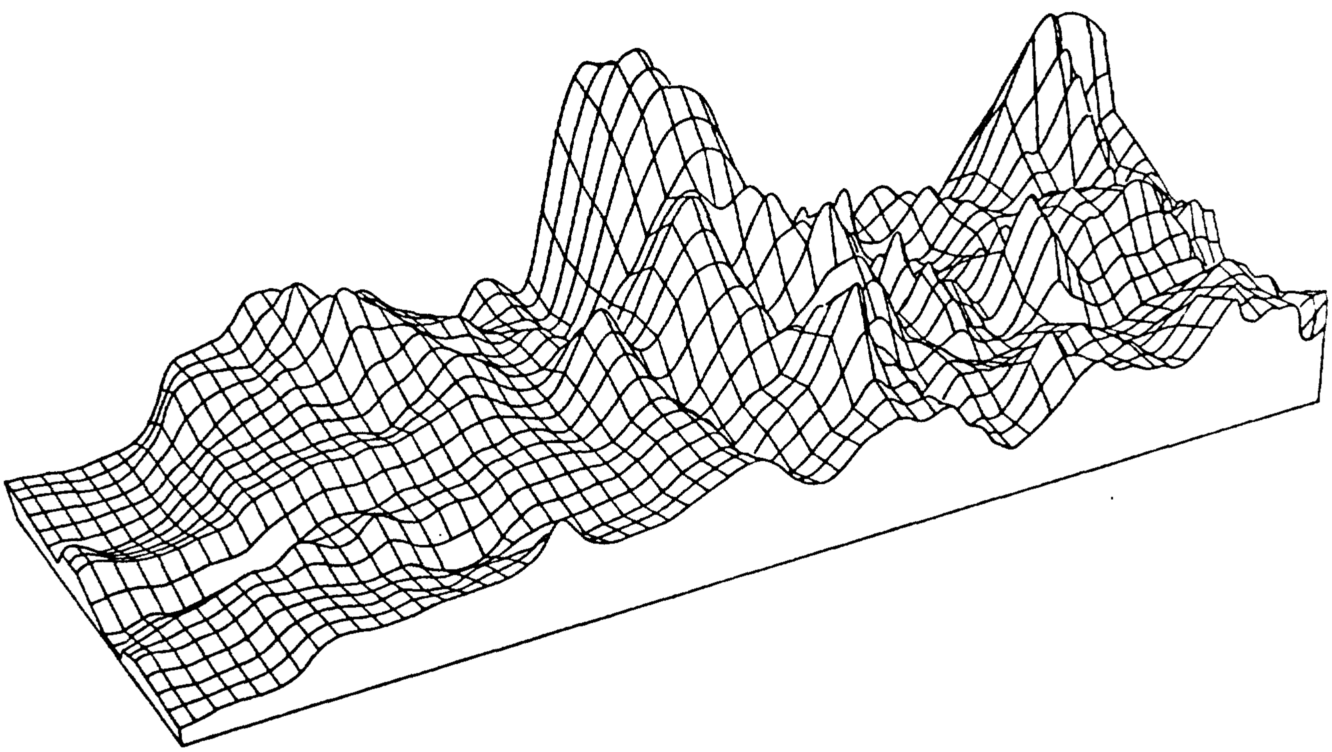


Figure 18. Three-dimensional perspective view of geophysical electrical conductivity data from parallel transects across a hazardous waste site.

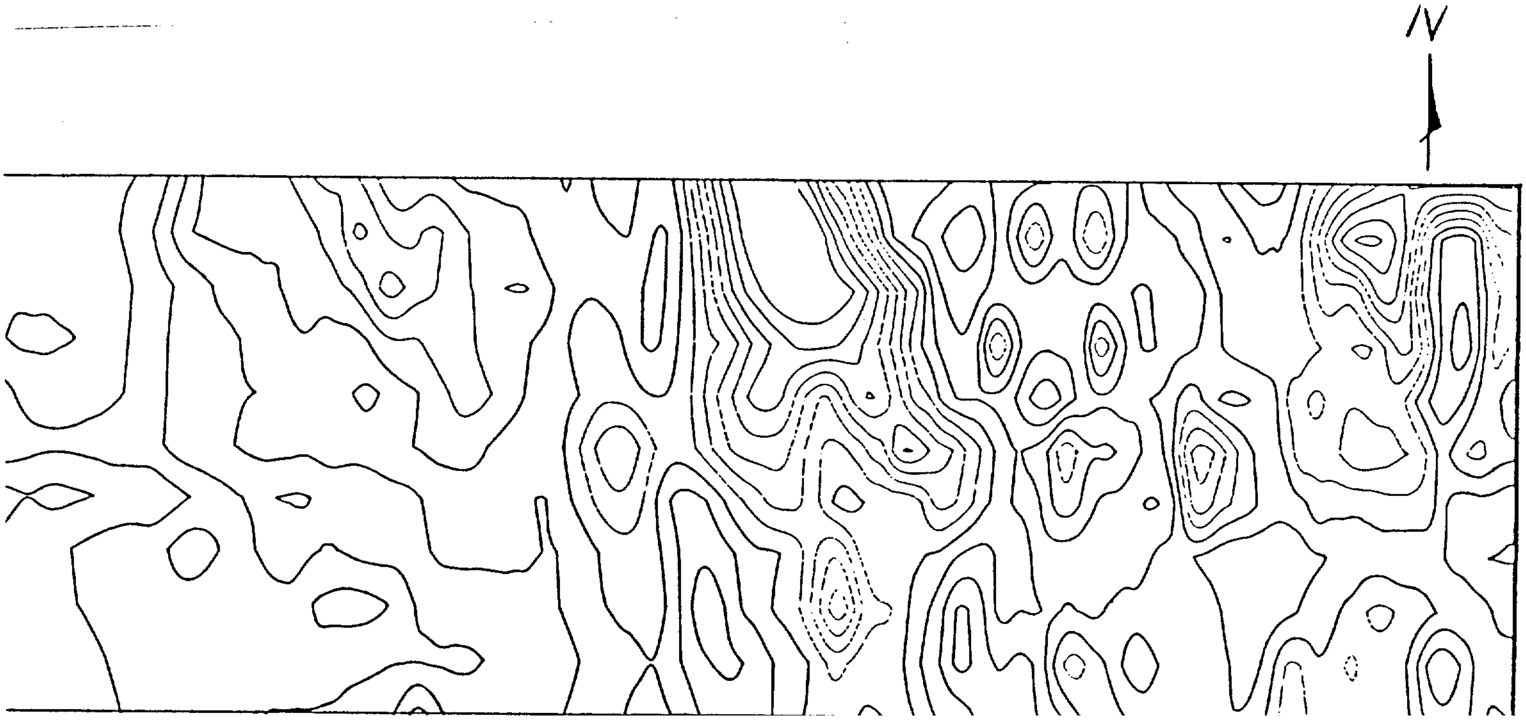


Figure 19. Isopleth map of geophysical electrical conductivity data shown in Figure 18.

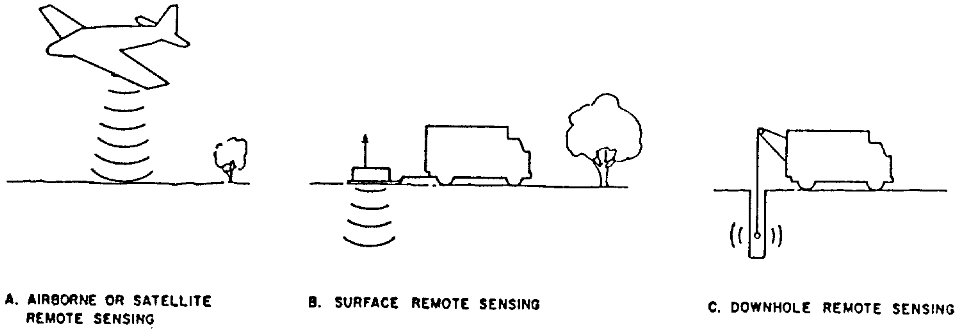


Figure 20. Three modes of using remote sensing (geophysical) methods.

down boreholes) will improve vertical resolution over surface methods, but the volume sampled is usually limited to the area immediately around the boring, or that between two borings, and the cost per unit area is high. However, if holes are already in place, or if they are to be drilled for other purposes, the overall cost can be reduced. The major benefit of downhole methods is that detailed high-resolution information may be acquired at significant depths.

All three approaches--airborne, surface, and downhole--have a place in subsurface investigation. However this document will be limited to a discussion of six selected surface geophysical methods.

Since each geophysical method measures a different subsurface parameter, the information obtained from one sensor is often complemented by that from another. The synergistic use of multiple geophysical techniques will often serve to enhance data interpretations. Those familiar with traditional well logging will recognize this concept, as multiple logs are commonly obtained for this purpose.

It should be noted that the performance of any geophysical technique depends on its specific application and site conditions. No single method, therefore, should be expected to solve all site evaluation problems. Furthermore, geophysical technology is not in itself a panacea; its successful application is dependent upon integrating the geophysical data with other sources of information. This must be done by persons with training and experience in the methodology, as well as the engineering and earth sciences.

An Integrated Systems Approach

In order to effectively utilize the benefits of both direct sampling and remote sensing techniques, an integrated systems approach is needed. The surface geophysical methods are generally used as reconnaissance tools to cover an area rapidly, searching for anomalous conditions. After these areas have been identified, the locations for drilling and monitor wells can be selected, with a high degree of confidence in their being located in the right places to produce a representative sampling of site conditions. Analyses of soil and water samples from such wells provide the necessary quantitative measurements of subsurface parameters. This approach creates much greater confidence in the final data interpretation with fewer wells and overall cost savings. Now the drilling operations are no longer being used for hit-or-miss reconnaissance, but rather as specific quantitative tools. The geophysical methods make rapid site coverage possible, followed by prompt convergence on potential. problem areas with direct sampling.

Even if monitor wells have already been installed, geophysical surveys can still provide significant benefits. The location of existing monitor wells relative to problem areas can be assessed, thus providing a means of evaluating the validity of data already acquired If additional wells are needed to fill gaps in the overall site coverage, they can be precisely placed.

Specific Geophysical Methods

The following sections of this document describe several surface geophysical methods and their applications. The six geophysical methods which have been selected for presentation are: Ground Penetrating Radar, Electromagnetic, Resistivity, Seismic Refraction, Metal Detection and Magnetometry. It is only in the past five to ten years that the geophysical methods have been extensively applied to shallow investigations, and only within the last five years have they been applied to hazardous waste site assessments. The results have been impressive and these methods are now rapidly gaining acceptance, often playing a pivotal role in hazardous waste site investigations.

Geophysical methods themselves have been used for many decades in the fields of exploration for oil, gas and minerals. The methods applied to these programs are highly developed and have been applied with great success for many years. Some geophysical methods have been found to be effective in engineering geology and ground water investigations, and their use has become widespread in these fields. While the basic concepts of the methods in all of these applications are similar, unfortunately the equipment and specifics, as applied to the deeper or larger oil, gas and mineral deposits, are not necessarily applicable to hazardous waste site investigations which require shallow, high-resolution surveys.

On the other hand, the seismic refraction and resistivity approaches used in the engineering geology and hydrologic fields are, in fact, directly applicable to hazardous waste sites. The electromagnetic and ground penetrating radar techniques discussed in this document are relatively new, and both have been readily adapted to hazardous waste site work. Metal detecting is not often considered to be a geophysical technique, although its principles of equipment operation are similar to the others. Treasure hunters, the armed services, and public utilities have used metal detectors to locate treasure, ordnance, and buried pipes and cables; the metal-detecting equipment and technology used at HWS has been developed from these applications. While the magnetometer does see extensive use in the fields of geology and geophysics, its primary use in the area of concern to this document is in finding ferrous metal objects: pipe/cable location, survey stake location, searching for lost aircraft and sunken ships, and archeology.

There are a number of new geophysical methods, and quite a few older ones, which in principle may be applicable to hazardous waste sute investigations. However, this document discusses only those methods which have met the following criteria:

- they are regularly used for hazardous waste site assessment;
- they have proven capability in hazardous waste site assessment;
- they are suitable for broad application to the problems typically found at hazardous waste sites.

The six selected geophysical methods are briefly described below, and are then described in further detail in sections IV through IX.

- Ground penetrating radar is a reflection technique using highfrequency radio waves, which are bounced off subsurface features. The picture-like presentation associated with the radar method is highly useful to evaluate details of subsurface conditions. Ground penetrating radar is used to detect natural geohydrologic conditions and the presence of both natural and man-made anomalous conditions. Of the contemporary geophysical methods, radar is one of the most effective and impressive; it offers the capability of continuous profiling information at speeds up to several miles per hour. Its performance, however, is highly site-specific and is limited to investigation at shallow depths.

- Electromagnetic allows measurement of subsurface electrical conductivities. Much as the chemist can measure the specific conductance of a water sample, the electromagnetic method can measure the conductivity of the subsurface including the water contained in the soil and rock. Measurements can be made as station measurements or as continuous profiling measurements. Because of the capability of making continuous profile measurements, the method enables subsurface details to be mapped effectively. The method provides the means of mapping contaminant plumes, locating trenches and buried waste, and identifying buried utility lines. It is one of the more powerful methods now being applied at hazardous waste sites.

- Resistivity is a traditional geophysical method by which measurements of subsurface electrical resistivity may be made. The method is somewhat analogous to the electromagnetic method and the data is related. Resistivity measurements must be made by station measurements and they can provide effective sounding, or vertical information, as to the depth and thickness of the subsurface layers. The method is also effective for profile measurements in the horizontal plane.

- Seismic refraction is also a traditional method, in that it has been extensively applied to shallow investigations. The method involves transmission of seismic waves into the ground, and by measurements of the travel time of the waves, the thicknesses and depths of geological layers can be established. The method can be applied to the location and definition of burial pits and trenches, as well as to providing information on the natural geohydrologic setting.

- Metal Detector--A metal detector will respond to both ferrous and non-ferrous metal objects. The metal detector can provide information as to drum location, as well as tank, pipe, and utility cable locations at or near a waste site.

- Magnetometry, the magnetic method, as discussed in this document, applies to the location of buried ferrous metals such as drums. By detecting anomalies in the earth's magnetic field caused by ferrous objects, the magnetometer provides a means of locating such objects. The magnetometer will respond only to ferrous metal, such as iron or steel; it does not respond to non-ferrous metals, such as copper, lead and brass.

Table 1 summarizes some applications of these six geophysical methods to hazardous waste site assessments.

SECTION IV

GROUND PENETRATING RADAR (GPR)*

Introduction

Ground penetrating radar (GPR) uses high frequency radio waves to acquire subsurface information. From a small antenna which is moved slowly across the surface of the ground, energy is radiated downward into the subsurface, then reflected back to the receiving antenna, where variations in the return signal are continuously recorded; this produces a continuous cross-sectional "picture" or profile of shallow subsurface conditions. These responses are caused by radar wave reflections from interfaces of materials having different electrical properties. Such reflections are often associated with natural geohydrologic conditions such as bedding, cementation, moisture and clay content, voids, fractures, and intrusions, as well as man-made objects. The radar method has been used at numerous HWS to evaluate natural soil and rock conditions, as well as to detect buried wastes.

Radar responds to changes in soil and rock conditions. An interface between two soil or rock layers having sufficiently different electrical properties will show up in the radar profile. Buried pipes and other discrete objects will also be detected.

Depth of penetration is highly site-specific, being dependent upon the properties of the site's soil and rock. The method is limited in depth by attenuation, primarily due to the higher electrical conductivity of subsurface materials. Generally, better overall penetration is achieved in dry, sandy or rocky areas; poorer results are obtained in

---

*GPR has been called by various names: ground piercing radar, ground probing radar and subsurface impulse radar. It is also known as an electromagnetic method (which in fact it is); however, since there are many other methods which are also electromagnetic, the term GPR has come into common use today, and will be used herein.

moist, clayey or conductive soils. However, many times data can be obtained from a considerable depth in saturated materials, if the specific conductance of the pore fluid is sufficiently low. Radar penetration from one to 10 meters is common.

The continuous nature of the radar method offers a number of advantages over some of the other geophysical methods. The continuous vertical profile produced by radar permits much more data to be gathered along a traverse, thereby providing a substantial increase in detail. The high speed of data acquisition permits many lines to be run across a site, and in some cases, total site coverage is economically feasible. Reconnaissance work or coverage of large areas can be accomplished using a vehicle to tow the radar antenna at speeds up to 8 KPH. Very high resolution work or work in areas where vehicles cannot travel can be accomplished by towing the antenna by hand at much slower speeds. Resolution ranges from centimeters to several meters depending upon the antenna (frequency) used.

Initial in-field analysis of the data is permitted by the picture-like quality of the radar results. Despite its simple graphic format, there are many pitfalls in the use of radar, and experienced personnel are required for its operation and for the interpretation of radar data.

Radar has effectively mapped soil layers, depth of bedrock, buried stream channels, rock fractures, and cavities in natural settings.

Radar applications to HWS assessments include:

- Evaluation of the natural soil and geologic conditions;
- Location and delineation of buried waste materials, including both bulk and drummed wastes;
- Location and delineation of contaminant plume areas;
- Location and mapping of buried utilities (both metallic and non-metallic).

Principles and Equipment

The radar system discussed in this document is a commercially-available impulse radar system. Continuous wave (CW) or other impulse systems exist, but they are generally one of a kind, being experimental. instruments, and are not discussed here.

Figure 21 shows a simplified block diagram of a radar system. The system consists of a control unit, antenna, graphic recorder and an optional magnetic tape recorder (Figure 22). In operation, the electronics are typically mounted in a vehicle. The antenna is connected by a cable and is mounted or towed behind the vehicle, or may be towed by hand. System power is usually supplied by a small gasoline generator. Various antennas may be used with the system to optimize the survey results for individual site conditions and specific requirements.

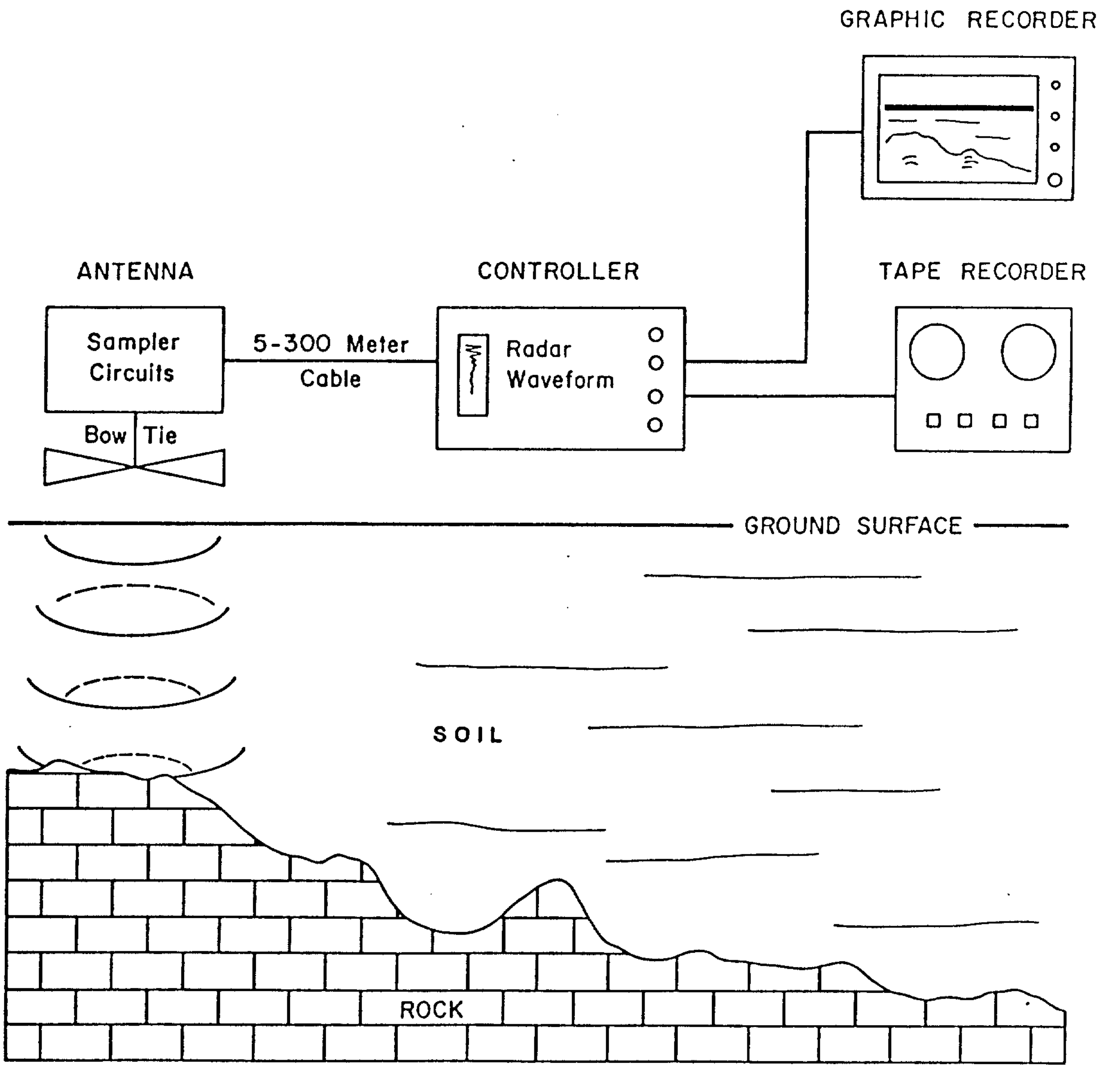


Figure 21. Block diagram of ground penetrating radar system. Radar waves are reflected from soil/rock interface.

The impulse radar transmits electromagnetic pulses of short duration into the ground from a broad-band antenna. The antenna is usually in close proximity to the surface of the ground.

Pulses radiated from the antenna are reflected from various interfaces within the subsurface and are picked up by the receiver section of the antenna. They are then returned to the control unit for processing and display. The radar data can be recorded by a graphic recorder and/or a magnetic tape recorder. The graphic recorder provides a picture-like display of the radar data (Figure 23). Radar reflections will be returned from any natural or man-made object which has a contrast in its dielectric properties. Reflections from deeper targets will appear lower on the graphic display.

The time the electromagnetic pulse takes to travel from the antenna to the buried object and back to the antenna is proportional to the depth of the buried interface or object. This time is called two-way travel time and is dependent on the dielectric properties of the media through which the pulse travels. These dielectric properties are in turn a complex function of the composition and moisture content of the subsurface soil and rock materials. Table 2 shows the range of dielectric values, velocities and two-way travel times for various natural materials. In almost all cases, the moisture content has the greatest influence, because water has a very high relative dielectric value compared to common soils and rock. The greater the amount of water saturation, the lower the radar velocity, as given by:

$$VM = \frac{c}{\sqrt{\varepsilon_r}}$$

Accordingly, the lower the velocity, the lower the object will appear in the radar record. Depth is calculated from this velocity using:

$$D = \frac{cT}{2\sqrt{\varepsilon_r}} = \frac{VmT}{2}$$

where Vm = velocity in material
c = a constant, the velocity of light (3 x 10 m/see)
εr = relative dielectric constant
T = two-way travel time in nanoseconds
(1 nanosecond (ns) = 10 seconds)

Depth of penetration is a function of the radar signal attenuation within the subsurface media. This attenuation consists of electrical losses, scattering losses and spreading losses. Since spreading losses are inherent in the radar systems, they are constant and will not be considered further.

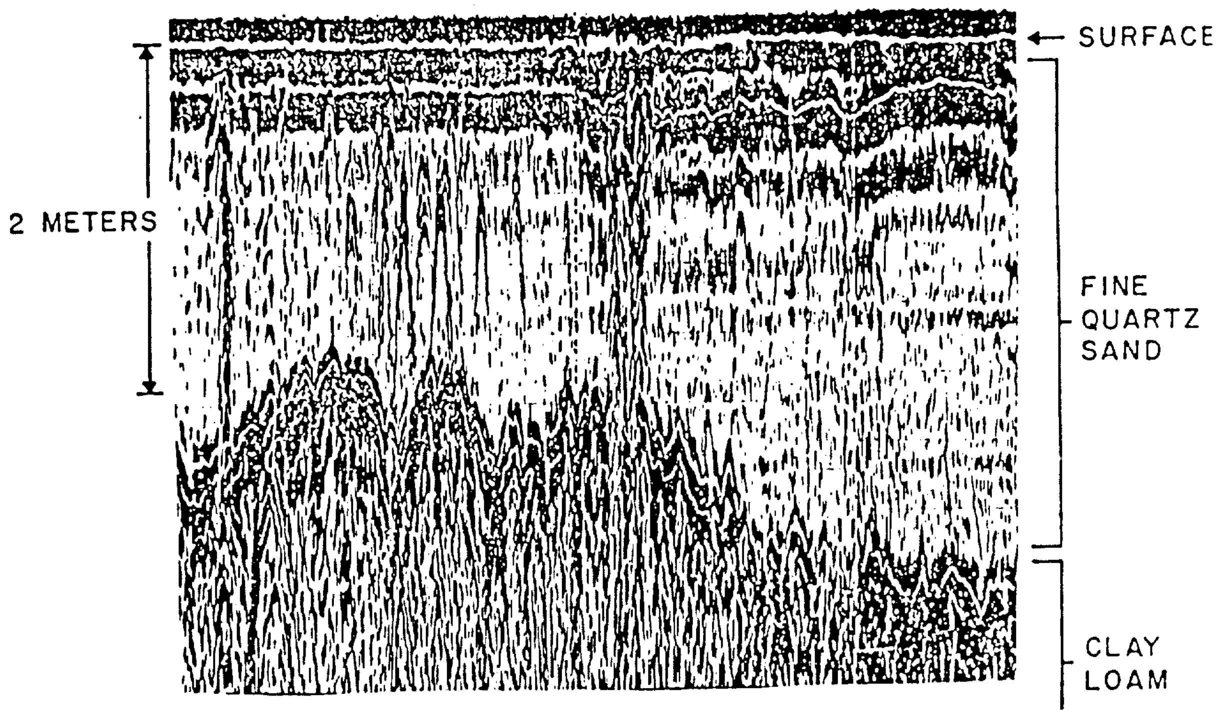


Figure 23. Radar record showing irregular clay horizon.

Electrical and scattering losses, however, are highly dependent on site conditions.

The primary factors controlling electrical attenuation of radar are the electrical conductivity of the soil/rock system and the radar frequency. An increase in either subsurface conductivity or the radar frequency will result in greater attenuation of the radar signal. The frequency of the radar may be varied by changing antennas. Unfortunately, the conductivity of the subsurface cannot be varied. High conductivities due to dissolved salts from natural sources or contamination will cause strong attenuation of the radar signal.

An increase in the water content of dry soil or rock can also increase its electrical conductivity greatly. Similarily, an increase in clay content will usually increase conductivity. However, water or clay content alone will not always seriously degrade radar performance. Experience has shown that penetrations of more than ten meters can be obtained in water-saturated sands where conductivity is low. Furthermore, the radar method has been used to profile bottom and sediment conditions through ice and fresh water.

TABLE 2. APPROXIMATE CONDUCTIVITIES, DIELECTRIC CONSTANTS, AND TRAVEL TIME FOR VARIOUS EARTH MATERIALS (Modified from Geophysical Survey Systems, Inc.)

Material	Approximate Conductivity σ (mho/m)	Approximate Dielectric Constant, ε_r	Two-way Travel Time Nanoseconds/Meter (one nanosecond = 10^{-9}sec)
Air	0	1	6.6
Fresh Water	10^{-4} to 3×10^{-2}	81	59
Fresh Water Ice	10^{-4} to 10^{-2}	4	13
Permafrost	10^{-5} to 10^{-2}	4 to 11	13 to 15
Granite	10^{-9} to 10^{-3}	5.6 to 8	18.7
Dry Sand	10^{-7} to 10^{-3}	4 to 6	13 to 16
Sand, Saturated (Fresh Water)	10^{-4} to 10^{-2}	30	36
Silt, Saturated (Fresh Water)	10^{-3} to 10^{-2}	10	21
Clay, Saturated (Fresh Water)	10^{-1} to 1	8 to 25	18.6 to 23
Average "Dirt"	10^{-4} to 10^{-2}	16	23 to 30

Resolution of the radar profile can be increased by increasing the frequency of the radar. A change in frequency is accomplished by selecting the appropriate antenna; antennas of higher frequency and shorter wavelength (500 to 900 MHz) provide resolution of a few centimeters, but are unable to penetrate the ground very far, due to increased losses at these higher frequencies. Lower-frequency antennas (80 to 125 MHz) are capable of working to greater depths and of operating in poor soil conditions, but lack the resolution to define features smaller than about one meter in size.

Radar reflections from a single interface generally result in a set of multiple black bands on the graphic display (see Figure 24). This type of response is inherent in the impulse method. Generally the location of an interface is picked at one of the white lines between the black bands. Occasionally, these multiple bands can obscure information if two interfaces are close together. If necessary, special processing techniques originally developed for seismic exploration can be employed to help alleviate this problem (see processing section).

Factors to be Considered for Field Use

During field operations, the radar system electronics are usually mounted in a van or other suitable vehicle, with the antenna towed behind (Figure 25). Vehicle-mounted or towed configurations can be used to acquire data at speeds up to 8 KPH. These speeds may be used for reconnaissance surveys, where subsurface details are not of interest. This permits much larger areas to be covered in relatively shorter periods of time. If there are access problems, the antenna may also be hand-towed over the site (Figure 26). With cable of sufficient length, the electronics may be located up to 300 meters from the antenna.

If necessary, extremely high lateral resolution may be obtained by slowly towing the antenna by hand across the site. Speeds as slow as 0.5 km/h are commonly used: This allows a greater number of radar signals to be transmitted and received per unit distance. At a traverse speed of 1 km/h, radar sampling density may yield up to 187 samples/meter (at 1 mi/h, 35 samples per foot).

In operation an appropriate time window (range) of the system is selected. The range is measured in units of nanoseconds (1 nanosecond = 10^{-9} seconds). An estimate of the radar wave’s travel time (velocity) is made based upon what is known about site conditions. A time window is then chosen which will usually provide coverage to a depth which is slightly greater than the depth of interest.

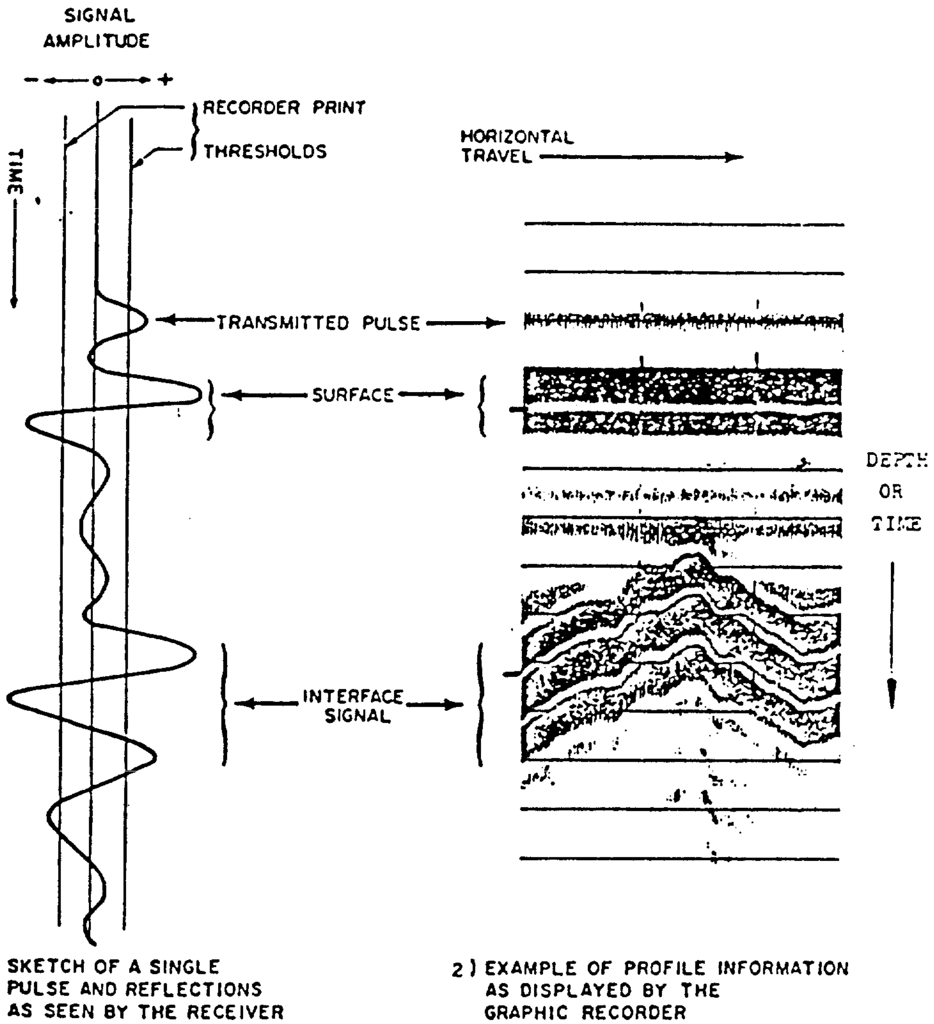


Figure 24. Example of single radar waveform and resulting graphic record. (from Geophysical Survey System, Inc. Manual).

Project requirements and site conditions will dictate which antenna will be used. Generally the requirement for attaining adequate penetration depth will be the major factor in determining the appropriate antenna. Once adequate radar penetration is achieved, the resolution requirements may then be considered. Generally results obtained with 250-500 MHz antennas are excellent for delineation of soil horizons, soil/rock surfaces, soil piping, buried trenches and other shallow and smaller targets. Attenuation caused by subsurface conditions may require the use of lower-frequency antennas. In these cases, the 80 MHz-125 MHz frequency antennas can be used at the expense of some resolution.

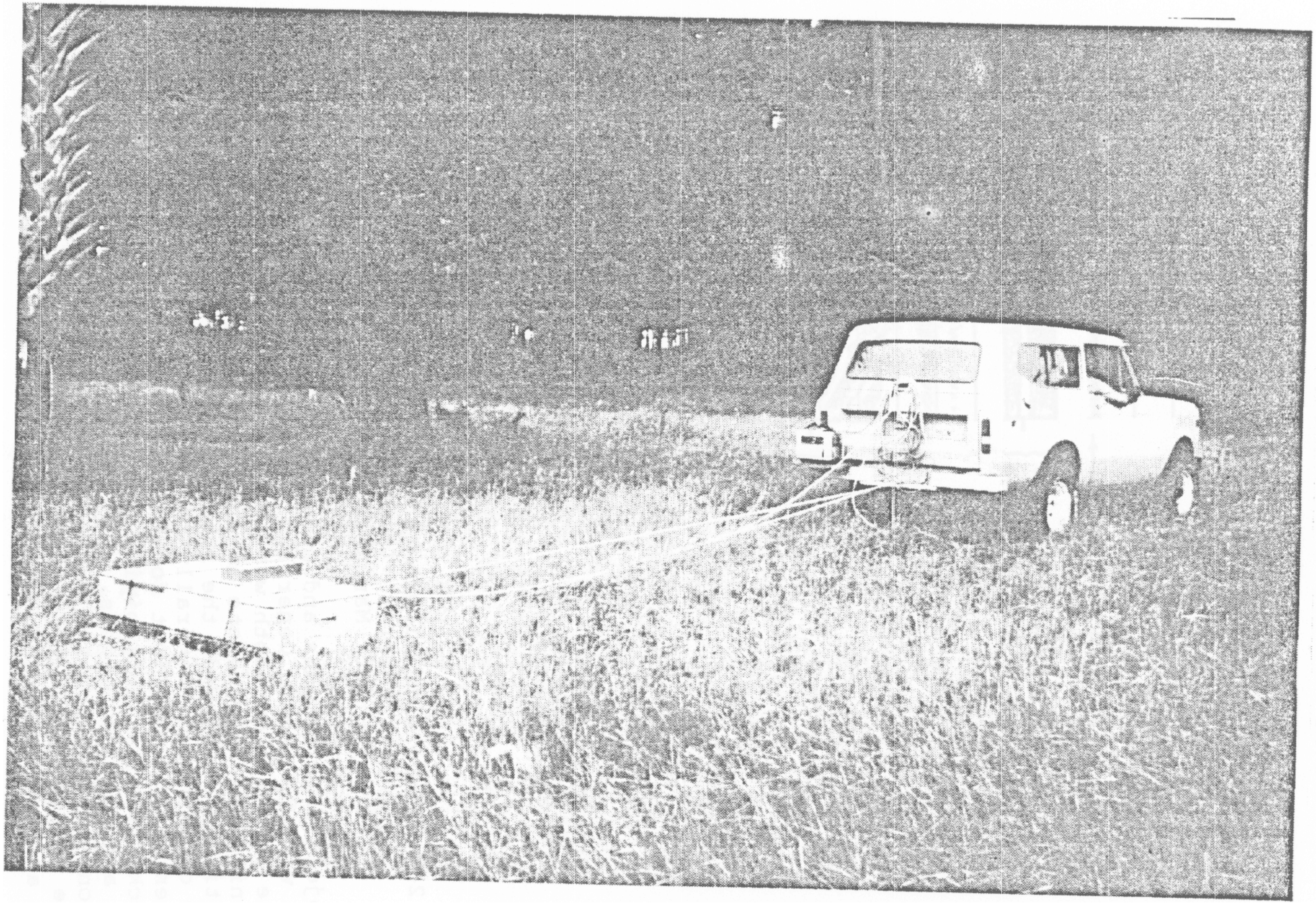


Figure 25. Vehicle-towed radar antenna.

Field operations are normally conducted using a single antenna structure which contains both transmitter and receiver (monostatic mode).

Multiple antennas may be deployed side by side to cover a greater area with one pass. Two antennas of different frequencies may be used to provide optimum benefits from low and high frequencies. In another configuration, two antennas may be used in the bistatic mode, one being used as the transmitter and the other as the receiver. This method can often minimize unwanted surface noise and can be used to detect small vertical fractures. While many optional configurations are possible to help solve particular site problems, the use of a single antenna (as in Figures 25 and 26) is the most common and cost-effective approach to most HWS problems.

Quality Control

The radar system measures two-way travel time from the transmitter antenna to a reflecting surface and back to the receiver antenna. Calibration of the radar system and data requires a two-step process:

- First, the total time window (range) set by the operator must be accurately determined.

- Second, the electromagnetic velocity (travel time) of the local soil/rock condition must be determined.

After completing these two steps, the radar data may then be calibrated for depths to particular features.

The time window (range) which has been picked for the survey is calibrated by use of a pulse generator in the field. This generator is used to produce a series of time marks on the graphic display, measured in nanoseconds. These pulses are counted to determine the total time range of the radar (see Figure 27). A calibration curve can be made up for each radar system.

In order to precisely relate travel time to actual depth units, the velocity (or two-way travel time per unit distance) must be determined for the particular soil or rock found at the site. Table 2 shows that a wide range of two-way travel times occurs for natural materials, ranging from 6 to 40 nanoseconds per meter (ns/m).

Various levels of accuracy in determining travel time can be used. These may range from first order estimates to precisely measured on-site values. Often, accurate depth determination may be relatively unimportant, and only the relative spatial changes may be of interest. A practical

Figure 26. Hand-towed radar antenna in limited-access area.

first approximation is to use 15 ns/meter (5 ns/ft.) in clean, dry, unsaturated soils and 30 ns/meter (10 ns/ft.) in silty, clayey and saturated soils. These two numbers are easy to remember and lend themselves to quick mental calculations. More refined estimates can be made if necessary, as one gains experience at a site.

Using the depth of a known target (trenches, drilling logs, road cuts or buried pipes/road culverts can provide a radar target of known depth), a radar record taken over the known target, and a time scale provided by the pulse generator will provide information as shown in Figure 22. From these data a two-way travel time can be accurately determined at the given target location. While this approach may give accurate calibration at the specific site, the assumption must be made that conditions in other areas to be surveyed are the same as in the calibration areas. If they are not, errors will occur in determining depths.

If significant changes in soil type or moisture content occur with depth, travel time will not be the same throughout the vertical radar profile, and the vertical radar depth scale may be non-linear. Such a condition is common, and occurs whenever an unsaturated zone exists over a saturated zone.

Noise

Sources of unwanted noise which can degrade radar data can be grouped as follows:

1) System noise;
2) Overhead reflections due to power lines, trees, etc. (unshielded antennas only);
3) Noise due to surface factors such as ditches, metal, etc. ;
4) Noise due to natural subsurface features or buried trash;
5) External electromagnetic noise from radio transmitters.

Of these factors, system noise is the most common problem. Steady-state noise may be introduced by improper cable placement. Locating antennas too close to the metal vehicle from which they are towed will also cause noise problems. (Such noise can be minimized, but not always eliminated, by system adjustments.)

Lower-frequency antennas are not shielded on their top surfaces and, therefore, receive radar reflections from overhead objects such as tree branches, power lines, and buildings. Such a reflection can be identified by an experienced operator by means of the characteristic signal associated with its very low two-way travel time in air. Once identified, such signals can he ignored in the analysis of the data.

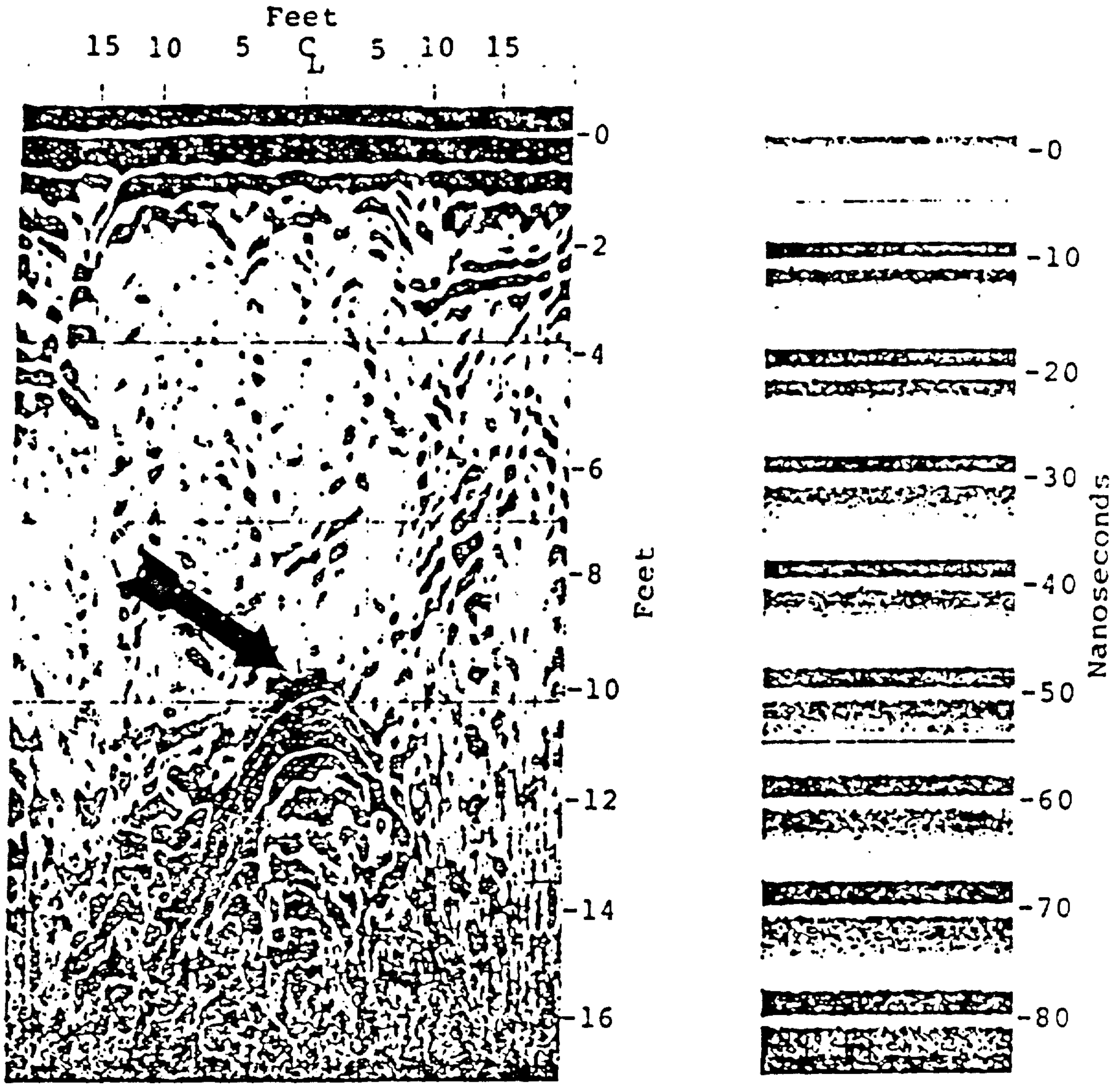


Figure 27. Radar profile over buried pipe. This profile was obtained for calibration purposes over a pipe of known 10-foot depth. The time calibration shows that fifty nanoseconds were required for the radar wave to travel from the antenna to the pipe and back to the antenna. This two-way travel time results in an average 5 nanoseconds/foot travel time or 0.2 feet/nanosecond velocity.

Surface noise may be generated by pieces of metal lying on the ground, which can cause a reverberation or ringing of the radar signal throughout the record. While smaller objects such as nails do not ordinarily cause problems, an object as small as a wire coat hanger can create a substantial problem. An effort should be made to remove such debris from the immediate area of the radar antenna path.

Small topographic variations may cause some variations in the data. Crossing a small ditch, for example, can introduce a band of noise in the data. Radar records acquired in areas having appreciable clay concentrations at the surface will often have a smeared or distorted appearance, which may mask useful information in the data. In addition, some natural geologic settings will result in apparent noisy data caused by scattering from a large number of natural boulders. If radio transmitters are in use nearby, their radiated signal will occasionally cause significant noise to appear on the graphic record.

Data Format, Processing, Interpretation and Presentation

The radar data may be generated in three general formats:

1. Individual waveforms (Figure 24);
2. Graphic record (picture-like record, Figure 23);
3. Data storage on magnetic tape media.

The individual radar waveforms may be observed directly on an oscilloscope in real time. Details of the signal may he observed and evaluated to select the time window (range) and optimize the radar signal. A graphic recorder may be used to print a copy of the data in the field for quality control and initial qualitative analysis. This graphic format is typically used for final display of the radar data. Radar data may be recorded on magnetic tape or other media. These magnetic records provide an archive copy of the data, permit the operator to play back data to optimize data quality, and provide a signal input to a computer system for processing options.

Various forms of processing may be applied to radar data to improve its interpretation or presentation. A limited amount of processing may be done in real time. Time-variable gain may he applied to radar data, so that a proper amount of gain is applied to both shallow and deep targets to improve overall data quality. The graphic recorder may also be adjusted to improve the visual quality of the data. Analog filtering of the radar waveforms is possible to eliminate unwanted high-frequency and/or low-frequency components (noise) which may obscure useful radar data. The horizontal and vertical scales of the radar data may be varied to obtain an optimal visual presentation of the data. The vertical scale of graphic data will usually be much less than the horizontal scale (see Figure 23). At present, real-time processing can be accomplished with a built-in microprocessor to remove steady-state background noise from the radar profile (see Figure 28).

Replaying radar data which has been recorded in the field on magnetic tape can provide a number of processing options:

1. Data may be played back in the same manner as described in real-time processing. The advantage of a post-survey playback is that various options may be tried to further optimize the quality of the data.
2. Various analog and digital filtering techniques may be applied to remove background noise, clutter, or steady-state systems noise.
3. Discrete waveform analysis methods may be applied to extract subtle information from the data.
4. Computer processing of the entire profile may include:
   a. Averaged waveforms to enhance trends:
   b. Deconvolution to remove multiple bands from the graphic record;
   c. Evaluation of the data in the frequency domain.

The process of deconvolution can remove the multiple signal which is an inherent part of the radar process. Since these multiple bands may obscure fine details in the graphic record, deconvolution can improve resolution in the graphic data and also aid an inexperienced interpreter.

Individual waveforms (Figure 24) may be analyzed via computer in order to determine very subtle conditions or details obscured by larger amplitude or lower-frequency signals. Such details are often lost in the graphic recorder's output, due to the resolution and saturation limits of the recorder. In addition, processing on digital oscilloscopes or computers can yield time measurements, thereby permitting accurate determinations of travel time, or conversely, aiding in the determination of dielectric constants.

Because of the large volume of information produced by the radar method, data processing procedures can be time consuming and may require very specialized computers: they therefore, are costly . The processed data may not yield an amount of new information commensurate with the level of costs incurred. The essential technical information can often be detected in raw data by an experienced professional. Many times, processing algorithms may improve data in the manner desired, but may remove other information. On the other hand, the improved appearance of processed data is often useful for presentation to lay personnel or to publications.

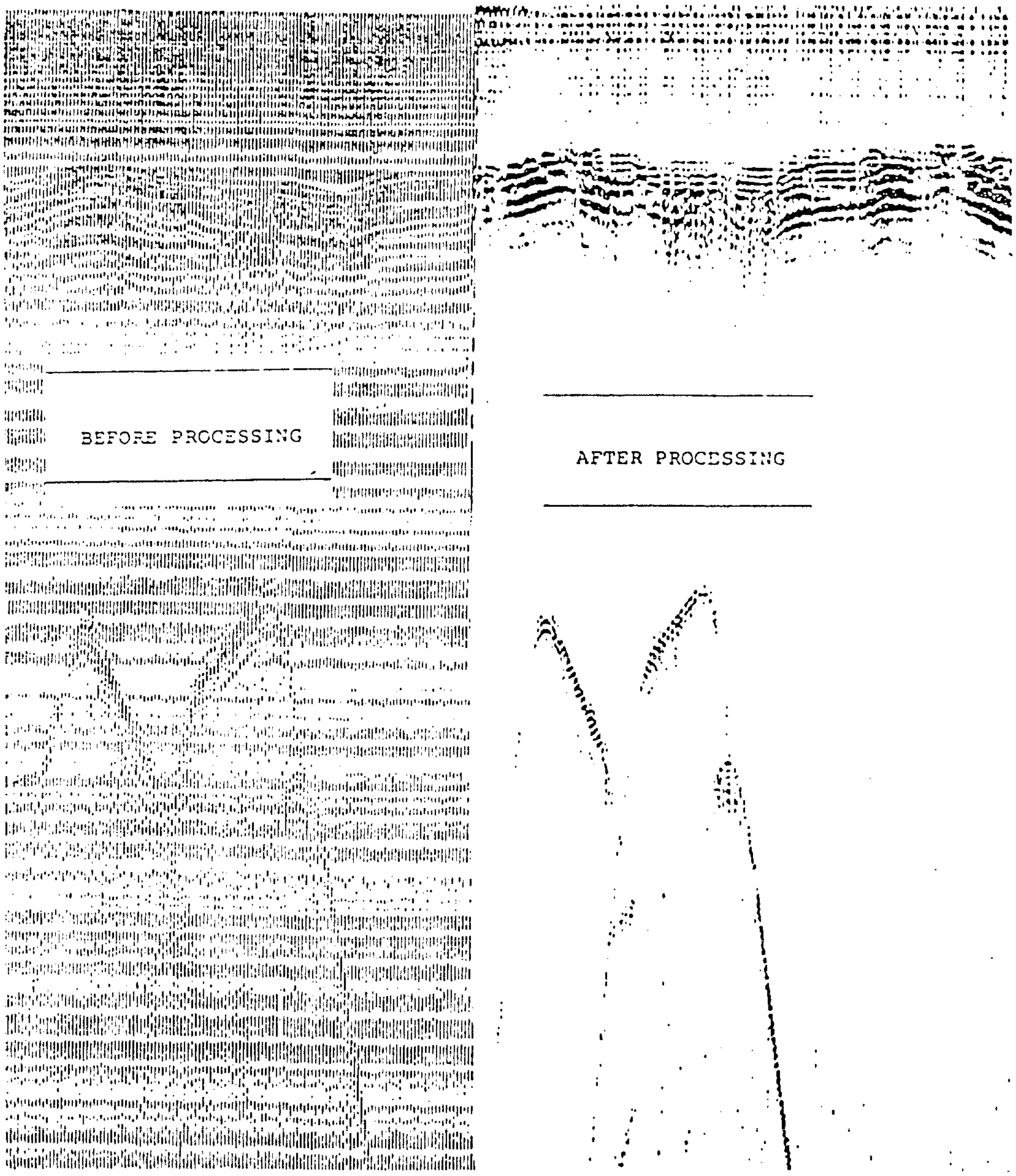


Figure 28. Real-time processing eliminates steady-state noise bands. Care must be exercised because valuable geologic information may also be removed. (from Geophysical survey systems, Inc.)

The primary reasons for the popularity of the radar method are its continuous "picture-like" format, high resolution, and spatial presentation of anomalous features.

Radar data is generally interpreted visually from the printed graphic record. A rapid qualitative analysis can be made in the field from this raw data. The continuity of soil/ rock layers and anomalous conditions can often be quickly located and evaluated. The use of calibration procedures and correlation to direct data such as drill logs will permit more quantitative assessment of depth measurement. Relating the graphic data to the local setting can he accomplished by marking the radar record during the survey at regularly spaced station marks along the traverse route. Variations in lateral traverse speeds can also be corrected or minimized by referring to these station marks. The radar data is referenced to the surface topography, and the interpretation must take this into account if the topography along a profile line changes.

Radar results are often presented as raw or processed radar profiles, as printed by the graphic recorder. Schematic interpretations of these profiles may be made if the site has a relatively complex setting (Figure 29). In instances where spatial trends are important, anomalies of interest can be extracted from the profile data and may be plotted on a map of the site. This may be accomplished manually or by computer processing. For example, the presence of burial trenches may be revealed by several parallel radar profiles across a site; a plan view of this data will show the location and areal extent of the trenches (See Figure 30).

Summary

In areas where sufficient ground penetration is achieved, the radar method provides a powerful assessment tool. Of the geophysical methods discussed in this document, radar offers the highest resolution. The method provides continuous spatial sampling and can be carried out very rapidly at traverse speeds from 0.5 to 8 KPH. Its continuous graphic format permits rapid semi–quantitative interpretation for in–field analysis.

Radar performance is highly site–specific. Depth of penetration is primarily dependent upon soil propert fluids which influence electrical conductivity. In the wide range of natural soil/rock conditions found throughout the United States, GPR penetration varies from less than a meter to more than 30 meters. Typical maximum penetrations at any given site are 1 to 10 meters.

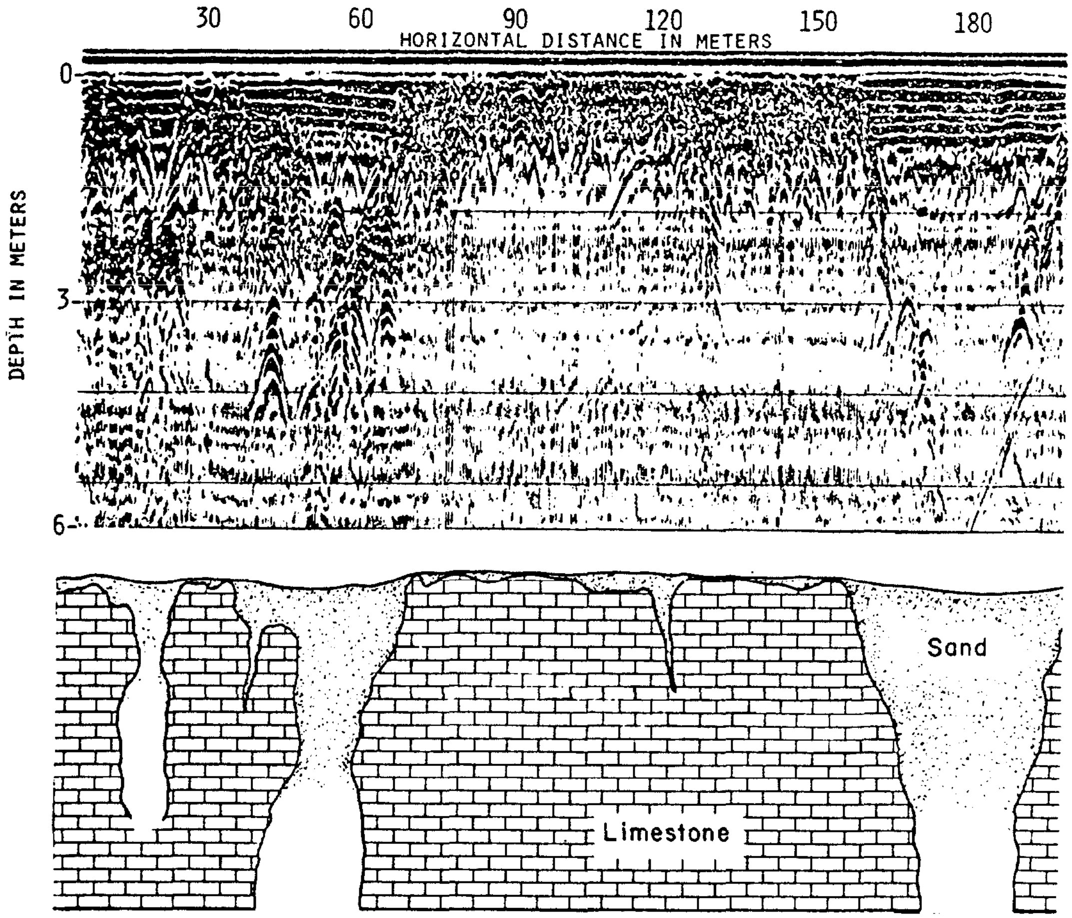


Figure 29. Interpretation of radar data results in geologic cross section.

Interpretation of radar data is relatively straightforward if site conditions are simple and a strong dielectric contrast exists between the features of interest and the surrounding soil. As subsurface conditions increase in complexity, interpretation of the data becomes difficult, and more elaborate interpretation and processing may be necessary. The high quality of the radar data shown in Figure 23 is not commonly obtained in the field; however, experienced interpreters are usually able to cope with field data of lower quality.

A radar system is a complex instrument. The results of a radar survey are dependent on many interacting system controls, various field procedures, site conditions, and interpretation. Therefore, the successful application of the radar method requires personnel with an understanding of electronics, physics, and basic earth sciences. The more complex the site problem, the greater the amount of training and experience required.

Capabilities

- The radar method provides continuous data along a traverse line, producing a picture-like display in real time.
- Traverse speeds range from 0.5 to 2 km/h for detailed studies and up to 8 km/h for lower-resolution reconnaissance work.
- The graphic record can often be interpreted in the field
- The method provides very high resolution from a few centimeters to 1 meter, depending upon the frequency used
- System optimization to local site conditions can be accomplished by changing antennas (frequency); high frequency provides the best resolution; lower frequency provides deeper penetration.
- Approximate depths and relative depths are easily established using simple assumptions and interpretation techniques.
- The method may be used in fresh water and through ice to obtain profiles of depth and sediments.
- A wide variety of processing techniques may be applied to radar data to aid interpretation and presentation.

Limitations

- Depth of penetration is very site-specific and limited by the electrical conductivity of pore fluids and clay minerals.
- Depth of penetration is commonly less than 10 meters. In extreme soil conditions, effective penetration may be less than 1 meter.
- Both the instrumentation and technique are sophisticated and, therefore, require experienced personnel for operation.
- Interpretation of raw data may be very difficult under some conditions.
- Semi-quantitative and quantitative assessments require considerable care to avoid numerous interpretation pitfalls.
- Processing of data may be required in some cases; however, costs will be increased, and processing may remove some of the important data.
- Depth calibration requires careful on-site work and if site conditions change the depth calibration wil be affected. Further, the depth scale is often nonlinear.
- The data can be affected by a variety of sources of noise.

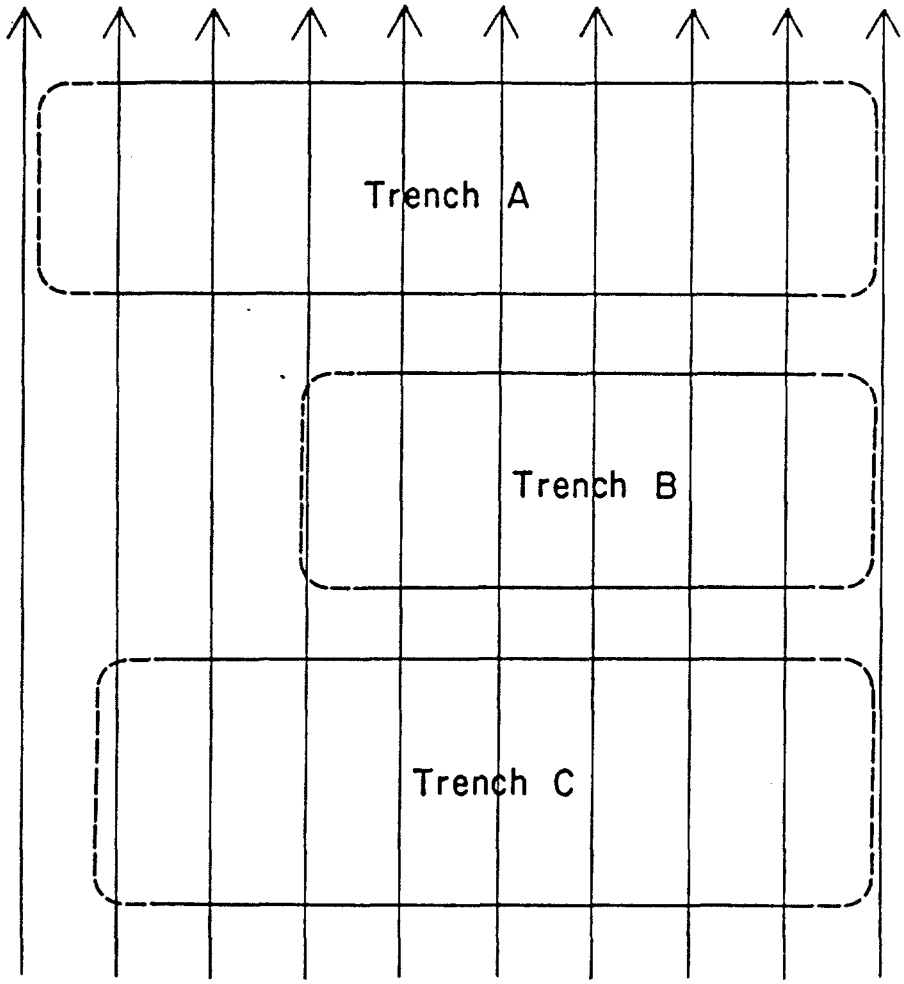


Figure 30. Location and boundaries of trenches may be obtained from parallel radar traverses. Radar is often able to detect the disturbed soil associated with burial sites.

Examples

Radar Assessment of Natural Setting

Figure 31 is an unprocessed radar record of a soil profile containing three layers in a karst area. The radar range window, set by the operator, was limited to about 3.5 meters for this particular survey, although radar penetration exceeded 6 meters in the area. Clean sand on the surface is underlain by an organic/iron-cemented sand (spodic) layer which, in turn, is underlain by a clay loam (argillic) horizon. The feature in the upper left corner of the record represents the edge of an ancient

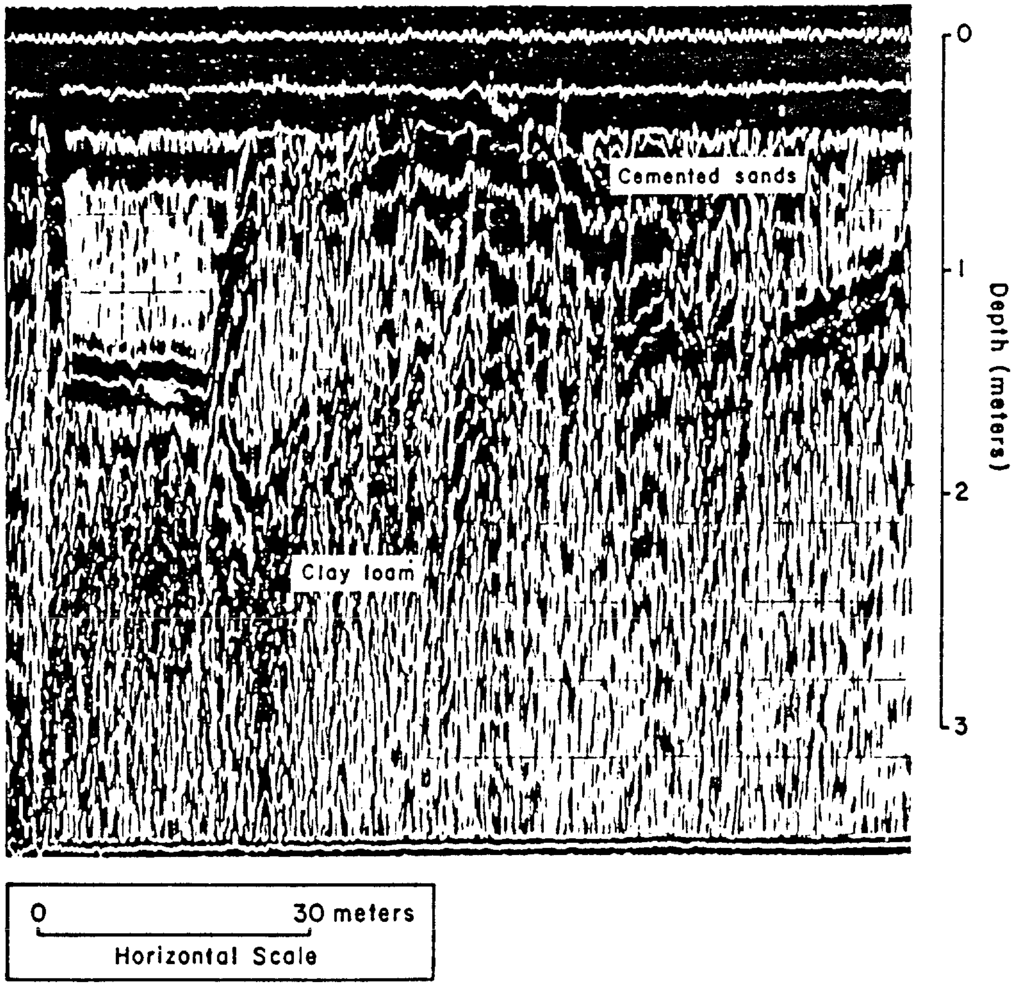


Figure 31. Soil profile showing two soil horizons and the edge of a Paleo sinkhole.

sink-hole which has long since been filled by the surface sands. No depression or other evidence of this sink-hole feature was observed at the surface. The significance of this profile is that it presents an understanding of the soil structure and irregularities, which will influence the movement of contaminants or leachate through the shallow ground water system. For example, in the soil section represented here, a surface spill or contaminant introduced near the right-hand side of the record might be expected to follow the clay horizon down dip to the left. Pockets of contaminant material may be perched in the low areas in the clay surface. Entering the old sink-hole area, contaminants could quickly enter the ground water system via a permeable recharge pathway.

Bedrock/Fracture Evaluation

Figure 32 is a radar profile showing a soil profile overlying granite bedrock. The soil/rock interface is revealed, as well as the zone of weathered rock. Fractures within the bedrock may also be located, as a consequence of increased moisture and clay content relative to the massive granite. Such fractures can permit the rapid migration of contaminating fluids into the ground water system. (Radar penetration can be substantial--ten to thirty meters--in massive dry igneous rocks.)

Location of Trenches

Figure 33 is a radar profile which was run perpendicular to a long burial trench known to contain steel drums. The trench boundaries can be seen in the radar data. Multiple parallel passes across the trench provided data for mapping the trench boundaries. While radar could, in fact, detect a single 55-gallon drum by itself, no discrete drums can be identified in this particular profile.

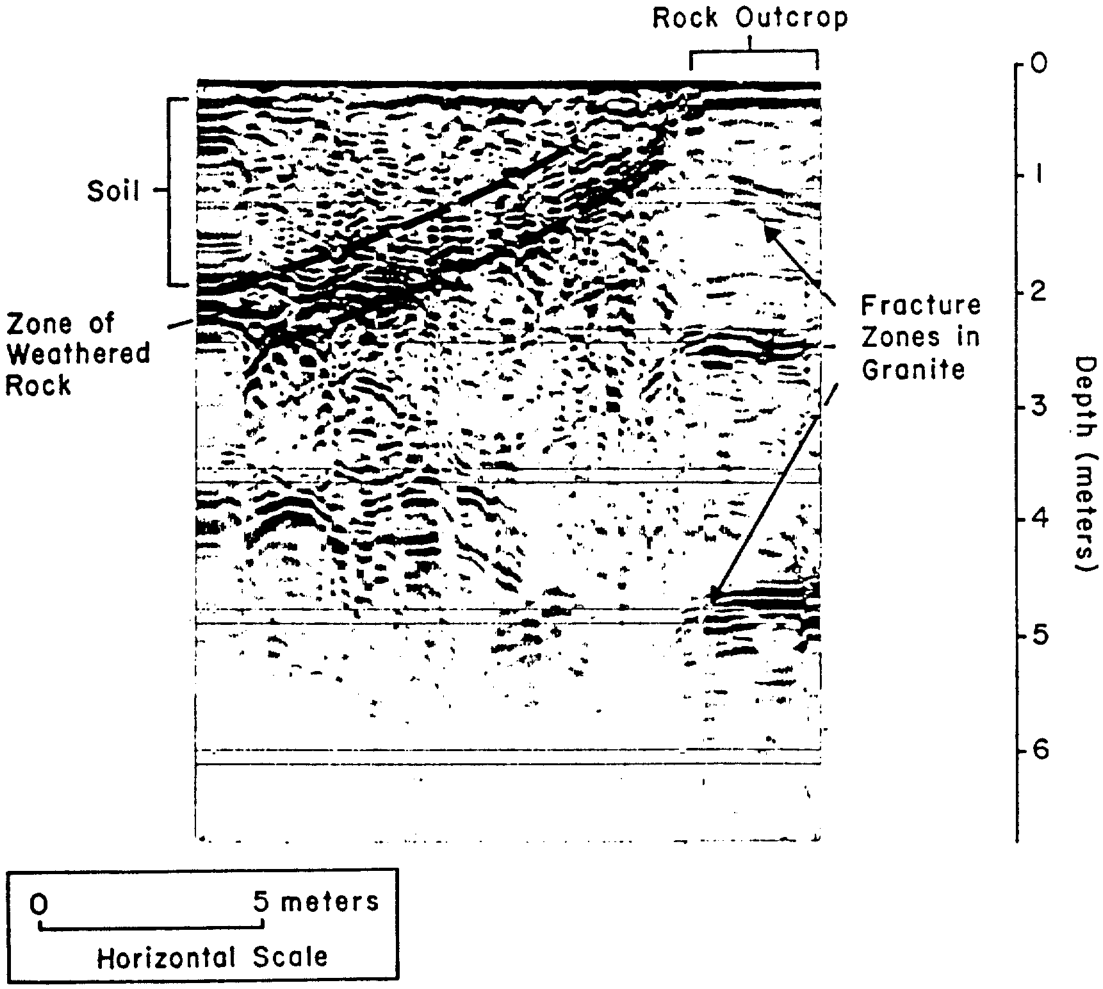


Figure 32. Radar profile of granite outcrop showing fracture zones.

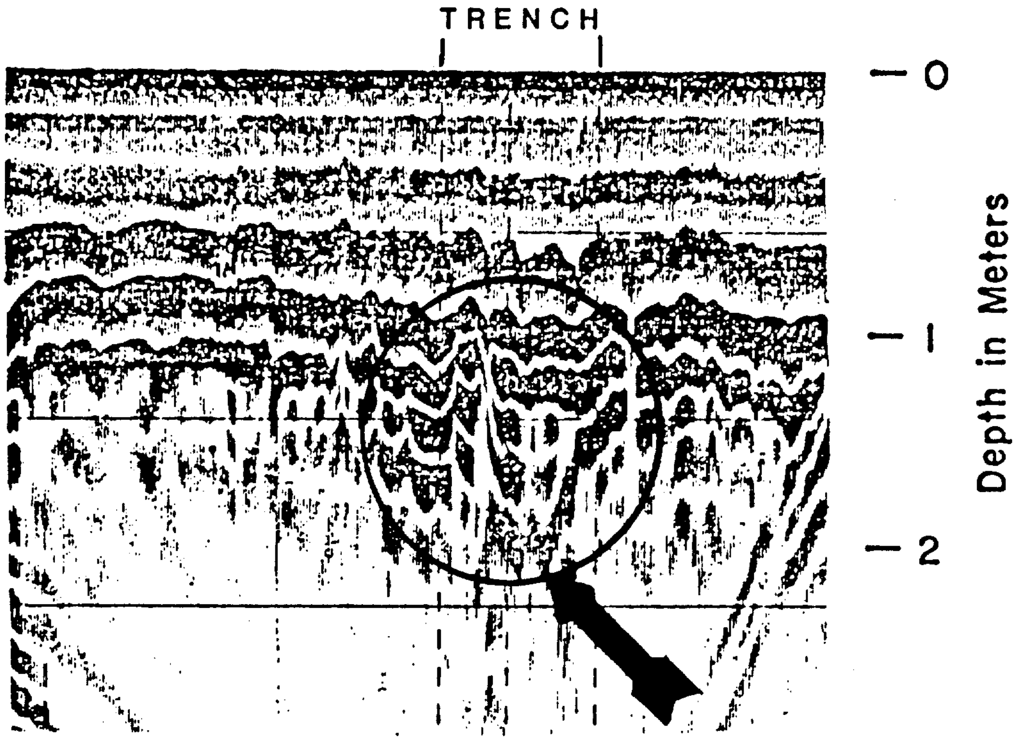


Figure 33. Example of radar traverse over trench.

SECTION V

ELECTROMAGNETIC (EM)*

Introduction

The electromagnetic (EM) method provides a means of measuring the electrical conductivity of subsurface soil, rock and ground water. Electrical conductivity is a function of the type of soil and rock, its porosity, its permeability and the fluids which fill the pore space. In most cases the conductivity (specific conductance) of the pore fluids will. dominate the measurement. Accordingly, the EM method is applicable both to assessment of natural. geohydrologic conditions and to mapping of many types of contaminant plumes. Additionally, trench boundaries, buried wastes and drums, as well as metallic utility lines can be located with FM techniques .

Natural variations in subsurface conductivity may be caused by changes in soil moisture content, ground water specific conductance, depth of soil cover over rock, and thickness of soil and rock layers. Changes in basic soil or rock types, and structural features such as fractures or

---

*The term electromagnetic has been used in contemporary literature as a descriptive term for other geophysical methods, including GPR and metal detectors which are based on electromagnetic principles. However, this document will use electromagnetic (EM) to specifically imply the measurement of subsurface conductivities by low-frequency electromagnetic induction. This is in keeping with the traditional use of the term in the geophysical industry from which the EM methods originated. While the authors recognize that there are many electromagnetic systems and manufacturers, the discussion in this section is based solely on instruments which are calibrated to read in electrical conductivity units and which have been effectively and extensively used at hazardous waste sites. There is only one manufacturer of such instruments at the time of this writing.

voids may also produce changes in conductivity. Localized deposits of natural organics, clay, sand, gravel, or saltrich zones will also affect subsurface conductivity.

Many contaminants will produce an increase in free ion concentration when introduced into the soil or ground water systems. This increase over background conductivity enables detection and mapping of contaminated soil and ground water at HWS, landfills and impoundments. Large amounts of organic fluids such as diesel fuel can displace the normal soil moisture, causing a decrease in conductivity which may also be mapped, although this is not commonly done. The mapping of a plume will usually define the local flow direction of contaminants. Contaminant migration rates can be established by comparing measurements taken at different times.

The absolute values of conductivity for geologic materials (and contaminants) are not necessarily diagnostic in themselves, but the variations in conductivity, laterally and with depth, are significant. It is these variations which enable the investigator to rapidly find anomalous conditions.

Since the EM method does not require ground contact, measurements may be made quite rapidly. Lateral. variations in conductivity can be detected and mapped by a field technique called profiling. Profiling measurements may be made to depths ranging from 0.75 to 60 meters. Instrumentation and field procedures have been developed recently which make it possible to obtain continuous EM profiling data to a depth of 15 meters. The data is recorded using strip chart and magnetic tape recorders. This continuous measurement allows increased rates of data acquisition and improved resolution for mapping small geohydrologic features. Further, recorded data enhanced by computer processing has proved invaluable in the evaluation of complex hazardous waste sites. The excellent lateral resolution obtained from EM profiling data has been used to advantage in efforts to outline closely-spaced burial pits, to reveal the migration of contaminants into the surrounding soil, or to delineate fracture patterns.

Vertical variations in conductivity can also be detected by the EM method. A station measurement technique called sounding is employed for this purpose. Data can be acquired rom depths ranging from 0.75 to 60 meters. This range of depth is achieved by combining results from a variety of EM instruments, each requiring different field application techniques. Other EM systems are capable of sounding to depths of 1000 feet or more, but have not yet been used at HWS and are not adaptable to continuous measurements.

Profiling is the most cost-effective use of the EM method. Continuous profiling can be used in many applications to increase resolution, data density and permit total site coverage at critical sites.

At HWS, applications of EM can provide:

- o Assessment of natural geohydrologic conditions;
- o Locating and mapping of burial trenches and pits containing drums and/or bulk wastes;
- o Locating and mapping of plume boundaries;
- o Determination of flow direction in both unsaturated and saturated zones;
- o Rate of plume movement by comparing measurements taken at different times;
- o Locating and mapping of utility pipes and cables which may affect other geophysical measurements, or whose trench may provide a permeable pathway for contaminant flow.

Principles and Equipment

Although there is available a wide variety of EM equipment, most of it is intended for geophysical exploration of mineral deposits. These units have not been used at HWS and do not provide a simple conductivity reading. This document discusses only those instruments which are designed and calibrated to read directly in units of conductivity.

The basic principle of operation of the electromagnetic method is shown in Figure 34. The transmitter coil radiates an electromagnetic field which induces eddy currents in the earth below the instrument. Each of these eddy current loops, in turn, generates a secondary electromagnetic field which is proportional to the magnitude of the current flowing within that loop. A part of the secondary magnetic field from each loop is intercepted by the receiver coil and produces an output voltage which (within limits) is linearly related to subsurface conductivity. This reading is a bulk measurement of conductivity; the cumulative response to subsurface conditions ranging all the way from the surface to the effective depth of the instrument.

The sampling depth of EM equipment is related to the instrument's coil spacing. Instruments with coil spacings of 1, 4, 10, 20 and 40 meters are commercially available: Figures 35, 36, 37 and 38 show several EM units and field configurations. The nominal sampling depth of an EM system is taken to be approximately 1.5 times the coil spacing. Accordingly, the

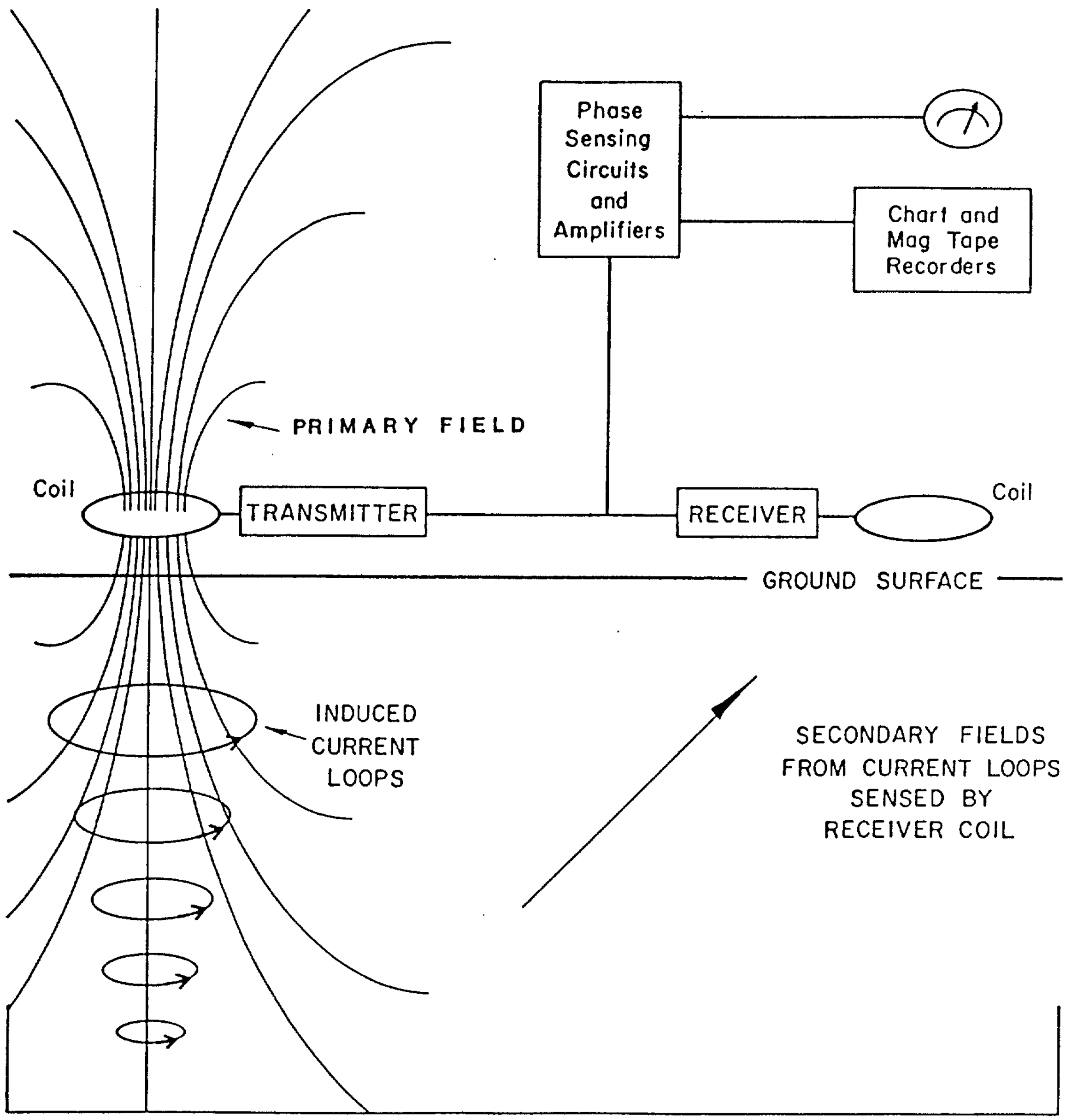


Figure 34. Block diagram showing EM principle of operations.

Figure 35. Small hand-held EM system used in soil survey. Depth range: 0.75 to 1.5 meters (Denney Farm Site).

Figure 36. Shallow EM system used in continuous record mode. Depth range: 3 to 6 meters. Man on left is carrying recorder (Love Canal).

Figure 37. Deep EM system used for station measurements. Depth range: 7-1/2 to 60 meters depending upon coil spacing and orientation selected.

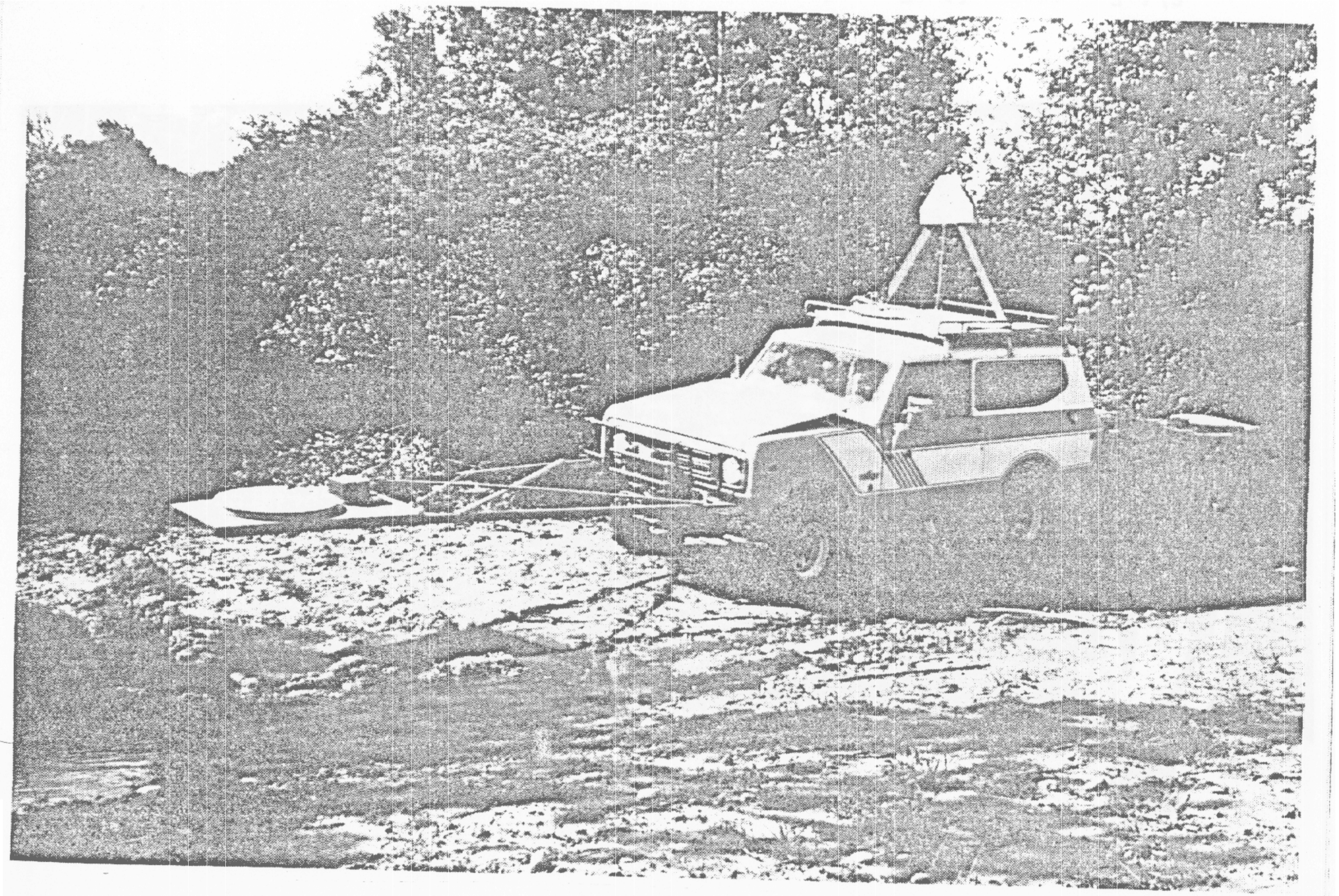


Figure 38. Truck-mounted EM system provides continuous conductivity data to 15 meters depth (Love Canal).

nominal depth of response for the coil spacings given above is 1.5, 6, 15, 30 and 60 meters.

The conductivity value resulting from an EM instrument is a composite, and represents the combined effects of the thickness of soil or rock layers, their depths, and the specific conductivities of the materials. The instrument reading represents the combination of these effects, extending from the surface to the arbitrary depth range of the instrument. The resulting values are influenced more strongly by shallow materials than by deeper layers, and this must be taken into consideration when interpreting the data. Conductivity conditions from the surface to the instrument's nominal depth range contribute about 75% of the instrument's response. However, contributions from highly conductive materials lying at greater depths may have a significant effect on the reading.

EM instruments are calibrated to read subsurface conductivity in millimhos per meter (mm/m). These units are related to resistivity units in the following manner:

1000/(millimhos/meter) = 1 ohm-meter
1000/(millimhos/meter) = 3.28 ohm-feet
1 millimho/meter = 1 siemen

The advantage of using millimhos/meter is that the common range of resistivities from 1 to 1000 ohm-meters is covered by the range of conductivities from 1000 to 1 millimhos/meter. This makes conversion of units relatively easy.

Most soil and rock minerals, when dry, have very low conductivities (Figure 39). On rare occasions, conductive minerals like magnetite, graphite and pyrite occur in sufficient concentrations to greatly increase natural subsurface conductivity. Most often, conductivity is overwhelmingly influenced by water content and the following soil/rock parameters:

- The porosity and permeability of the material;
- The extent to which the pore space is saturated;
- The concentration of dissolved electrolytes and colloids in the pore fluids;
- The temperature and phase state (i.e., liquid or ice) of the pore water.

A unique conductivity value cannot be assigned to a particular material, because the interrelationships of soil composition, structure and pore fluids are highly variable in nature.

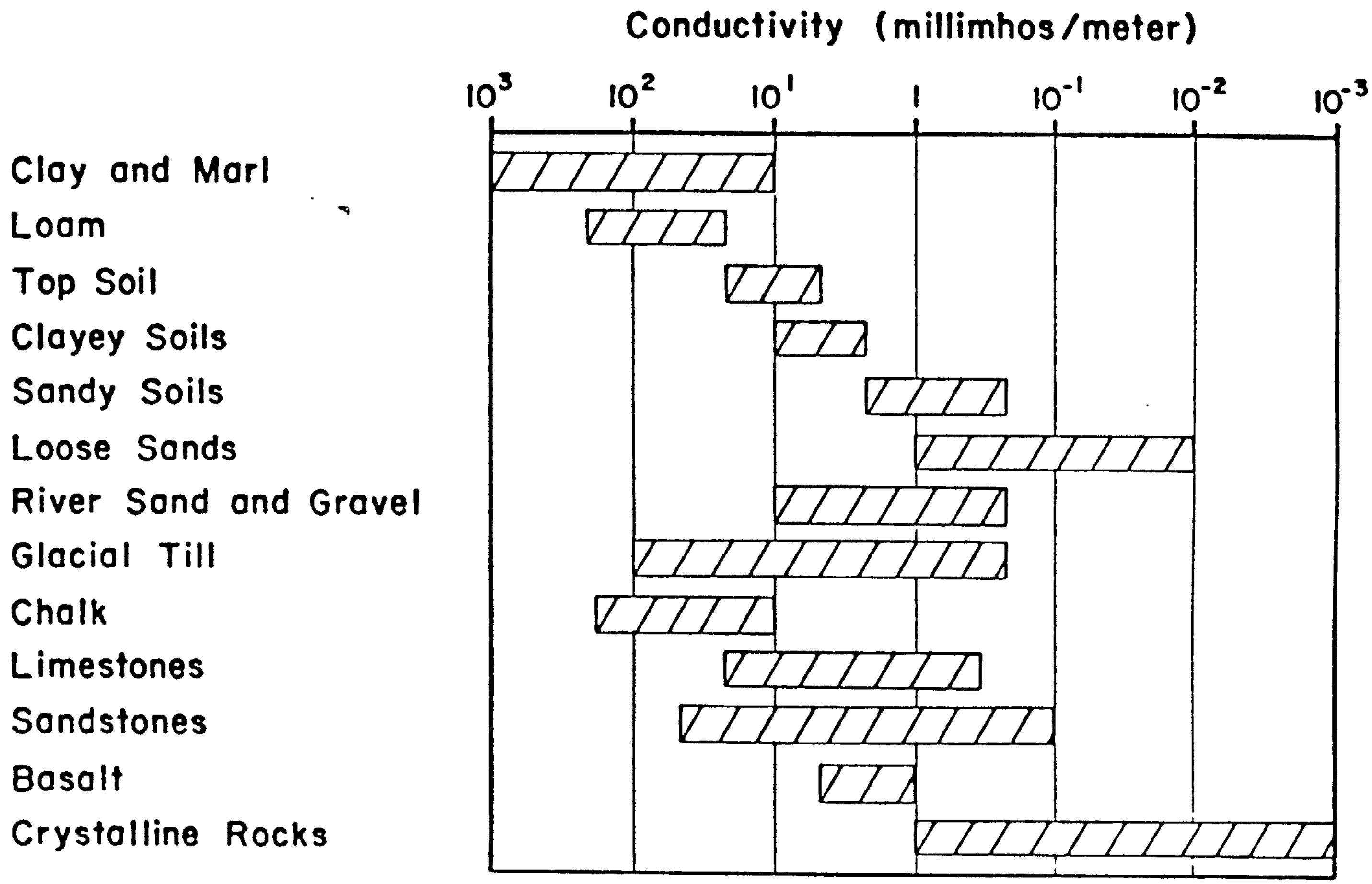


Figure 39. Range of electrical conductivities in natural soil and rock. (Modified after Culley et al.)

In areas surrounding HWS, contaminants may escape into the soil and the ground water system. In many cases, these fluids contribute large amounts of electrolytes and colloids to both the unsaturated and saturated zones. In either case, the ground conductivity may be greatly affected, sometimes increasing by one to three orders of magnitude above background values. However, if the natural variations in subsurface conductivity are very low, contaminant plumes of only 10 to 20 percent above background may be mapped.

In the case of spills involving heavy non-polar, organic fluids such as diesel oil, the normal soil moisture may be displaced, or a sizeable pool of oil may develop at the water table. In these cases, subsurface conductivities may decrease causing a negative EM anomaly. (A negative anomaly will occur only if substantial quantities of non-conductive contaminants are present.)

Factors To Be Considered for Field Use

Profiling--is accomplished by making fixed-depth FM measurements along a traverse line (see Figure 40). Profiling data has traditionally been obtained from discrete station measurements along the traverse line (see Figure 37); recently, continuous data has been collected at depths up to 15 meters with a truck-mounted system (see Figure 38).

Profiling provides an effective means of mapping lateral changes in subsurface conditions and is the primary EM field technique. The continuity of the information obtained is invaluable in resolving details of complex subsurface features along traverse lines.

Two examples of profiling data are shown in Figure 41. The first profile (a) shows data plotted from a field log-the station interval was 30 meters. The second (b) shows the same survey line, continuously recorded. It can be seen that the continuously-recorded data provides a more accurate representation of local variations.

Sounding--is accomplished by making conductivity measurements to various depths at a given location (see Figure 42). EM soundings will provide information on major vertical changes related to natural conditions or contamination. The method is generally limited to resolving 2 or 3 soil/rock layers. As soundings are always accomplished by using station measurements, more field time and quantitative analysis of the data is required than with the profiling method.

A number of different field techniques can be used to obtain sounding information. Within its depth limitation, a single EM instrument can be used for soundings. Simple qualitative

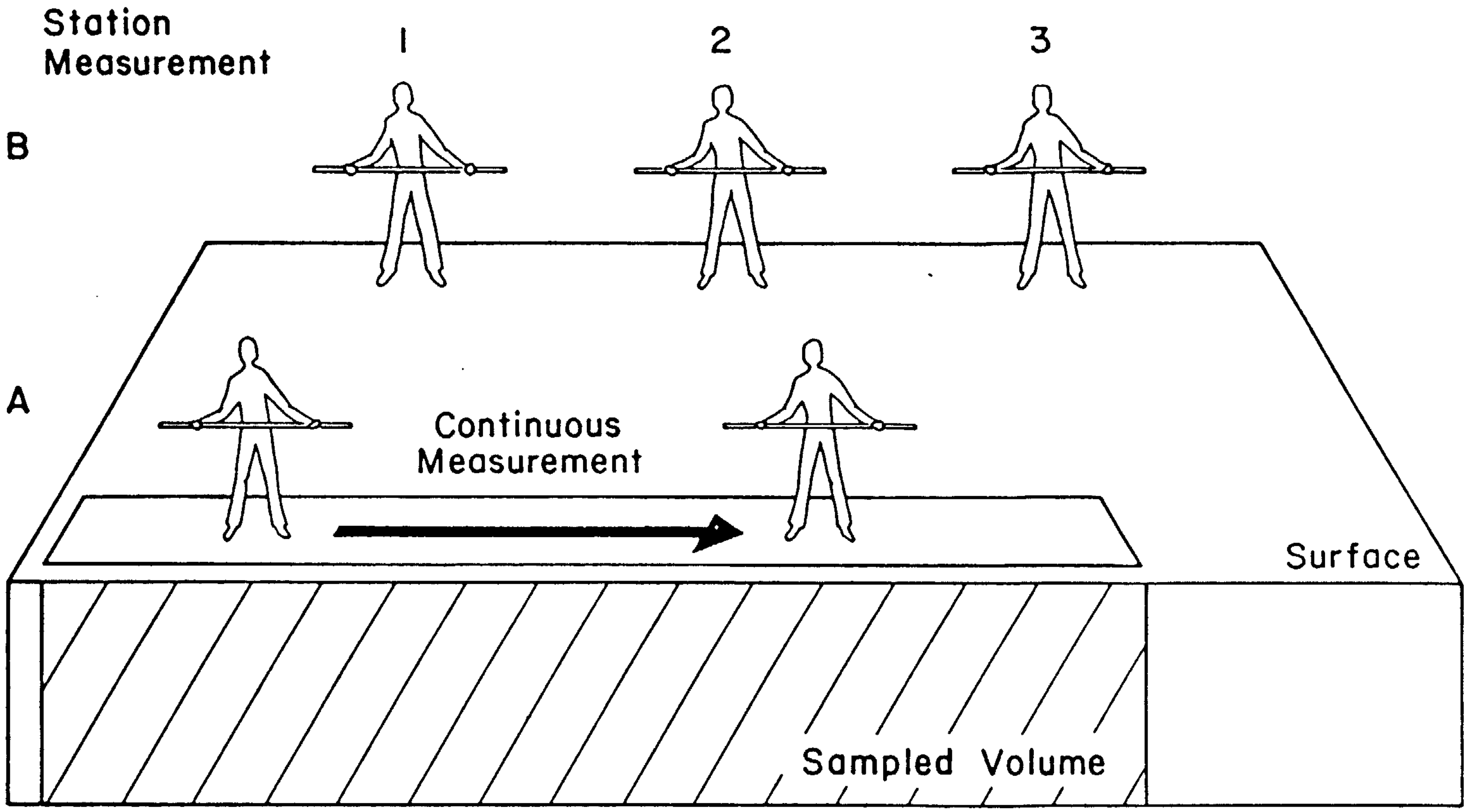
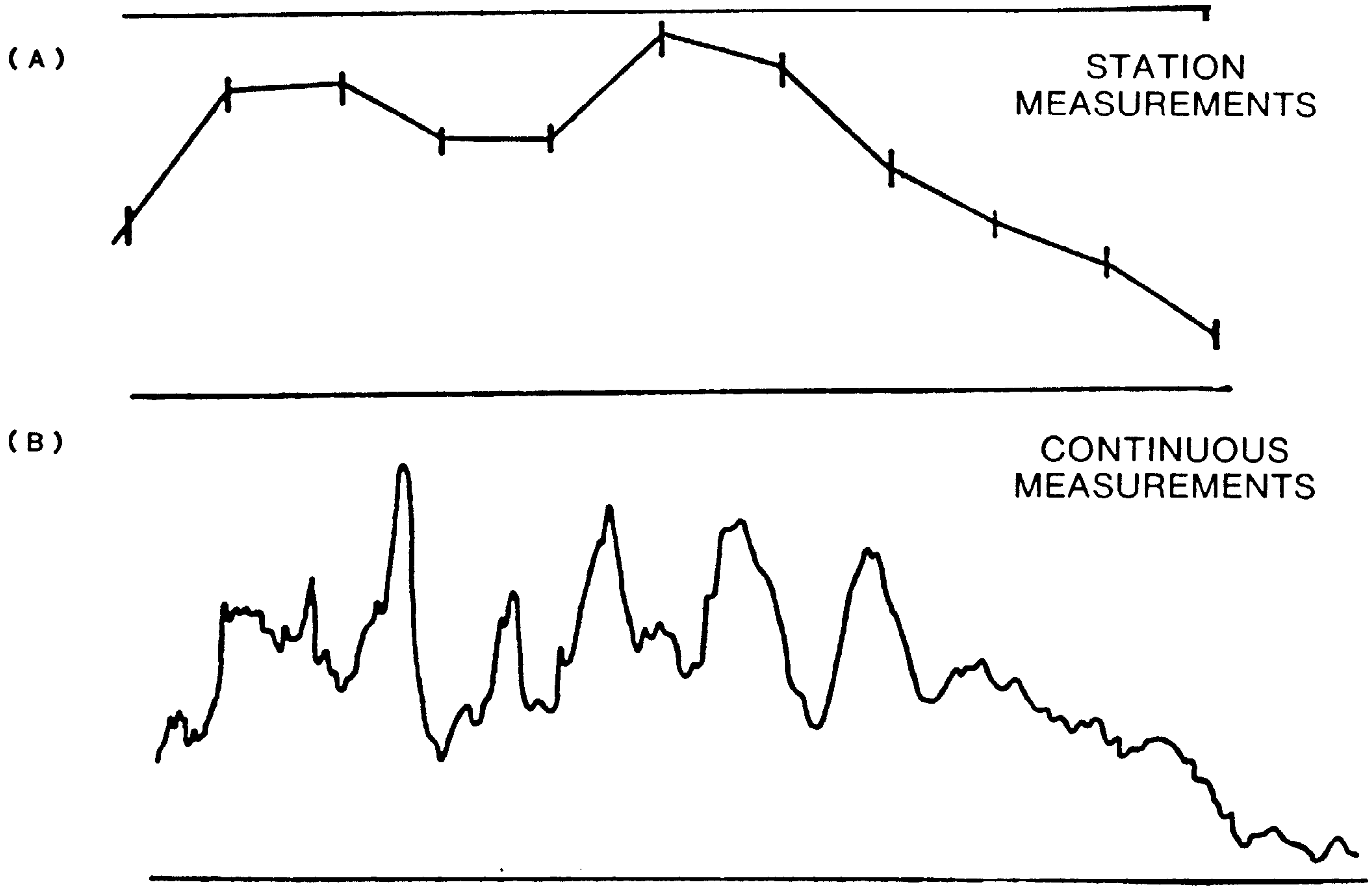


Figure 40. Continuous EM measurement (A) provides greater resolution than limited station measurements (B).



DISCRETE SAMPLING VS CONTINUOUS MEASUREMENTS

Figure 41. Continuous EM measurement provides greater resolution than limited station measurements.

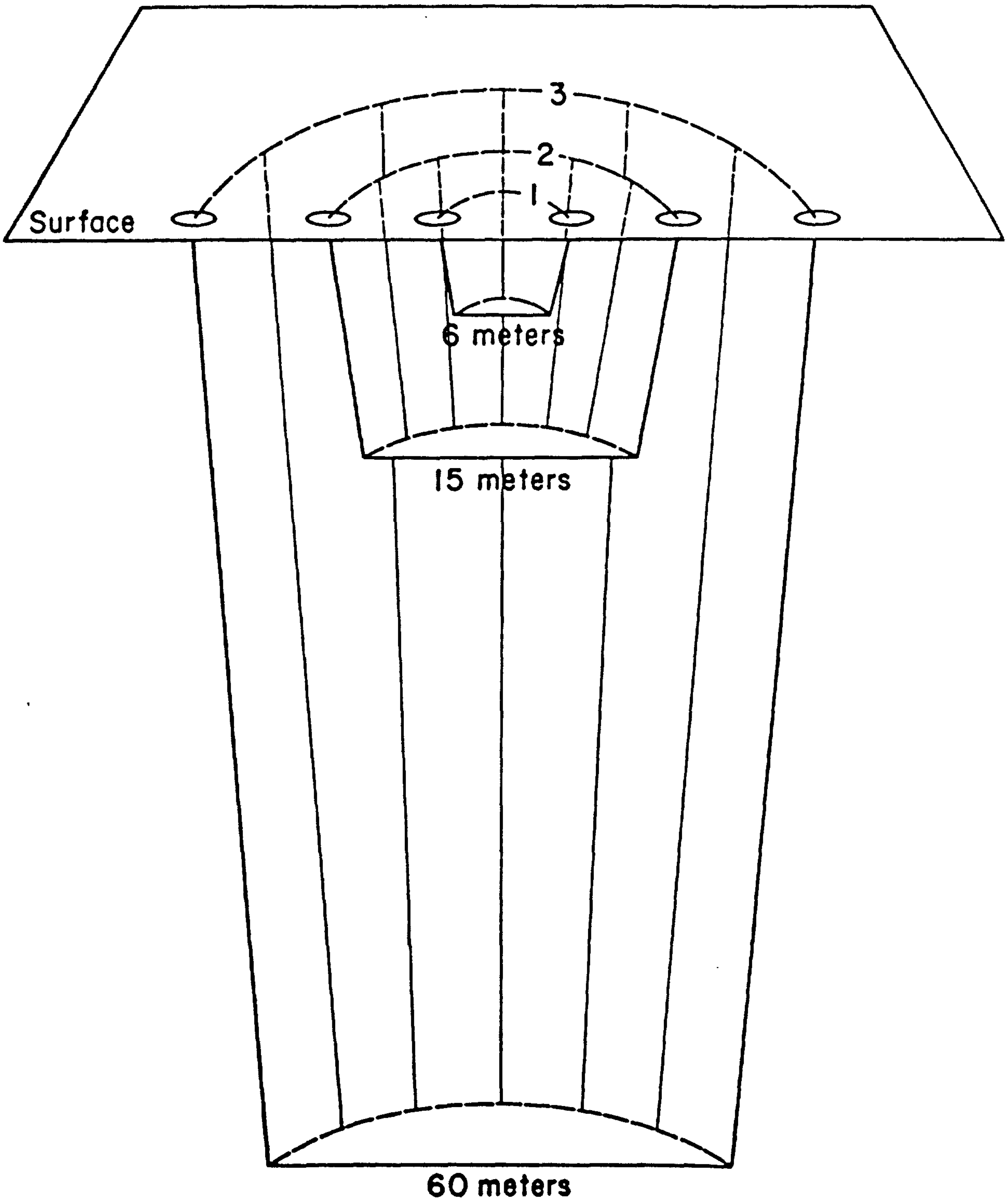


Figure 42. EM soundings are obtained by discrete station measurements. Maximum depth is dependent upon coil spacing and orientation selected. (for clarity only three depths shown).

information can be rapidly obtained with a single instrument by reorienting the coils 90 degrees. Another instrument (Figure 36) enables sounding information to be obtained by changing coil spacing and orientation. Additional information can he obtained by combining sounding data from several EM instruments having different depth ranges.

EM instruments are calibrated by the manufacturer to measure the absolute conductivity over a uniform section of earth; however, the earth is rarely uniform. For example, in a layered earth, each layer may have a different conductivity; the resulting instrument reading will be some intermediate value depending on the thickness of each of the layers, their depths, and the specific conductivities of the individual materials. The instrument reading is then the result of the cumulative contributions of all the layers from the surface to the depth range of the instrument. A strict solution for this function would require knowledge of the thicknesses of the layers and their respective conductivities. Hence, a unique interpretation of subsurface conditions generally cannot be obtained from EM sounding data alone; it must be supported by drilling data or other geologic information.

Generally, the most cost-effective approach is to use profiling to locate anomalous features. Subsequent analysis, using soundings at selected areas, can assist in a semi-quantitative depth evaluation of anomalies and background conditions.

When planning an investigation, careful consideration should be given to the selection of an EM system to match site requirements. Some factors which will influence survey planning are:

- Basic objective(s) of the survey;
- Total area to be covered;
- Depth(s) of profile data needed;
- Site coverage density and resolution requirements;
- Sounding requirements;
- Computer processing requirements;
- Site access:
- Possible cultural interferences which may inhibit or restrict results.

Final choice of the system(s) to be used will be most dependent on depth and resolution requirements. For example, to detect a plume from a landfill in a shal1ow (less than 6 meters) aquifer, the continuous "6-meter-depth" EM system would be ideal, offering both the correct depth range and high resolution in the profiling mode. Generally, spatial coverage using parallel lines spaced at 15 to 30 meters or more has been adequate for most landfill evaluations where continuous profiles are possible.

Quality Control

EM instruments are calibrated over a massive rock outcrop used as a geologic "standard" by the manufacturer. After calibration, the instruments will generally retain their accuracy for long periods. However, a secondary standard area should be established by the user for periodic recalibration. On large projects a local standard site may be established in the field. This will provide a reference base station, to check "drift" in the instrument's performance and to permit correlation between instruments.

While precision (repeatability) can be easily checked simply by comparing the instrument to a standard site, accuracy (closeness to the truth) is much more difficult to establish and maintain.

EM instruments are often used to obtain relative measurements. For these applications, maintenance of absolute accuracy is not critical; however, the precision of the instrument can be important. For example, in the initial mapping of the spatial extent of a contaminant plume, a moderate level of precision is necessary. If the same site is to be resurveyed annually to detect small changes in plume growth and movement, a very high level of precision is necessary. If the objective of the survey is to obtain quantitative results from the EM data, for correlation to other measurable parameters (e.g., specific conductance), the accuracy of the measurement becomes critical. Under these conditions, proper steps should be taken to assure good instrument calibration. This is particularly important when performing surveys in areas of low conductivity, where the accuracy error can be significant.

The dynamic range of EM instruments varies from 1 to 1000 mm/m. At the lower conductivties, near 1 mm/m and less, it is difficult to induce sufficient current in the ground to produce a detectable response, hence readings may become unreliable. At conductivity values greater than about 100 mm/m, the received signal is no longer linearly proportional to subsurface conductivites, and corrections must he applied to the data, if it is to be used for quantitative purposes.

Noise

EM systems are susceptible to signal interference from a variety of sources, originating both above the ground and below. Electromagnetic noise may be caused by nearby power lines, powerful radio transmitters, and atmospheric conditions. At some sites shallow EM surveys can be carried out in the immediate vicinity of power lines; at others, conditions may be so bad that measurements are impossible. Generally, deeper measurements using larger coil spacings will be more susceptible to noise than shallower measurements. In addition to other forms of electromagnetic noise, instrument responses from subsurface or surface metal may make it difficult to obtain a valid measurement. For instance, piles of drums, nearby vehicles, fences or railroad tracks can act as targets and produce an unwanted response. Within a range of 1.5 to 2 times the coil spacing, these large items may influence the data. Small items of metallic trash usually create no problem. Buried pipes and cables will cause very large EM anomalies. However, because of their characteristic response, they can be recognized, and then either ignored or filtered out of the data. Unfortunately, near such buried objects, important information of lesser magnitude is often lost.

EM surveys have been successfully carried out in scrap iron yards over construction debris fill. The acquisition of a large amount of data by station measurements and continuous measurements, and the use of special field techniques and computer processing permitted the location and delineation of contaminated ground waters. While the total effort was time-consuming and costly, useful results were obtained under extremely difficult conditions.

Data Format, Processing, Interpretation and Presentation

EM data can be recorded in the field in several formats:

- Field notebooks;
- Strip chart records;
- Magnetic tape.

EM system output, whether profiling or sounding, may be taken directly from the instrument and recorded in a field log. Continuous profile data must be recorded on a strip chart recorder or on magnetic media. When recorders are used some means of noting survey marks and comments must be provided.

Corrections may be applied to EM data for:

- Accuracy (calibration);
- Drift (precision);
- Spatial variations (due to changes in speed while recording continuous data);
- Scale changes (necessary to provide adequate resolution);
- Nonlinearities (associated with high conductivity values).

These corrections may be applied manually or by computer; however, raw uncorrected data may be adequate for a given problem.

Profiling Data--A simple profile line may be drawn from station field data (Figure 41A) or a raw strip chart record may be used (Figure 41B). EM profile data are commonly acquired from a series of parallel traverses across the site and recorded in the strip chart or magnetic tape format. Because of the large quantity produced, the data usually must be handled by computer. The data may be presented as single profile lines, stacked profile lines, as a three–dimensional, composite view of the data set, or as an isopleth map. Examples of these different formats are given in Figures 43, 44, and 45. These figures represent changes in subsurface conductivities due to varying amounts of soil moisture related to fractured bedrock. Major trends can be located in the series of stacked profile lines (Figure 43). Trends and other details ae often better understood through the use of a three–dimensional perspective plot of the data (Figure 44). This format gives the viewer a complete graphic picture of the data at a glance. The isopleth plot (Figure 45) presents these features in a manner which facilitates accurate location and determination of size.

Besides handling large amounts of data and creating the presentation shown above, computer processing can be applied to achieve a variety of results. For example, filtering may be applied to remove small unwanted spatial features in order to emphasize the major characteristics of the plume. In addition, cultural noise from buried pipes or cables can be removed from the data to clean up the presentation. Subtle features which might otherwise have been overlooked have been enhanced and identified by processing.

Although computer processing is generally applied to continuous profile data acquired on strip charts or magnetic tape, it is also applicable to high-density discrete station measurements.

The most common use of profile data is to locate anomalous conditions. The spatial relationships of relative values are noted, enabling the user to locate and follow trends over the site (see Figures 43, 44 and 45). Drilling sites or other measurements may then be precisely located. Two profile lines, run at different effective depths, will provide semi-quantitative information on the relative conductivities of shallow and deeper layers. Such information is invaluable in assessing the three-dimensional nature of site conditions. Contour plots can be used to accurately determine the spatial extent and direction of flow, as well as to make an estimate of the magnitude of contamination. In addition, if complete sets of data are obtained on two different occasions, the rate of movement can be established by direct in-situ measurement.

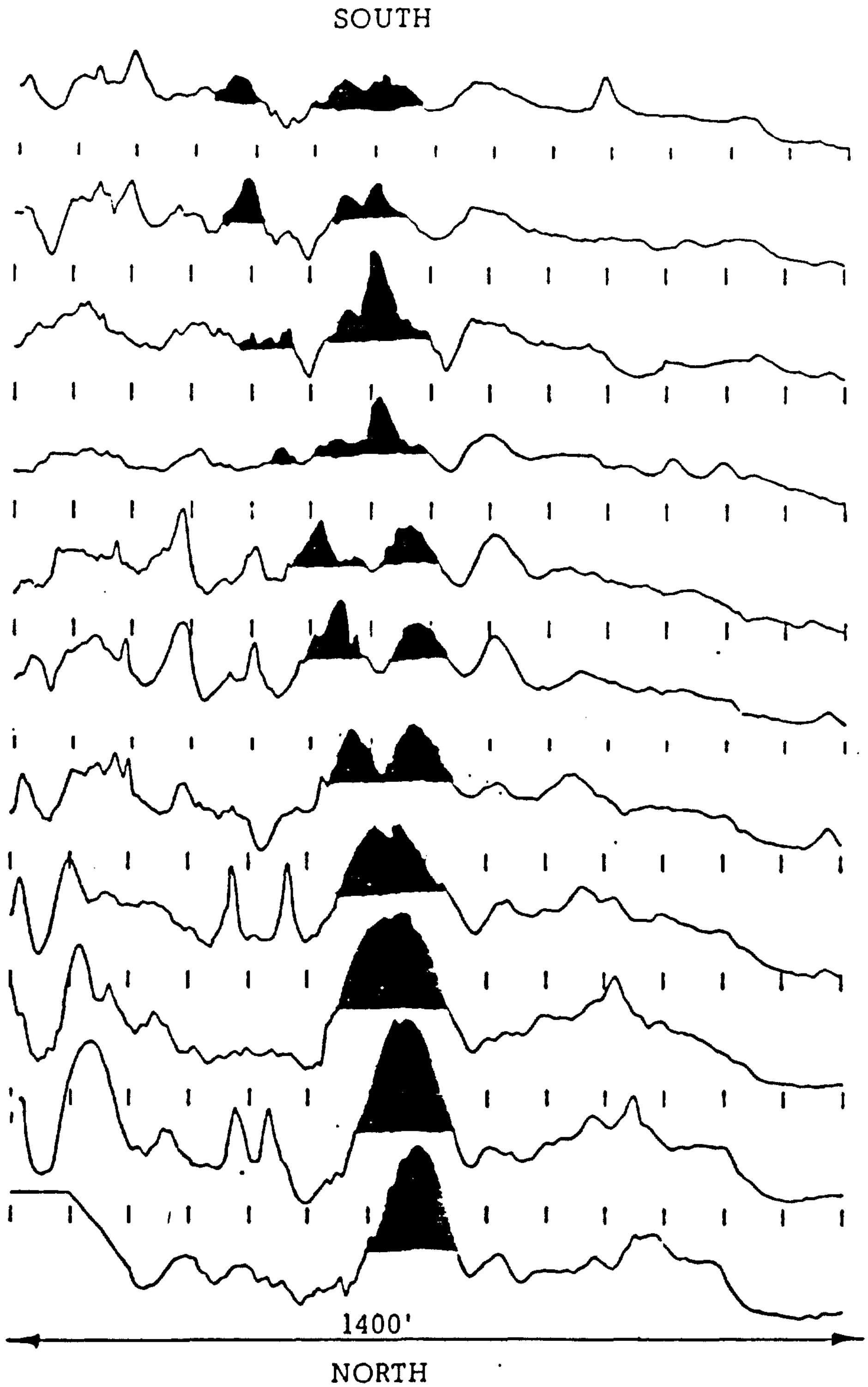


Figure 43. Eleven parallel, continuously recorded EM profiles. This format shows the extreme variability of conductivity values across the site and locates fracture trends in underlying rock.

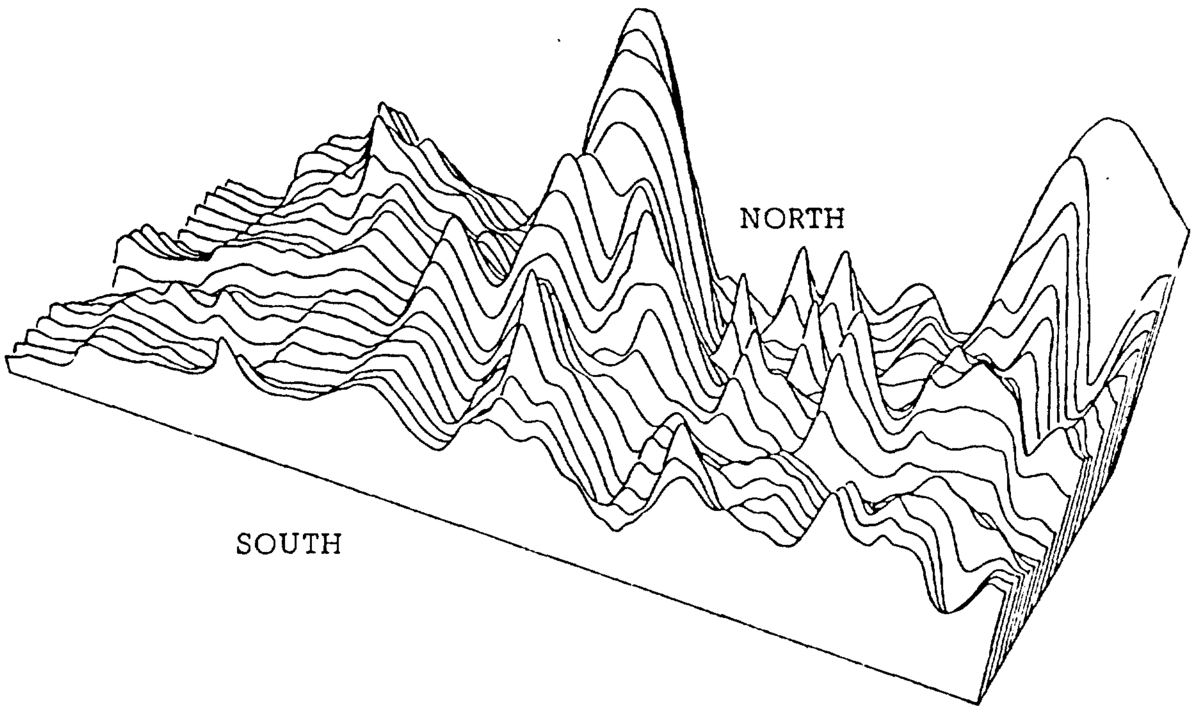


Figure 44. Three-dimensional perspective computer plot of EM data shown in Figure 43. This format allows the interpreter to quickly grasp the spatial and amplitude relationshops in the data. Subtle as well as major trends are emphasized.

Sounding data--is always acquired from a number of discrete station readings. A simple qualitative assessment may be obtained using a single instrument. It is fairly easy to establish the conductivity of near-surface conditions relative to deeper conditions.

More quantitative evaluations of the vertical layering of the subsurface can be obtained from detailed sounding measurements. One or more instruments may be required. Field data can be compared to calculated conductivities derived from the EM response equations, using estimated layer parameters. This iterative process will converge on a model of the vertical section. This approach will not necessarily yield a unique solution; however, if good geologic information is available for the area, a unique solution may be obtained.

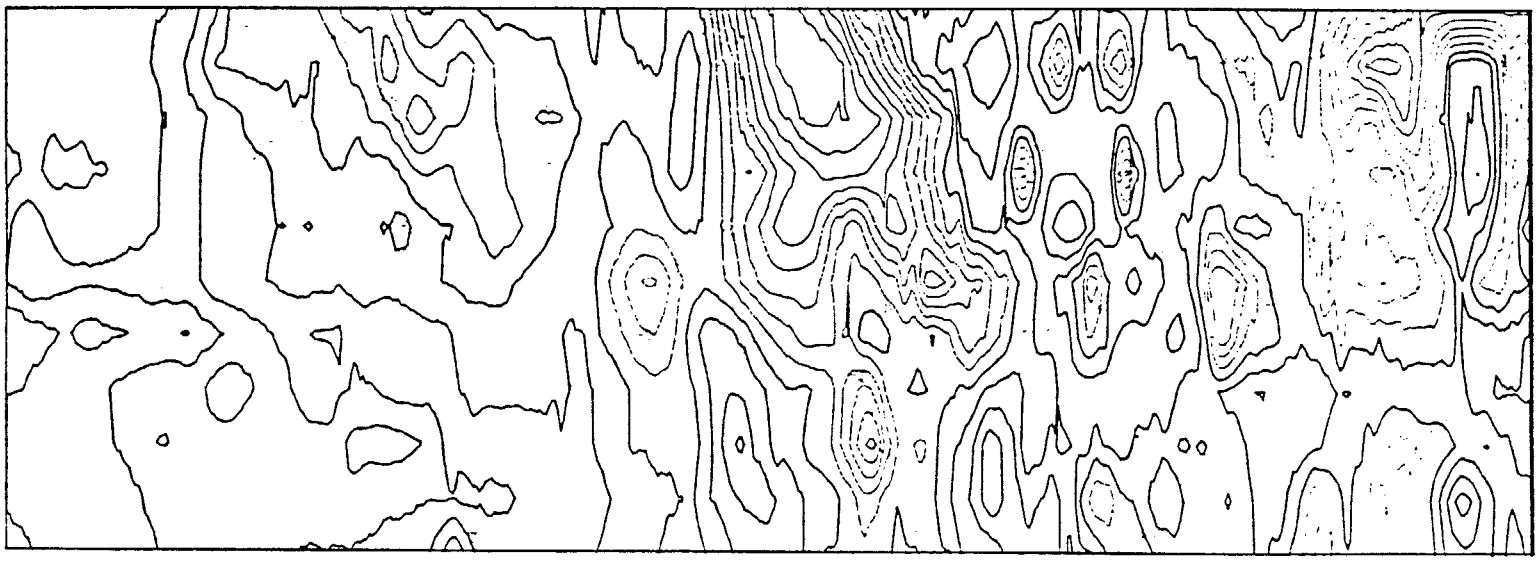


Figure 45. Computer-generated isopleth plot of EM data shown in Figures 43 and 44. Plan view isopleth plots are effective in determining exact location of features.

The EM sounding method can rarely identify more than 2 or 3 layers with reasonable confidence. The greater the contrast in the conductivity values of each layer, the better the results. Often, the more detailed resistivity sounding method is used to complement EM profiling data.

The results of a sounding analysis are usually presented as a vertical section, in which the conductivity layers are identified as a function of depth. The analyst may be able to correlate these layers to geohydrologic units believed to exist at the site (Figure 46).

Summary

Although the EM technique can be used for profiling or sounding, profiling is the most effective use of the EM method. Profiling makes possible the rapid mapping of subsurface conductivity changes, and the location, delineation and assessment of spatial variables resulting from changes in the natural setting or from many contaminants.

EM is a very effective reconnaissance tool. The use of qualitative non-recorded data can provide initial interpretation in the field. If site conditions are complex, the use of a high-density survey grid, continuously-recording instruments, and computer processing may be necessary, in order to properly evaluate subsurface conditions. When continuously-recording instruments are used, total site coverage is feasible. More quantitative information can be obtained by using conductivity data from different depth ranges. At present, three different systems must be used to acquire data from 0.75 meters to 60 meters. Very often, however, data from two standard depths, e.g. 6 and 15 meters, is adequate to furnish depth information.

Capabilities

- The EM profile method permits rapid data acquisition, resulting in high-density and high-resolution surveys.
- Profiling data may be acquired from various discrete depths, ranging from 0.75 meters to 60 meters.
- Continuously-recording instruments (to 15 meter depth) can increase survey speed, density and resolution permitting total site coverage, if required.
- EM reads directly in conductivity units (mm/m) permitting use of raw data in the field, and correlation to specific conductance of ground water samples.
- EM can map local and general changes in the natural geohydrologic setting.
- EM can detect and measure the boundaries of a conductivity plume.
- Direction of plume flow can be determined from an EM conductivity map.

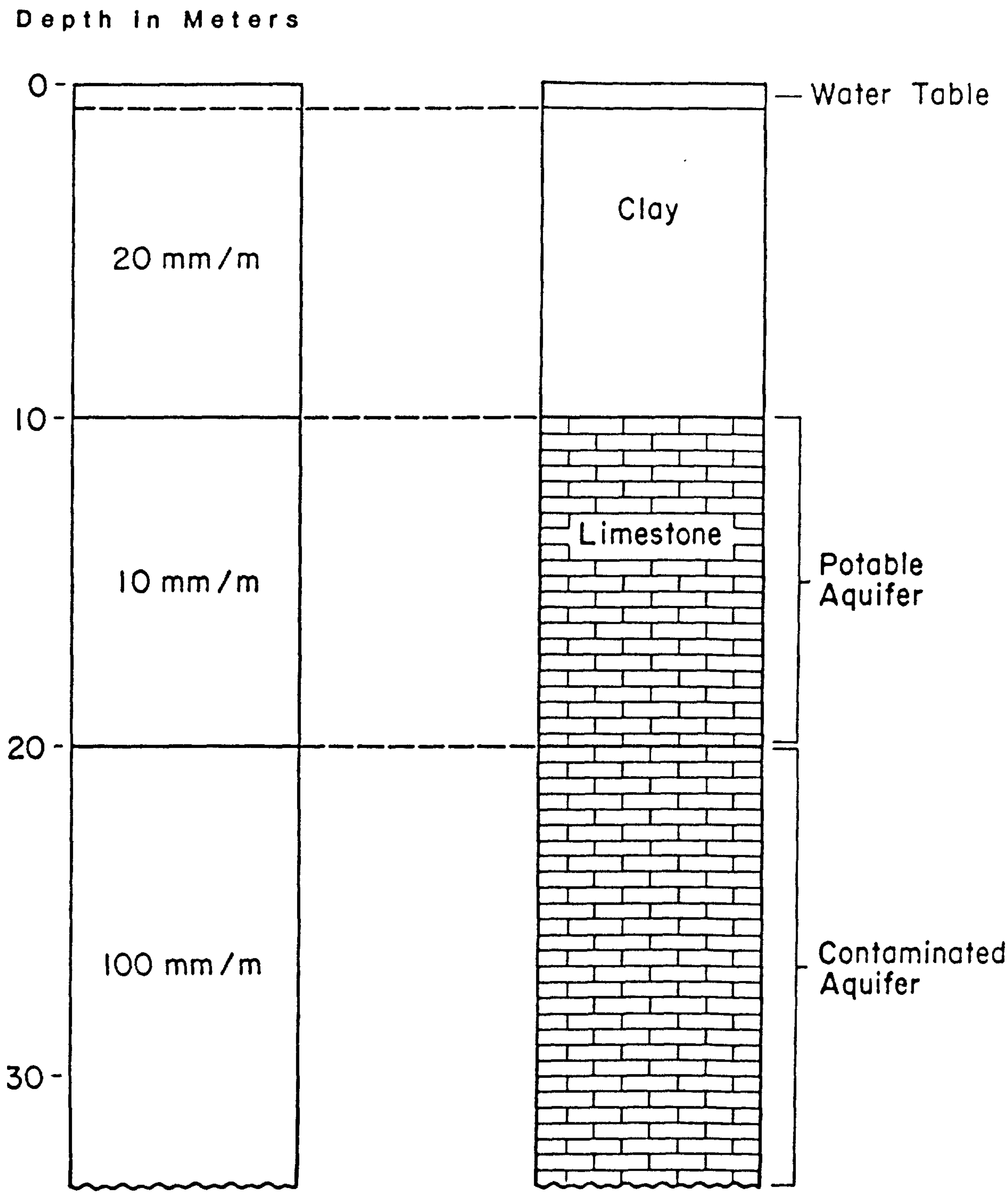


Figure 46. Sounding data yields vertical electric section which can be related to geohydrologic section.

- EM measurements taken at different times can provide the means to compute movement rates of conservative contaminants.
- EM can detect and map burial pits and trenches of both bulk and drummed wastes.
- EM can detect and map the location of buried metallic utility lines.

Limitations

- EM has less sounding (vertical) resolution than the resistivity method, due to its limited number of depth intervals.
- The acquisition of data from depths of 0.75 to 60 meters requires the use of three different EM systems.
- Continuous data can be obtained only to depths up to approximately 15 meters.
- An EM measurement is influenced by the shallower materials more than the deeper ones; this must be considered when evaluating the data.
- EM measurements become non-linear in zones of very high conductivity.
- The EM method is susceptible to noise from a number of sources, including natural atmospheric noise, powerlines, radio transmitters, buried metallic trash, pipes, cables, nearby fences, vehicles and buildings.

Examples

Buried Natural Organics

The understanding of natural geologic/hydrologic conditions and the location of permeable migration routes in the soil and rock are important considerations in an evaluation of a HWS. Many constituents of soils, such as natural organic deposits, have strong sorption properties. Their presence and extent can be of major concern in evaluating potential migration.

Figure 47 shows the thickness of natural organics (peats) over an eroded limestone bedrock. Because of the relatively high conductivity of peat compared to that of limestone, the conductivity reading was primarily a function of the thickness of the peat. Three borings were made to the top of rock, which provided a means of correlating the EM data to peat thickness. The EM data was then calibrated from the boring data, and higher values of conductivity could be related to greater thicknesses of peat. Figure 47 shows the results of the three borings and the calibrated EM data which represents the approximate profile thickness of the peats.

The use of EM measurements combined with borings to

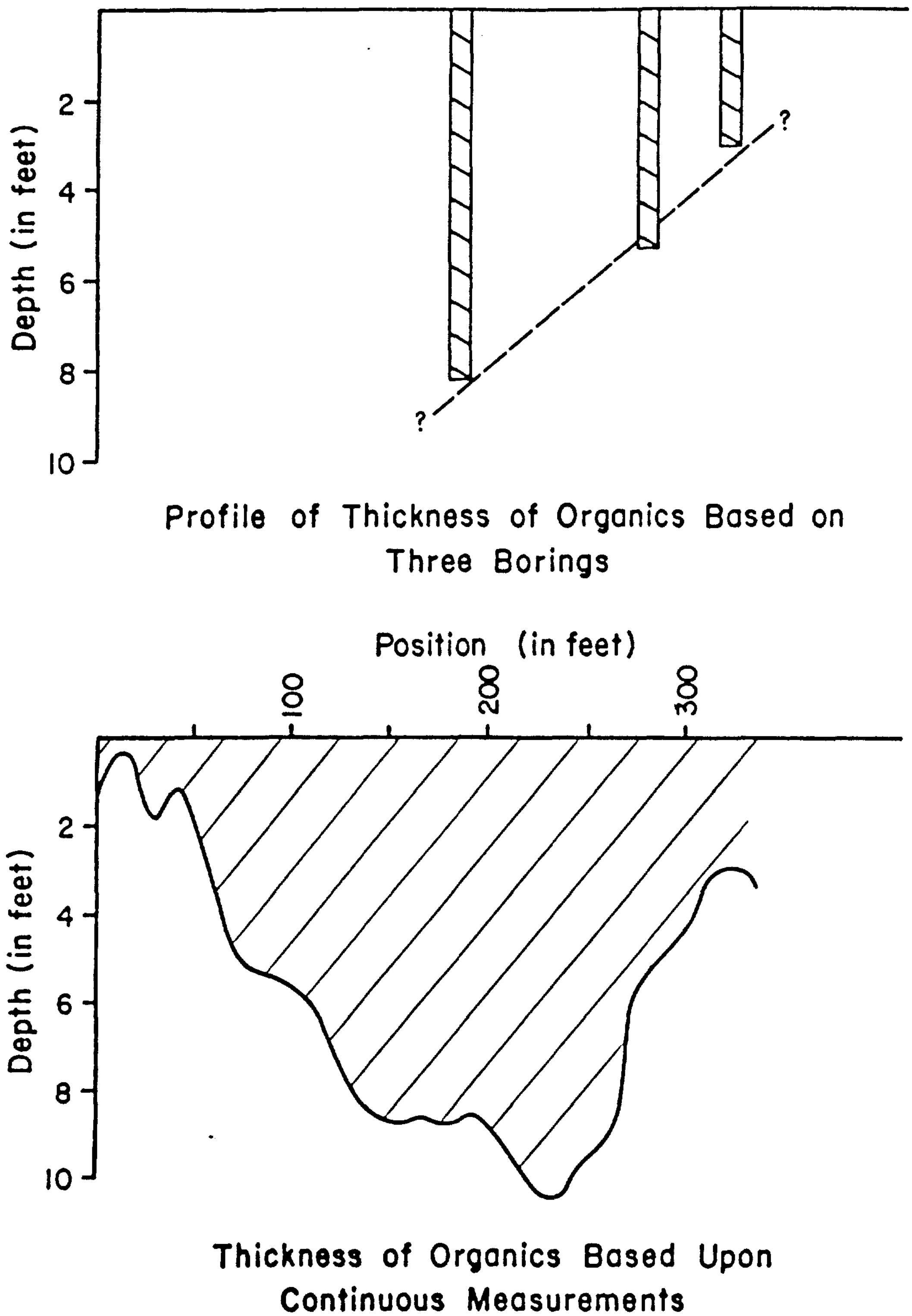


Figure 47. Continuous EM data (bottom) is calibrated by three borings (top). Results show thickness of natural organics (Peats).

calibrate the data enabled a large site to be mapped in a relatively short time with a reasonable degree of accuracy and at a much higher level of evaluation of the spatial variables.

Contamination from Flowing Abandoned Well

Since 1945, water from an artesian well tapping the top of the Floridan Aquifer had been flowing continuously at a rate of about 5500 cubic meters per day, allowing water high in total dissolved solids to spill onto the surface of the ground. Exploratory monitor wells had been established downgradient from the source.

Analysis of water samples indicated the presence of elevated concentrations of chloride (1150 ppm) over the full thickness of the aquifer (approximately 15 meters) and about 1.7 kilometers from the artesian source. The areal and vertical extent of the plume was measured using EM methods. The EM method was selected because it could provide very rapid profile measurements, with a reasonable number of stations for the large area (70 square kilometers) which the plume was suspected to occupy.

This study revealed that the plume was about 12 kilometers long and two kilometers wide (Figure 48). These results show that this area of the aquifer is highly permeable, as the plume had traveled over 12 kilometers in a period of 35 years--an average of about 1 meter/day. This is due to the highly porous nature of the limestone and the general lack of sand infilling, allowing polluted water to travel faster with much less filtering than in other more sandy regimes of the aquifer.

Buried Bulk Wastes and Drums

Many burial sites were believed to exist in a certain area. The EM technique was selected to provide a rapid reconnaissance in order to locate possible trenches. Determination of the extent of contaminant migration into the surrounding soil was also of interest at this site. Twelve parallel survey lines, 120 meters long, spaced 15 meters apart were established in the area. The survey lines were oriented approximately perpendicular to the suspected trenches. These lines were traversed using a shallow (6 meter) EM system, with its output continuously recorded on a strip chart. The data was entered into a computer system for spatial corrections, smoothing and plotting. To provide perspective, a three-dimensional view of the data set was developed, as shown in Figure 49.

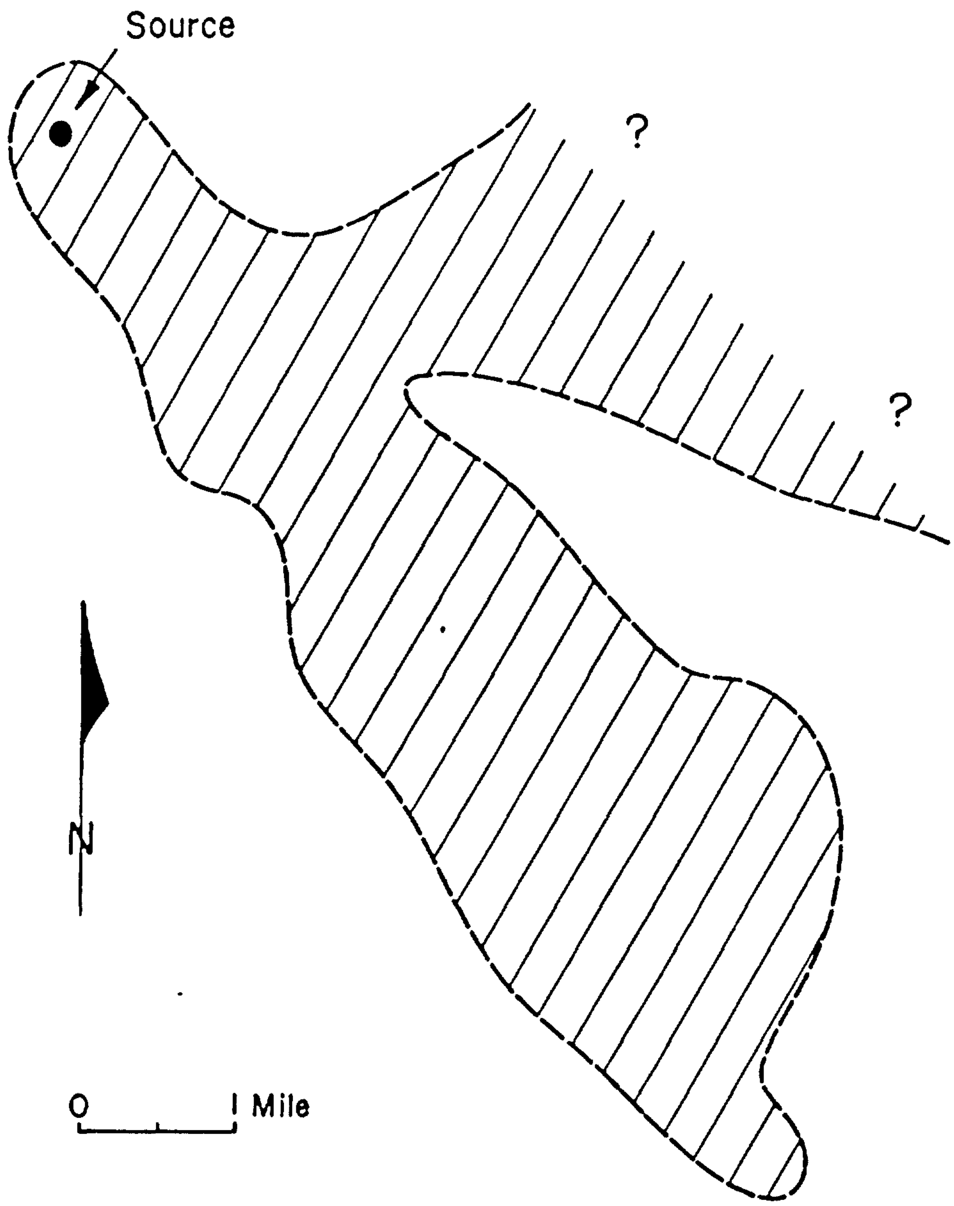


Figure 48. EM method was used to map widespread contamination of ground water caused by free flowing brackish well. Over 10 square miles have been contaminated.

These results indicate that a large contrast exists between the relatively high conductivities of the waste material and that of the surrounding natural dry soil. Moreover, analysis of the processed data indicates that conductivity highs can be correlated from line to line, revealing the linear extent of a series of narrow trenches. The data also reveals that the trenches are relatively close together. The fact that no obvious high EM values exist in the area surrounding these trenches indicates that the soil is relatively tight essentially containing the fluid wastes in the trench area.

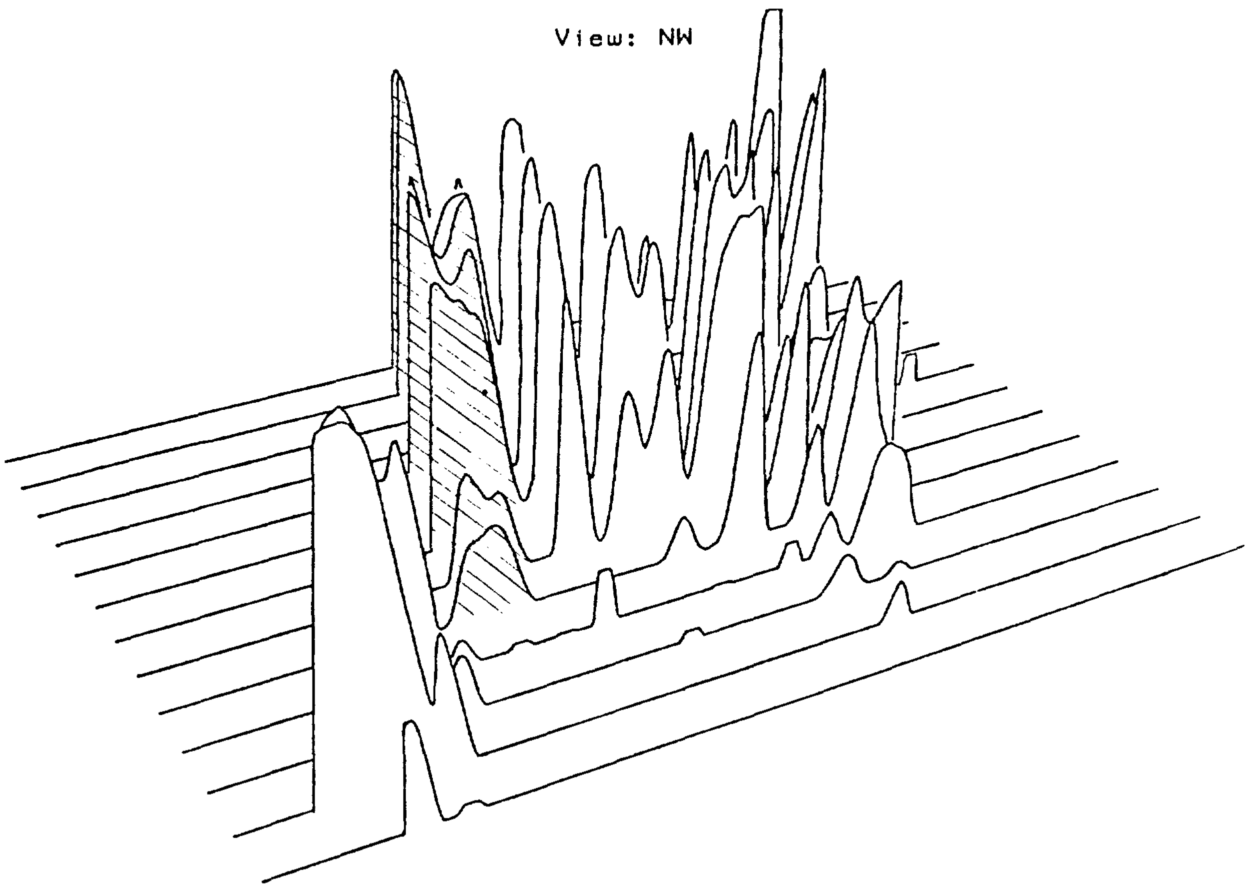


Figure 49. Computer plot of EM conductivity data, obtained over a buried waste site. The linear patterns of conductivity highs indicate buried trenches. (One linear trend is shaded to show trench.)

SECTION VI

RESISTIVITY

Introduction

The resistivity method is used to measure the electrical resistivity of the geohydrologic section which includes the soil, rock and ground water. Accordingly, the method may be used to assess lateral changes and vertical cross sections of the natural geohydrologic settings. In addition, it can be used to evaluate contaminant plumes and locate buried wastes at hazardous waste sites.

Application of the method requires that an electrical current be injected into the ground by a pair of surface electrodes. The resulting potential field (voltage) is measured at the surface between a second pair of electrodes. The subsurface resistivity can be calculated by knowing the electrode separation and geometry of the electrode positions, applied current, and measured voltage. (Resistivity is the reciprocal of conductivity, the parameter directly measured by the EM technique.)

In general, most soil and rock minerals are electrical insulators (highly resistive); hence the flow of current is conducted primarily through the moisture-filled pore spaces within the soil and rock. Therefore, the resistivity of soils and rocks is predominantly controlled by the porosity and permeability of the system, the amount of pore water, and the concentration of dissolved solids in the pore water.

The resistivity technique may be used for "profiling" or "sounding". Profiling provides a means of mapping lateral changes in subsurface electrical properties. This field technique is well suited to the delineation of contaminant plumes and the detection and location of changes in natural geohydrologic conditions. Sounding provides a means of determining the vertical changes in subsurface electrical properties. Interpretation of sounding data provides the depth and thickness of subsurface layers having different resistivities. Commonly up to 4 layers may be resolved with this technique.

Applications of the resistivity method at hazardous waste sites include:

- Locating and mapping contaminant plumes;
- Establishing direction and rate of flow of contaminant plumes;
- Defining burial sites by
  - locating trenches,
  - defining trench boundaries,
  - determining the depths of trenches.
- Defining natural geohydrologic conditions such as
  - depth to water table or to water-bearing horizons,
  - depth to bedrock, thickness of soil, etc.

Principles and Equipment

Most dry mineral components of soil and rock are highly resistive except for a few metallic ore minerals. Under most circumstances, the amount of soil/rock moisture dominates the measurement greatly reducing the resistivity value. Current flow is essentially electrolytic, being conducted by water contained within pores and cracks. A few minerals like clays actually contribute to conduction. In general, soils and rocks become less resistive as:

- Moisture or water content increases;
- Porosity and permeability of the formation increases;
- Dissolved solid and colloid (electrolyte) content increases;
- Temperature increases (a minor factor, except in areas of permafrost).

Figure 50 illustrates the range of resistivity found in commonly-occurring soils and rocks. Very dry sand, gravel or rock as encountered in arid or semi-arid areas will have very high resistivity. As the empty pore spaces fill with water, resistivity will drop. Conversely, the resistivity of earth materials which occur below the water table but lack pore space (such as massive granite and limestone) will be relatively high and will be primarily controlled by current conduction along cracks and fissures in the formation. Clayey soils and shale layers generally have low resistivity values, due to their inherent moisture and clay mineral content. In all cases, an increase in the electrolyte, total dissolved solids (TDS) or specific conductance of the system will cause a marked increase in current conduction and a corresponding drop in resistivity. This fact makes resistivity an excellent technique for the detection and mapping of conductive contaminant plumes.

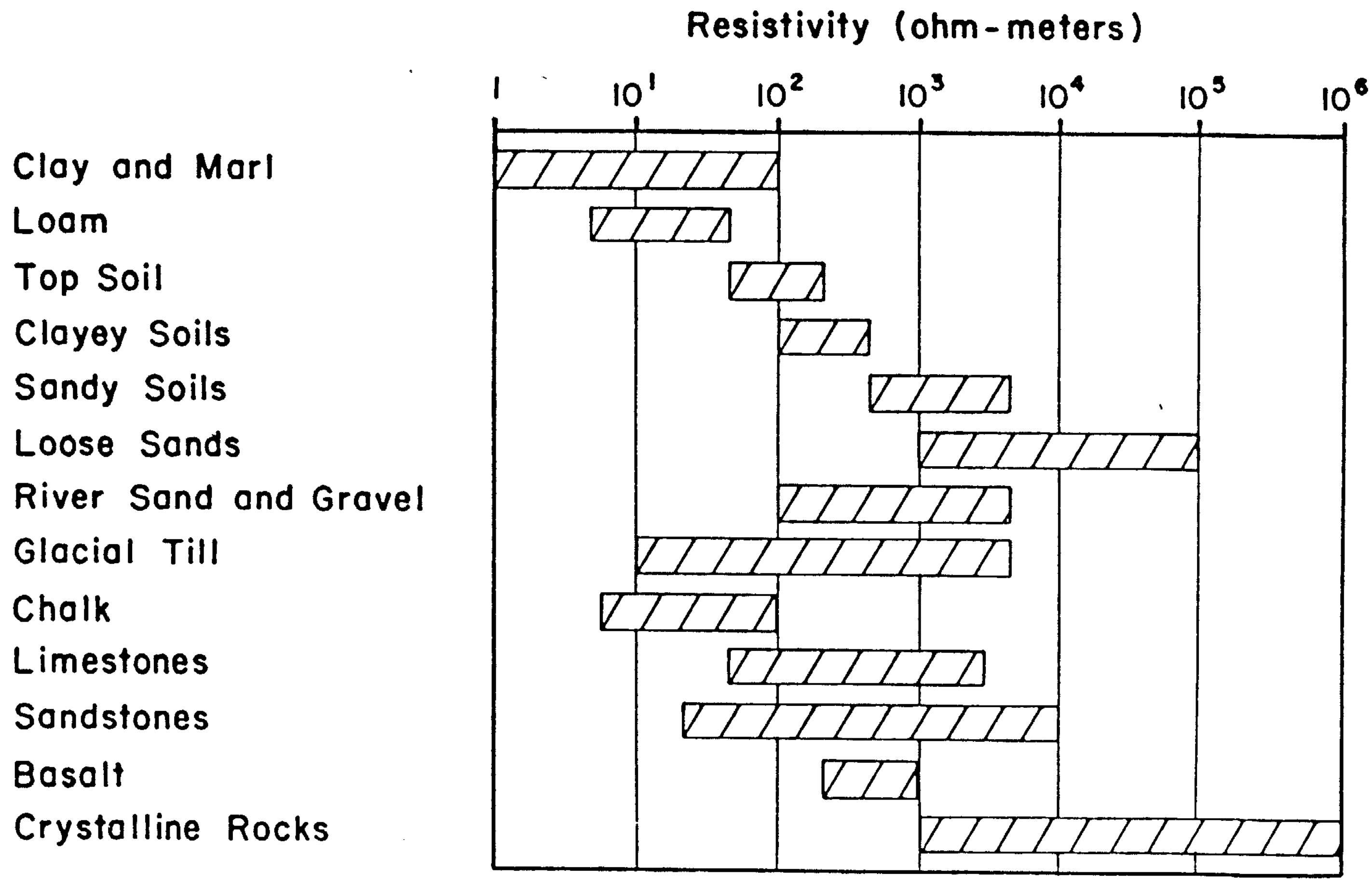


Figure 50. Range of resistivities in commonly-occurring soils and rocks. (Modified after Culley et al.).

It is important to note that no geologic unit or plume has a unique or characteristic resistivity value. Its measured resistivity is dependent on the natural soil and rock present, the relative amount of moisture, and its specific conductance. However, the natural resistivity value of a particular formation or unit may remain within a small range for a given area.

Figure 51 shows typical field equipment for making resistivity measurements; Figure 52 is a schematic diagram showing the basic principles of operation. The resistivity method is inherently limited to station measurements, since electrodes must be in physical and electrical contact with the ground. This requirement makes the resistivity method slower than a non-contract method such as EM.

Many different types of electrode spacing arrays may be used to make resistivity measurements; the more commonly used include Wenner, Schlumberger, and dipole-dipole (Figure 53). Due to its simple electrical geometry, the Wenner array will be used as an example in the remainder of this section; however, its use is not necessarily recommended for all site conditions. The choice of array will depend upon project objectives and site conditions and should be made by an experienced geophysicist.

Using the Wenner array (Figure 53), potential electrodes are centered on a line between the current electrodes; an equal spacing between electrodes is maintained. These "A" spacings used during HWS evaluation commonly range from 0.3 meter to more than 100 meters. The depth of measurement is related to the "A" spacing and may vary depending upon the geohydrology.

Current is injected into the ground by the two outer electrodes which are connected by cables to a DC or low-frequency AC current source. (If true DC is used, special non-polarizing electrodes must be used.) The distribution of current within the earth is influenced by the relative resistivity of subsurface features. For example, homogeneous subsurface conditions will have the uniform current flow distribution shown in Figure 54a and will yield a resistivity value characteristic of the sampled section. On the other hand, Figure 54 shows a case where the electrodes spacing has been increased, and current distribution is pulled downward by a low-resistivity layer at depth. In this case the apparent resistivity will be lower than that of the surface layer, due to the influence of the lower resistivity material at depth.

The current flow within the subsurface produces an electric field with lines of equal potential, perpendicular to the lines of current (Figure 52). The potential field is measured by a voltmeter at the two inner electrodes.

Figure 51. Typical field setup for resistivity sounding (clay cap at Love Canal). "A" spacing between electrodes is one meter at beginning of sounding.

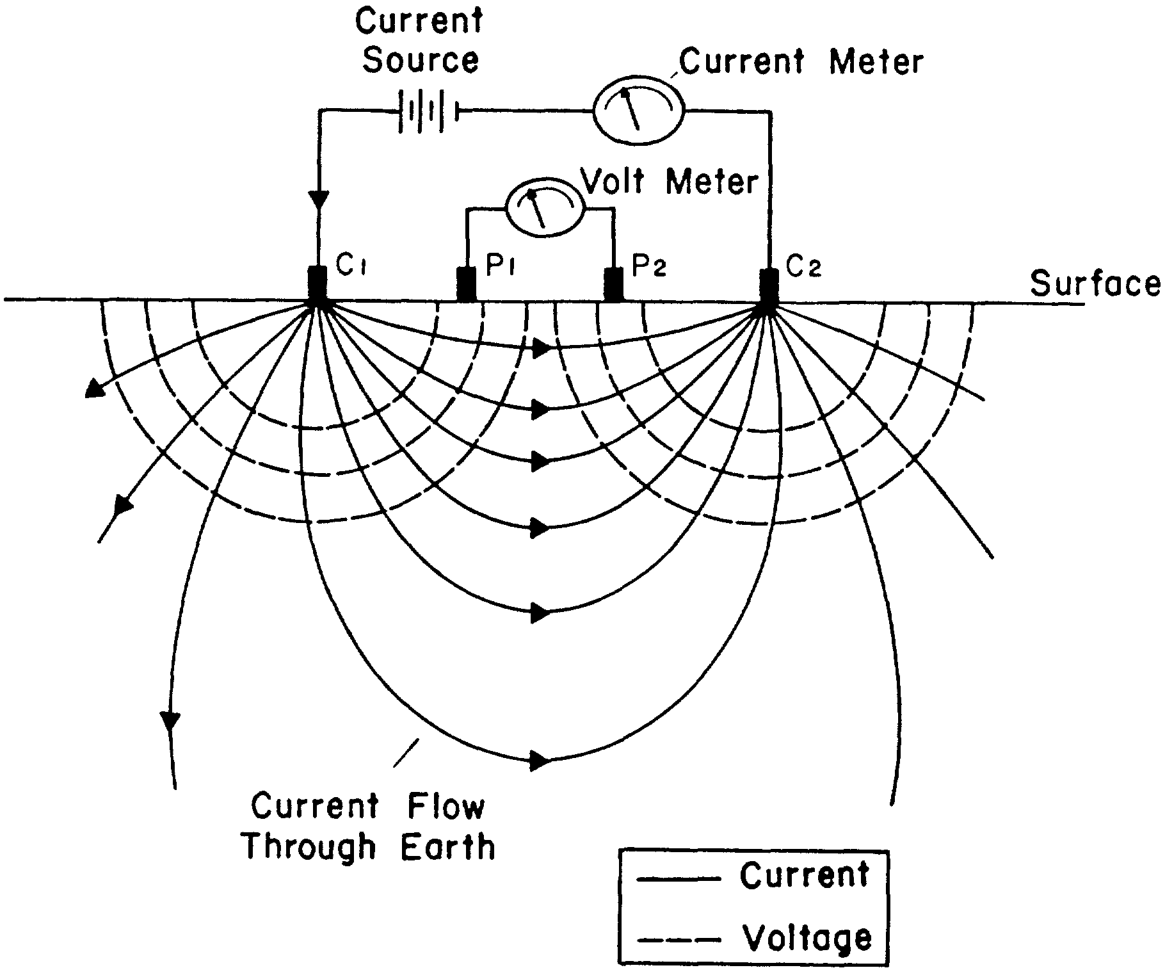


Figure 52. Diagram showing basic concept of resistivity measurement.

Apparent resistivity values using the Wenner array are calculated from the measured voltage and current and the spacing between electrodes as shown in the following equation:

$$\rho a = (2\pi A)(V/I)$$

where ρa = apparent resistivity (ohm-meters or ohm-feet)
A = "A" spacing (meters or feet)
V = potential (volts)
I = current (ampers)

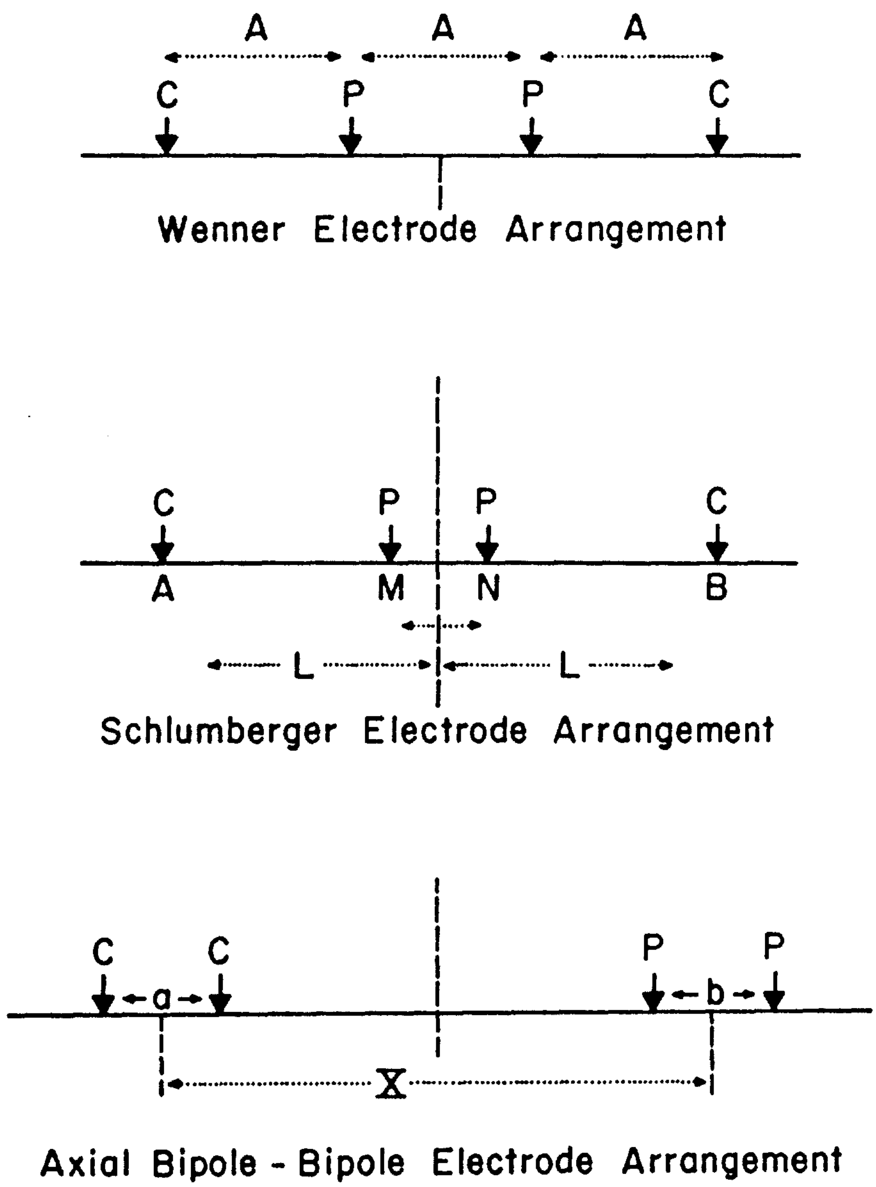


Figure 53. Three common electrode arrangements. C - designates a current electrode. P - designates a potential electrode.

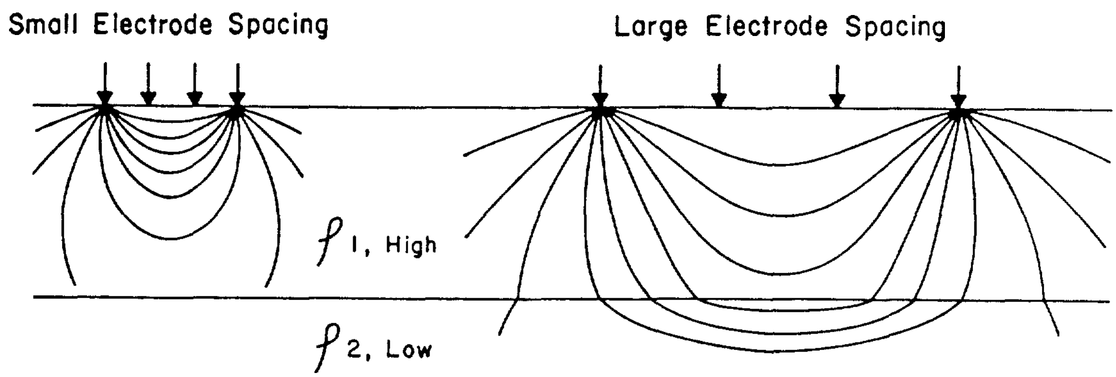


Figure 54. Increased electrode spacing samples greater depth and volume of earth.

The apparent resistivities are usually calculated and plotted as the measurements are made, permitting immediate quality control of the measurement in the field.

For acquisition of relatively shallow data, typically required at many HWS, the lower-power, self-contained resistivity units are quite satisfactory. Their transmitter is capable of obtaining data to about 50 to 100 meters, using self-contained rechargeable batteries. Very deep surveys will require higher-power transmitters using generators. Much of the newer equipment utilizes electronic signal enhancement to improve the signal-to-noise ratio and to allow measurement of lower voltages.

Cables of specific length to fit the selected "A" spacing are advantageous for extensive profiling surveys to speed data acquisition. Sounding measurements require a wide range of cable lengths; therefore, wire on reels is normally used.

Steel stakes are commonly used for electrodes and are driven into the ground to a depth of about 10 to 30 centimeters. Longer or multiple electrodes may be needed in dry sandy areas to provide better electrical contact with the ground. Water or salty water is also used to increase the effective electrode contact with dry soils.

<u>Factors to be Considered for Field Use</u>

<u>Profiling</u>--Profiling is the technique of making resistivity measurements with a fixed electrode spacing. Electrode "A" spacing should be 1 to 2 times the depth of interest. The fixed-spacing electrode array is moved to a number of different

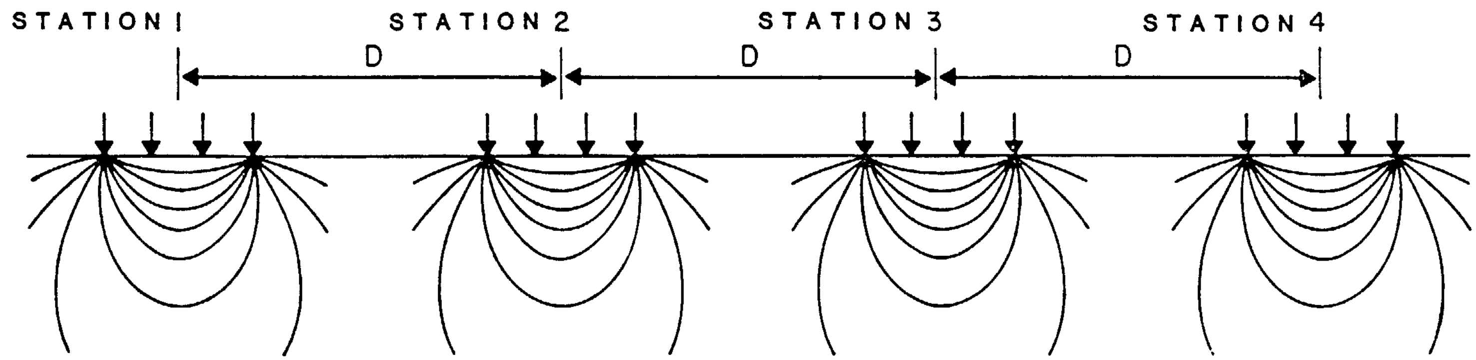


Figure 55. Profile measurements are accomplished by fixing the electrode spacing and moving the entire array. The distance between stations, D, is dictated by the lateral resolution desired.

locations to obtain data over the entire area of interest (Figure 55). Since depth of influence remains constant from one station to the next, profiling measures lateral changes in resistivity. Such changes permit the detection and mapping of anomalous spatial features over the area surveyed. The method may be modified to include measurements at more than one depth, thereby providing additional information on lateral variations with depth.

By making many profiling measurements along a traverse, a profile of subsurface resistivity may be obtained (Figure 56). Multiple profile lines or numerous profile stations may be placed at intervals across the area of interest to generate a contour map (Figure 57). The lateral resolution requirements of the investigation will dictate the distance between successive profiling stations.

Sounding--The sounding technique measures vertical changes in the geologic section. A series of resistivity measurements is made, each with successively larger electrode spacings (Figure 54). As the "A" spacing is increased, the depth of sampling at the sounding station also increases. The maximum "A" spacing should be at least 3 to 4 times the depth of interest in order to permit adequate characterization of deeper layers. Therefore, the overall array length including current electrodes will be 9 to 12 times the depth of interest. With such long arrays, the operator must insure that adequate space is available at the site and that it is relatively clear of buried pipes and fences.

Successive electrode spacings should be equally spaced on a logarithmic scale with a minimum of three per decade, although six are recommended. Commonly, more measurements are used to evaluate noise and provide reasonable quality in the data. For a typical sounding, 12 to 16 separate measurements may be made over an "A" spacing range of 0.3 meter to 100 meters.

The resulting data is plotted on log/log graph paper with apparent resistivity versus electrode "A" spacing (Figure 58). This graph can be visually interpreted for qualitative trends, or compared to master curves to determine layer thicknesses, depths and true resistivities. Computer processing may be applied to achieve quantitative results, as obtained by master curves or to analyze more complex data.

Although resistivity sounding methods are intended for use in uniformly layered geological conditions, useful data may often be obtained from the complex subsurface conditions often found at HWS.

With both profiling and sounding techniques, inhomogeneities in the near-surface soils may induce noise in the data.

Some surface conditions may limit or preclude use of the resistivity method. Dry surface material having extremely high resistivity will make injection of the current difficult and require special field procedures. In areas with paved surfaces such as asphalt and concrete roads or parking lots, electrode contact may not be possible.

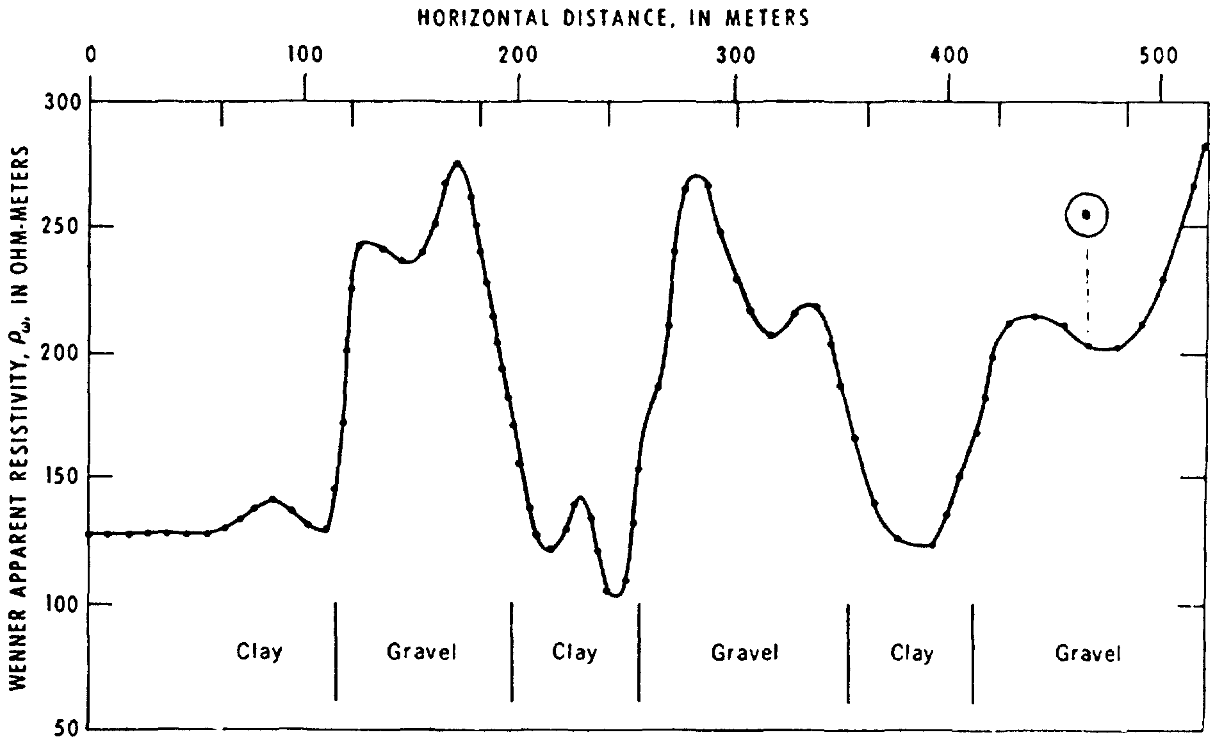


Figure 56. Resistivity profile across glacial clays and gravels. (from Zohdy, 1964).

Survey objectives will determine whether profiling or sounding data is required. For example, profiling should be used for mapping contaminant plumes. Because profiling is a faster field technique, a larger number of stations may be occupied with the higher density providing better lateral resolution. The selection of the proper "A" spacing for the profiling survey may be determined from several initial soundings in the area of the suspected plume.

STATION SPACING 10 METERS
A SPACING = 10 METERS ISOPLETH INTERVAL = 20 OHM METERS

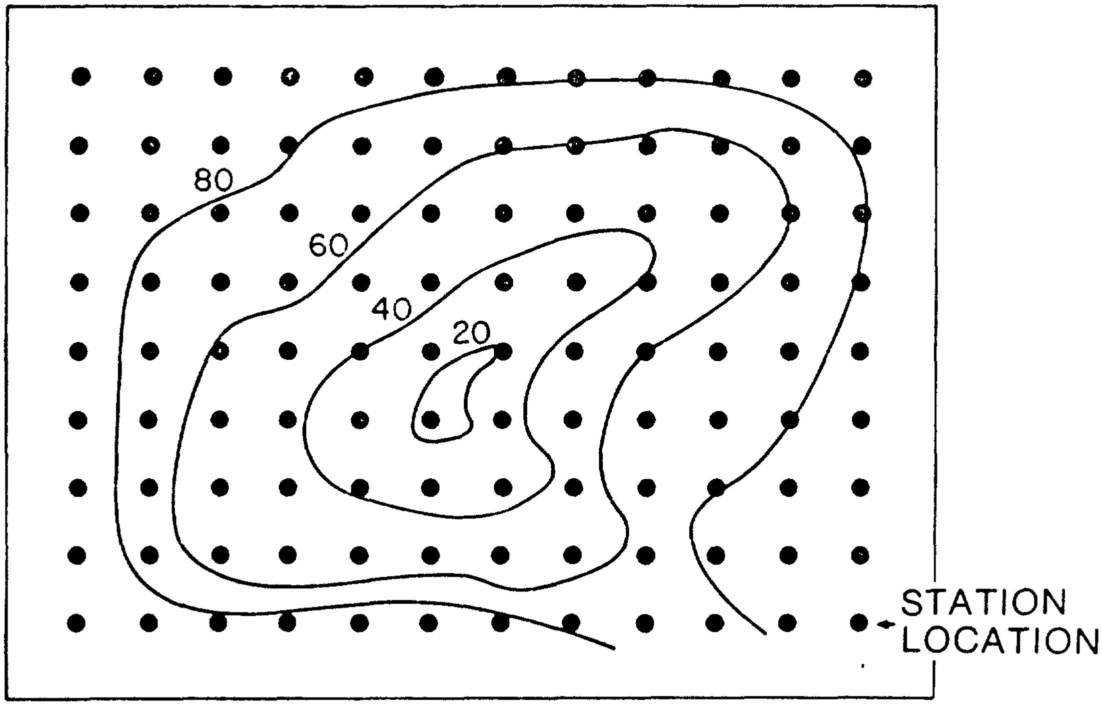


Figure 57. Isopleth resistivity map of profiling data.

A potential safety hazard exists during the operation of the resistivity unit; substantial amounts of current and voltage are present at the current electrodes during the time the transmitter is energized. Field procedures must be designed to insure that none of the field crew are in contact with the electrodes during this period. An experienced field crew will not have problems, but if persons unfamiliar with the techniques are involved with the field operations, additional caution should be exercised.

Quality Control

Considering the length of the wire cables, their connections to the stakes and the stakes contact with the ground, there are a number of possibilities for poor electrical contact and short circuits in the resistivity array. These conditions can be monitored by observing instrument readings and trends in the data.

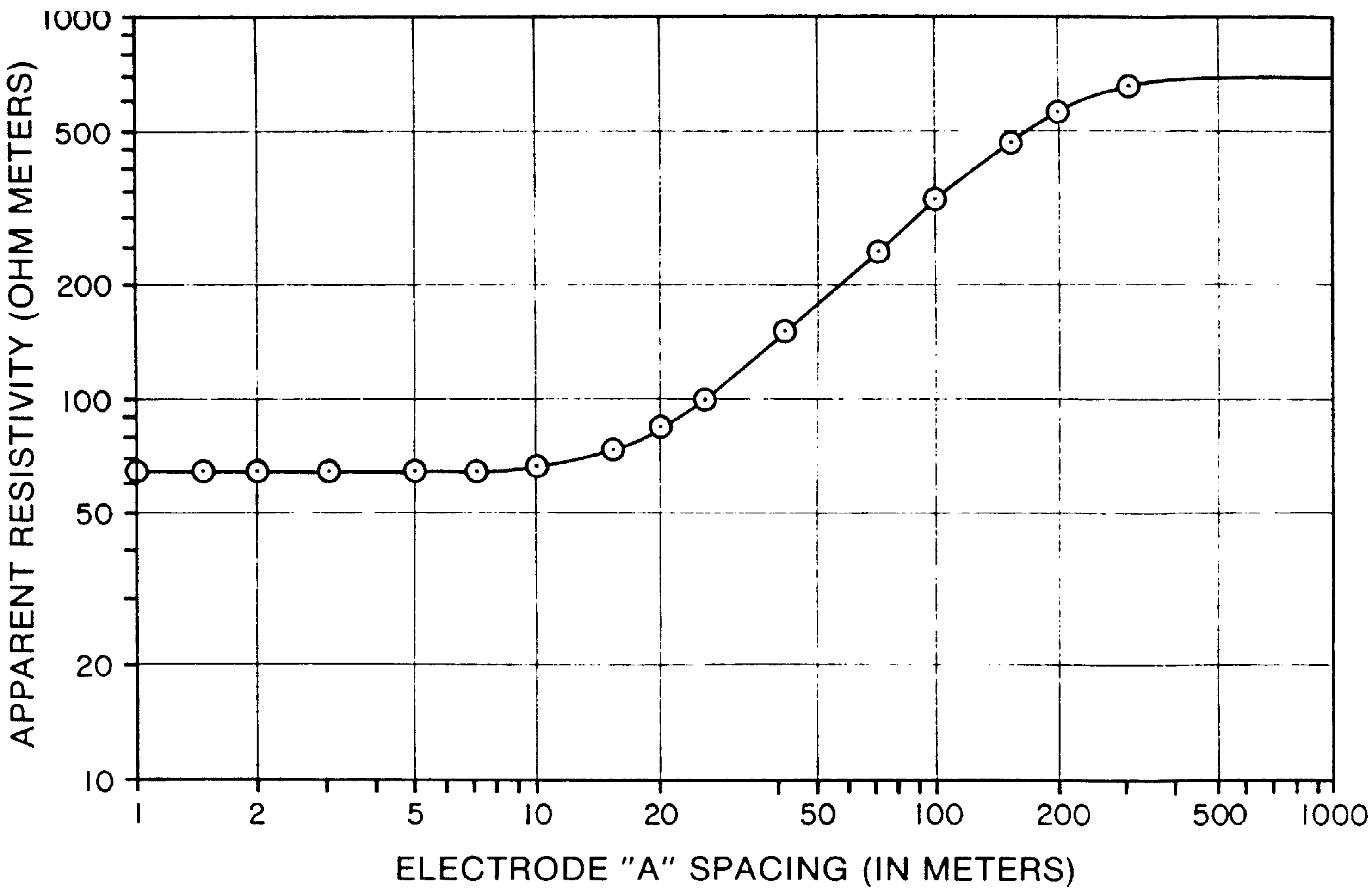


Figure 58. Resistivity sounding curve showing two-layer system.

Apparent resistivities should be calculated and plotted during field acquisition as a means of quality control. Sounding curves should be smooth, and jumps in the data should not occur (Figure 58). Note that the one circled data point at 80 foot "A" spacing lies off the main trend of the data and hence is disregarded in the plot and analysis. Profiling data should also show a general trend in the data from one station to the next (Figure 57). Note that there is a general trend in the data from one point to the next which provides confidence in the quality of the data, but the circled data point to the upper right lies off the main trend. This point will be ignored in the final analysis as it is caused by some source of noise at the specific station. However, abrupt changes do commonly occur in both sounding and profiling data; these may be unwanted "noise" due to near-surface inhomogeneities or electrode contact problems or, in the case of a profile line, may indicate a real change in geohydrology. Experienced interpreters can often evaluate these problems in the field and take corrective action if it is required.

The resistivity instrument can be calibrated using standard resistors. Calibration is particularly important if the data is to be compared to resistivity measurements from other instruments or other parameters, such as specific conductance of water samples.

Noise

Noise from several sources may affect resistivity measurements.

Equipment-related noise may occur due to coupling between wires or between reels of long cable arrays. Poor electrical contact between the ground and electrodes will also produce noisy data. Exceeding the depth capability (power and receiver sensitivity) of the resistivity instrumentation will also yield poor data at very large electrode spacings. In most cases, however, experienced field personnel will be able to mitigate such problems.

Cultural noise caused by stray currents, potential fields and electromagnetic energy can interfere with the resistivity measurement. This interference can be caused by nearby power lines and man-induced ground currents. The influence of nearby fences, railroad tracks and buried metallic pipes and cables can "short" or strongly distort current flow. These effects of proximity to metallic structures must be evaluated by experienced personnel.

Natural sources of electrical noise include earth currents and spontaneous potential (SP). Most modern instruments are designed to cope with such noise problems.

Poor electrode contact with the earth, and local variations in shallow subsurface conditions near the electrodes can produce significant scatter in the data. Decreasing the spacing between stations, using appropriate field arrays and using averaging techniques can minimize the influence of these variations.

Data Format, Processing, Interpretation and Presentation

The resistivity instrument measures the voltage and current between the electrodes. This value is converted to apparent resistivity, using the proper equation for the type of array being used and for the specific electrode spacing. (A hand calculator will speed this calculation.) This value is then logged and usually plotted on a graph in the field for quality control. Additional steps to be taken in processing and interpretation depend upon the application of the data, and whether data was obtained from profiling or sounding. The flow diagram in Figure 59 outlines typical steps in the processing and interpretation of resistivity data as discussed below.

Profiling--The calculated apparent resistivity values from many profile stations can be plotted as profile lines (Figure 56). A contour map (Figure 57) can be developed from many profile stations. These stations can be along a straight line or randomly located over the area. Profile lines and contour maps can then be used to locate geologic variations or contaminant plumes. The apparent resistivity values are typically used because the primary objective is to use the data for location. purposes.

Sounding--Calculated apparent resistivities are plotted against "A" spacing on log/log graph paper for each station (Figure 58). These data points define a curve which can be used qualitatively and quantitatively to determine vertical changes in resistivity. Relative trends and semi-quantitative analysis are often immediately obvious to the experienced interpreter from such a plot.

Subsequent analysis requires analytical techniques which provide a means of modeling. Two approaches or a combination may be employed. A Forward Model produces a resistivity sounding curve from a specified geologic section whose resistivities are known. The analysis can be carried out by making an estimate of the geoelectric properties and calculating a forward model (sounding curve). These results are then compared to the field data. Iteration of the above process occurs until a reasonable match between the model and the field data is found. An Inverse Model provides the geoelectric cross section from the field data; in this case the solution is not unique in that a number of possible combinations exist that will fit the field data. In this case, knowledge of the geohydrologic

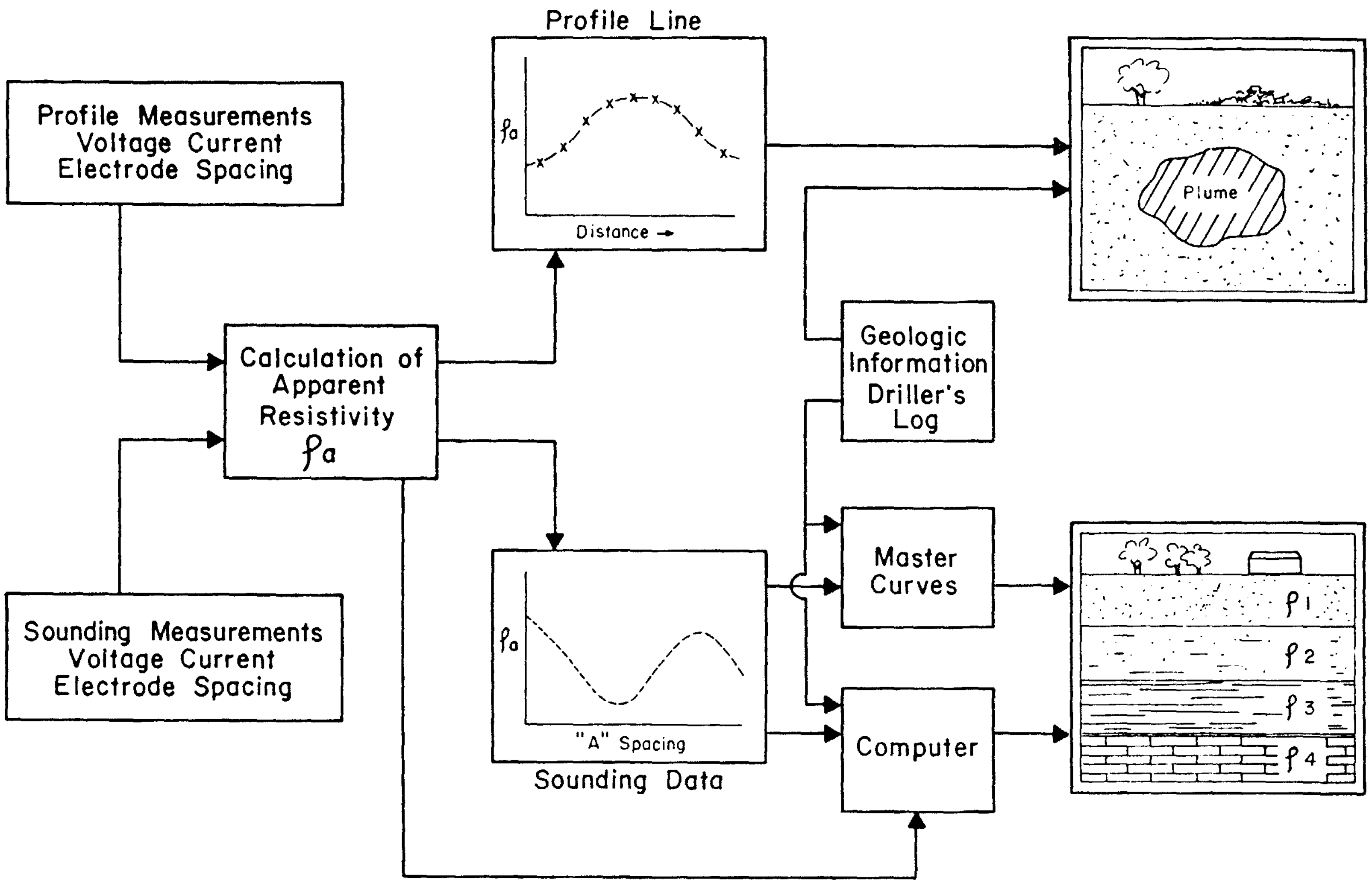


Figure 59. Flow diagram showing steps in processing and interpretation of resistivity data

sections must be employed to select the most likely situation. Both of these methods require a small computer (the forward method can be carried out on a small hand-held programmable calculator).

The computer programs offer a more effective means of processing, by allowing considerable interaction and iteration. The computer is used only as a processing tool; it is not a means of obtaining a final answer without interaction.

Another approach is to use computer-generated master curves which are compared to the field data. The use of master curves can produce quantitative depth information and true resistivities for up to three- to four-layer simple geologic systems. A master curve for a uniform two-layer geologic section is shown in Figure 60. This curve covers both high resistivities underlain by lower values (lower half of the curves) and low surface values underlain by high resistivity values (upper half of the set of curves). A number of ratios between the two-layer resistivities are provided which make up the family of two-layer curves. Often the field data will not fit the set of master curves exactly and interpolation and extrapolation must be carried out. Although simple geologic conditions may be easily interpreted, generally the use of master curves and computer analysis requires considerable knowledge of the overall methodology and geohydrology.

A number of shortcut interpretation procedures exist such as Barnes layer and cumulative methods. These methods are commonly employed because of their simplicity, and because they avoid the use of the more complicated procedures of master curves or computer processing. It should be recognized that these shortcut methods are only approximations and may provide erroneous data under some conditions; therefore their use is not generally recommended.

The resistivity sounding results will indicate the number of geologic layers present as well as their depth and thickness, but only those layers that are sufficiently thick and have adequate contrast in their electrical properties will be detected. Data from a number of soundings can be used to create a cross section plot of resistivities (Figure 61), called a geoelectric section. This figure shows a two-dimensional representation of the data. Single soundings can be represented in a similar manner to provide one-dimensional data. If soundings are available over a large area or along somewhat perpendicular traverse lines, the resulting data can be shown as a three-dimensional section or as a fence diagram (Figure 62).

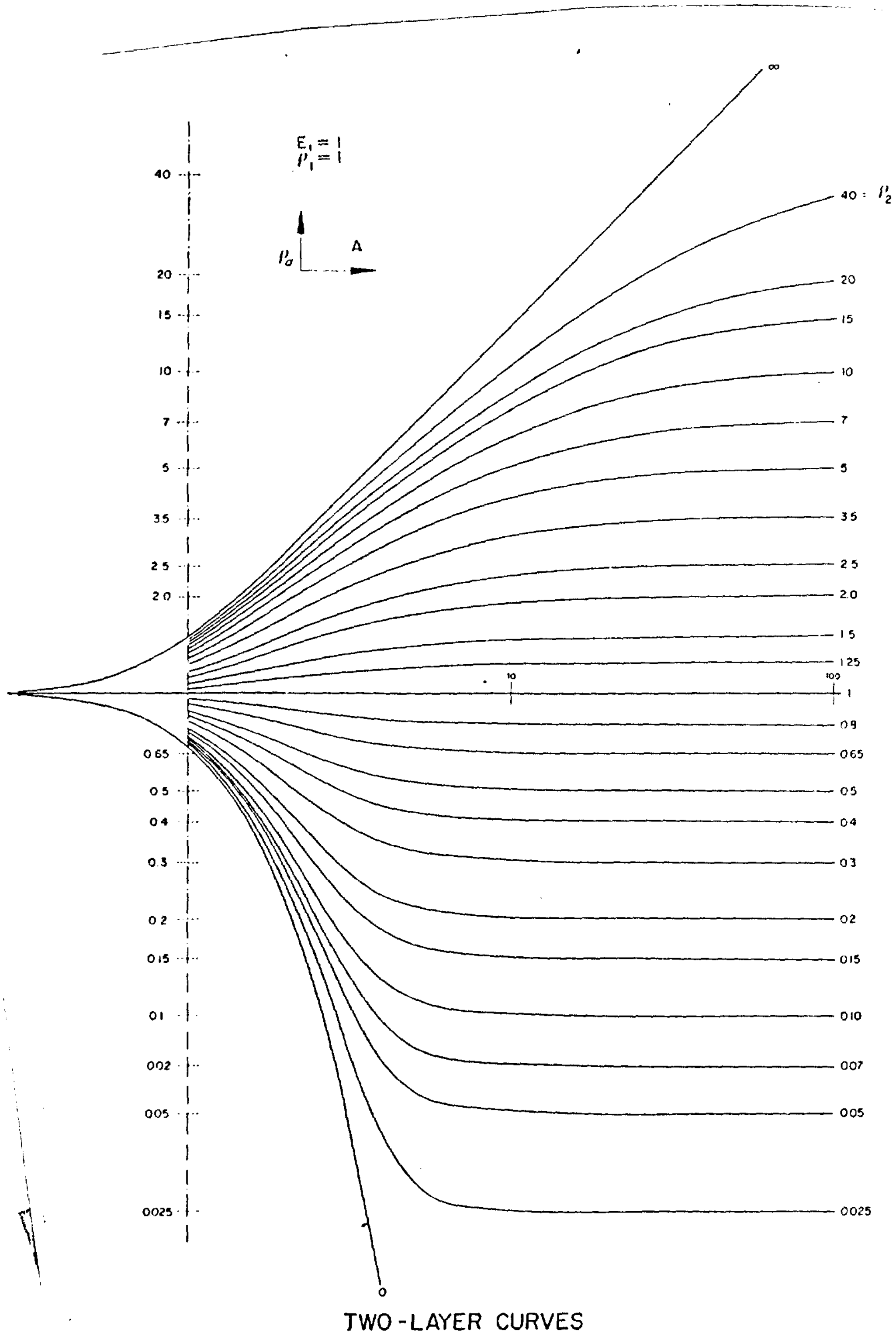


Figure 60. Two-layer master curves used to interpret Wenner sounding data. (from Orellana - Mooney master curves for V.E.s.).

Summary

The resistivity method provides a means of measuring one of the electrical properties of the geohydrologic section including soil, rock and ground water. These measurements may be used to assess lateral changes and vertical cross sections of the natural geohydrologic settings. Since the resistivity of soils and rocks is predominantly controlled by porosity, permeability, amount of water, and concentration of dissolved solids in the water, the method provides a tool to evaluate contaminant plumes and to locate buried wastes at hazardous waste sites.

The resistivity technique may be used for "profiling" or "sounding". Profiling provides a means of mapping lateral changes in subsurface electrical properties. This field technique is well suited to the delineation of contaminant plumes and to the detection and location of changes in natural geohydrologic conditions. Profile lines and contour maps can be used to locate geologic variations or contaminant plumes. The apparent resistivity values are typically used, because the primary objective is to use the data for location purposes. Relative trends and semi-quantitative analyses are often immediately obvious to the experienced interpreter from a plot of sounding data.

Sounding provides a means of determining the vertical changes in subsurface electrical properties. Interpretation of sounding data provides the depth and thickness of subsurface layers having different resistivities. Commonly, 3 to 4 layers may be resolved with this technique. The resistivity sounding method is in general a more effective method than the EM sounding method described. The analysis of resistivity sounding data requires that the interpreter be knowledgeable about the resistivity method, the conditions under which the data were obtained, the geohydrologic conditions, as well as the specific techniques, computer models, or curve matching.

The operator must insure that adequate space is available at the site and that it is relatively clear of buried pipes and fences. Finding sufficient space for a long profile array with an overall length three to six times the depth of interest, or a sounding array with an overall length nine to twelve times times the depth of interest can sometimes be a problem.

Although resistivity sounding methods are primarily intended for use in uniformly layered geological conditions, useful data may be obtained from the complex subsurface conditions often found at HWS. With both profiling and sounding techniques, inhomogeneities in the near-surface soils may introduce noise in the data. Some surface conditions such as

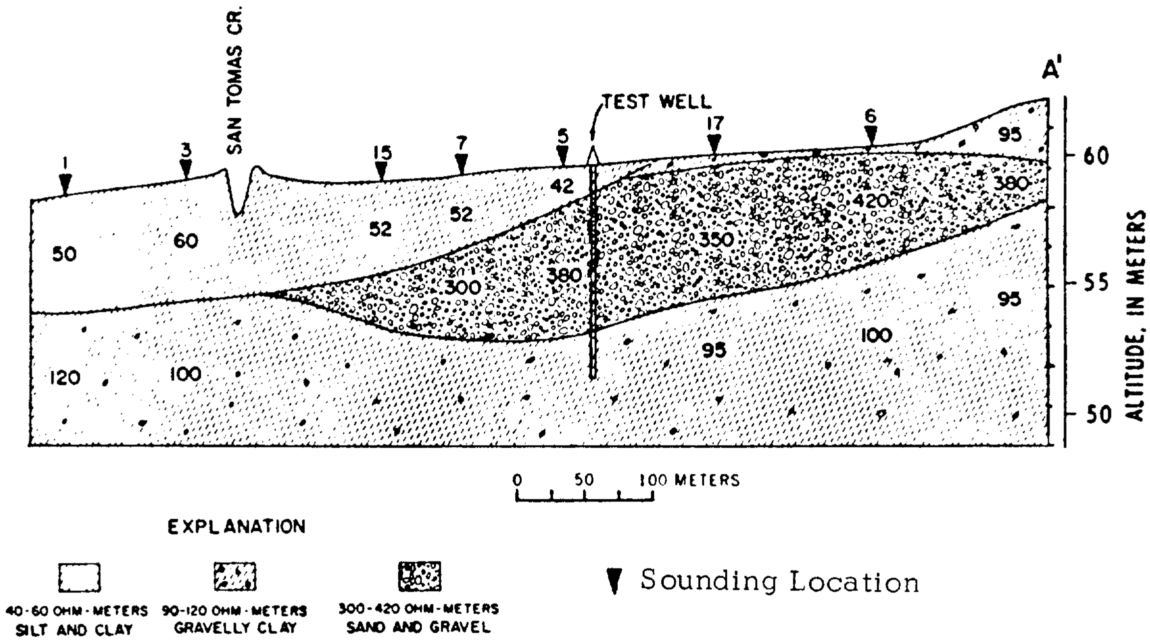


Figure 61. Geoelectric cross section derived from seven resistivity soundings (from Zohdy, 1964).

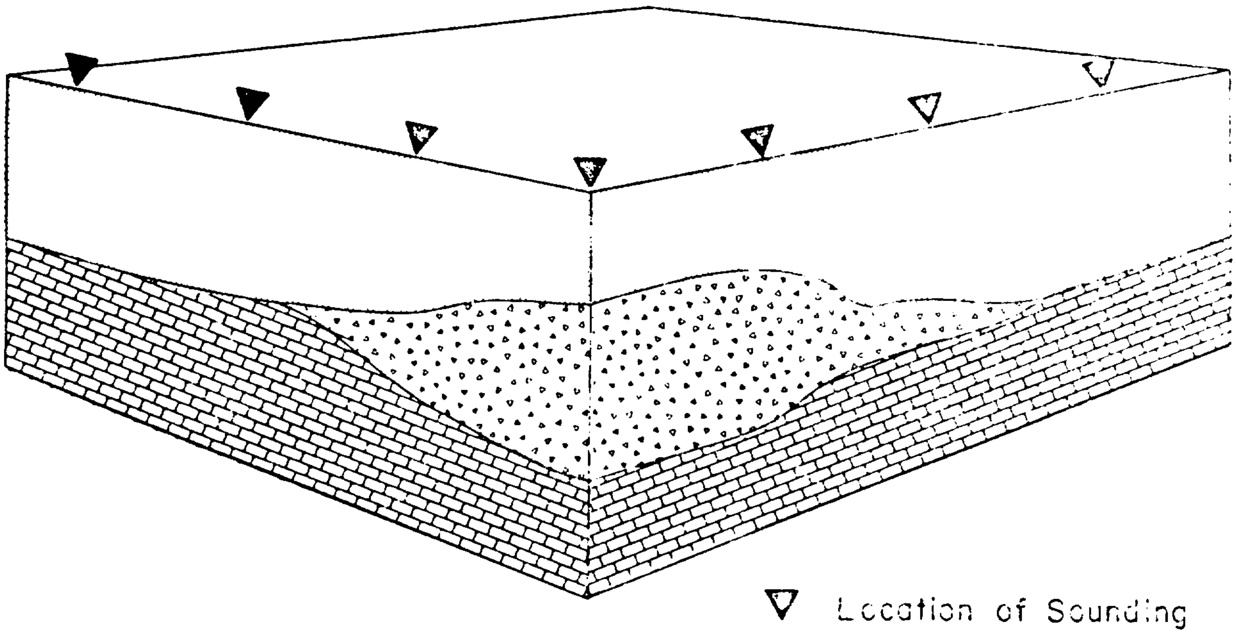


Figure 62. A three-dimensional or fence diagram may be constructed from multiple resistivity soundings.

dry surface materials, concrete roads or parking lots may preclude the use of the resistivity method.

The resistivity method is inherently limited to station measurements, since electrodes must be in physical and electrical contact with the ground. This requirement makes the resistivity method slower than a non-contact method such as EM.

Capabilities

- Resistivity profiling techniques can be used to detect and map contaminant plumes and changes in geohydrology.
- Resistivity sounding methods can estimate the depth, thickness and resistivity of subsurface layers, or depth to the water table.
- Both profiling and sounding data can be evaluated qualitatively or semi-quantitatively in the field.
- Resistivity values can be used to identify the probable geologic composition of a layer or to estimate the specific conductance of a plume
- Depth to bottom of landfills and large burial sites can sometimes be estimated.

Limitations

- The sounding technique requires that site conditions be relatively homogeneous laterally.
- The method is susceptible to noise caused by nearby fences, pipes and geologic scatter, which may interfere with usefulness of the data.
- Quantitative interpretation requires the use of master curves and/or computer programs, and experience in their use.

Examples

Determining Depth and Thickness of a Clay Layer for a Proposed Disposal Site

The depth and thickness of a clay layer was required in an assessment of natural site conditions. Several resistivity soundings were conducted over the area of interest, using "A" spacings from 1 to 300 feet (0.3 to 100 meters).

Figure 63 shows one of the sounding curves. A visual, in-the-field qualitative evaluation of the curve indicates that three, and possibly four, resistivity layers are present. The relative resistivities are

(1) very high at the surface,

(2) extremely low near an "A" spacing of 70 to 100 feet. (21 to 30 meters),and
(3) increasing beyond 100 foot (30 meters) "A" spacing.

A general knowledge of the local geology suggested that these layers were dry quartz sand (which was observed at the surface), massive clay, and limestone bedrock. An intermediate layer, possibly a sand-to-clay transition, existed between the high-resistivity surface layer and the low-resistivity layer.

Computer analysis using an inverse resistivity model provided the results shown in Figure 64. An intermediate layer was identified as a transition zone of clayey sand between the surface sand and the top of the clay.

Mapping of Landfill Leachate Plume

A leachate plume was known to exist at a large landfill, based on samples from existing monitor wells (Figure 65). However, its lateral extent was unknown, as was its maximum distance from the landfill. The landfill was situated in an unconfined limestone aquifer with a shallow water table. Several soundings were made initially in the area of the landfill to determine the approximate depth of the leachate plume within the aquifer. It was found to lie between the surface and a depth of 20 meters. Electrode "A" spacings of 5 and 15 meters were selected to map lateral changes in resistivity around the landfill. The 5-meter spacing would indicate the existence of a shallow plume and provide a measure of the variations due to shallow geohydrologic conditions. The 15-meter spacing was selected to provide a reasonable average measure of the main core of the plume. The area was somewhat developed, which made the location of long profile lines difficult; therefore, profiling stations were placed wherever sufficient space was available. The data for each station was plotted and contoured in map form (Figure 66). A large plume extending two kilometers downgradient from the site was mapped. The shallow data shows considerable variation in the plume, due to the influence of many near-surface variables. The deeper data shows a more uniform plume pattern, as the plume is less influenced by the surface variables.

Existing monitor well data was evaluated based upon this new information and additional monitor well sites were selected to provide a more extended chemical analysis of the plume.

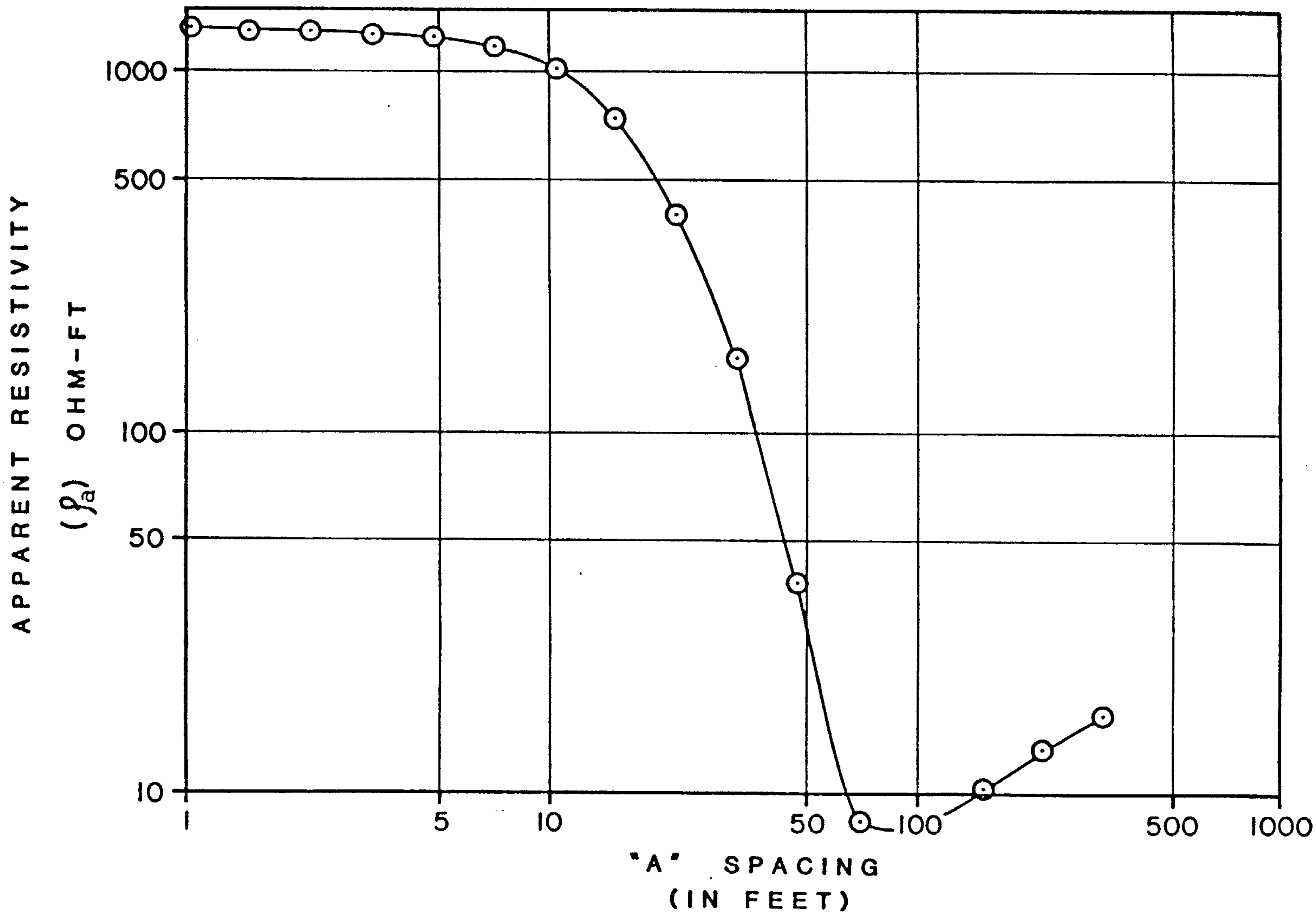


Figure 63. Field sounding curve over a four-layer geologic section.

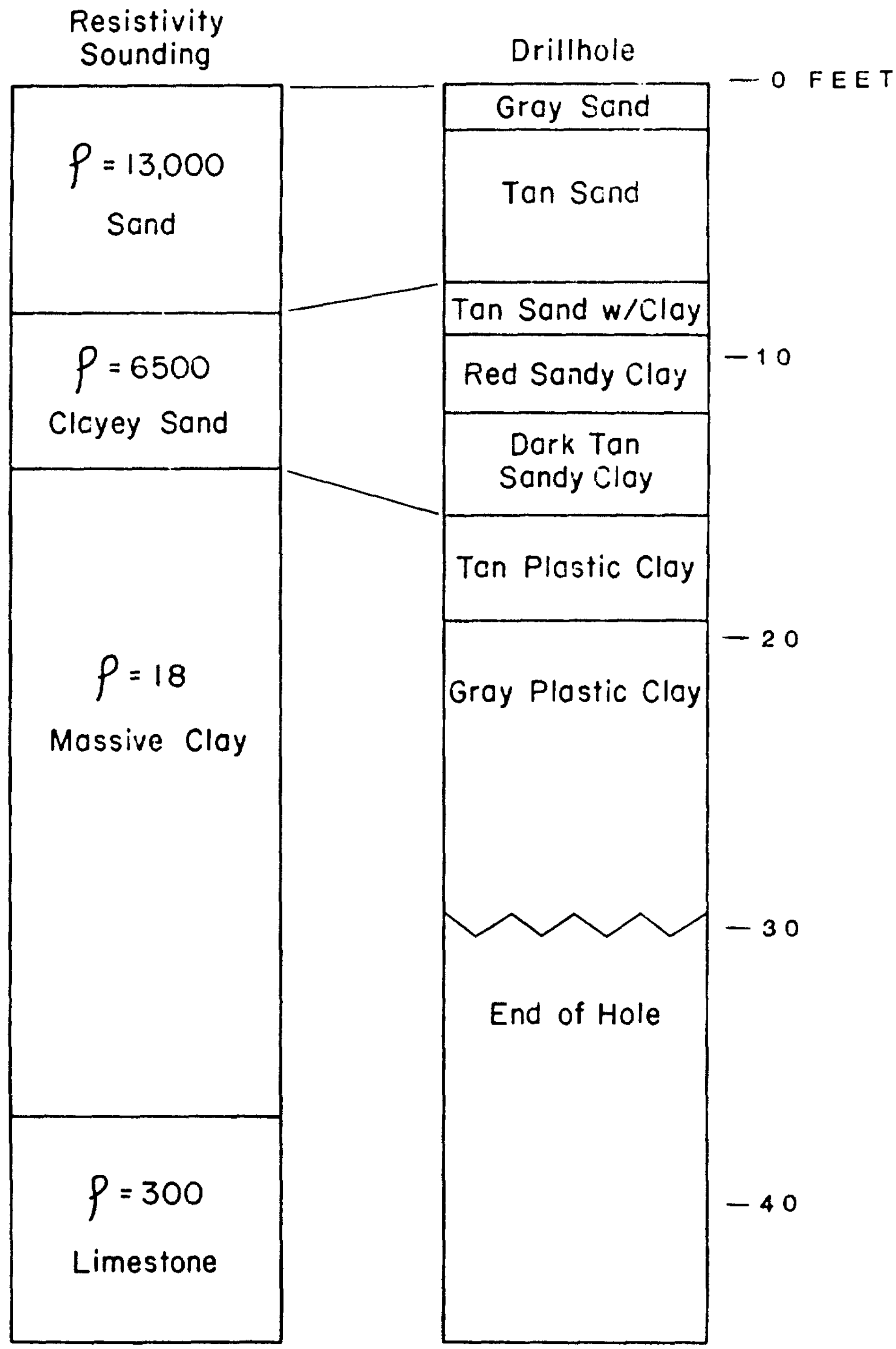


Figure 64. Correlation of resistivity sounding results to a driller's log. (Resistivity values are in ohm-ft).

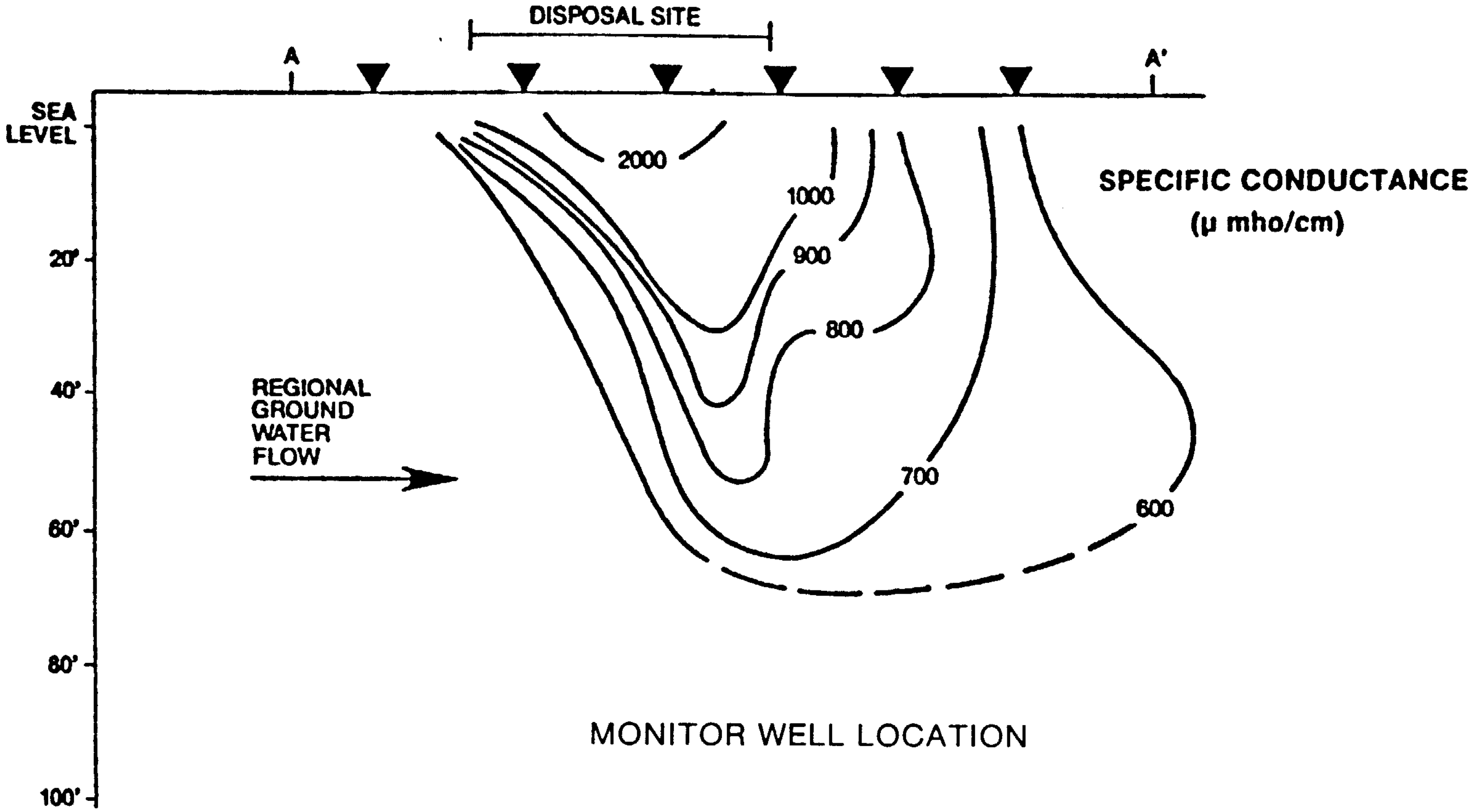


Figure 65. Cross section of leachate plume based upon specific conductance from 1974 well data (locations shown in Figure 66).

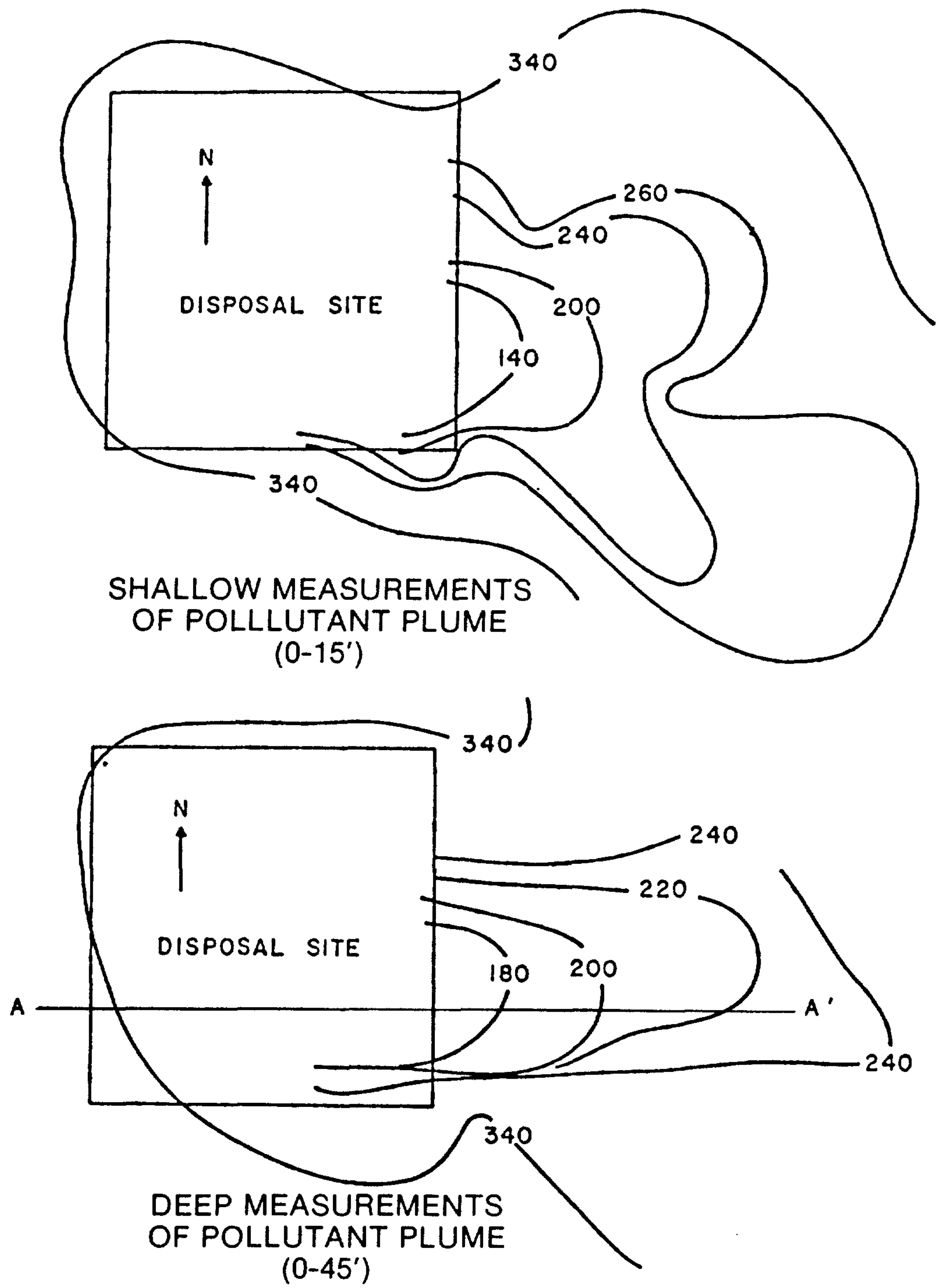


Figure 66. Isopleths of resistivity profiling data showing extent of landfill plume. Values in ohm-feet.

SECTION VII

SEISMIC REFRACTION

Introduction

Seismic refraction techniques are used to determine the thickness and depth of geologic layers and the travel time or velocity of seismic waves within the layers. Seismic refraction methods are often used to map depths to specific horizons such as bedrock, clay layers, and water table. In addition to mapping natural features, other secondary applications of the seismic method include the location and definition of burial pits and trenches at HWS.

Seismic waves transmitted into the subsurface travel at different velocities in various types of soil and rock and are refracted (or bent) at the interfaces between layers. This refraction affects their path of travel. An array of geophones on the surface measures the travel time of the seismic waves from the source to the geophones at a number of spacings. The time required for the wave to complete this path is measured, permitting a determination to be made of the number of layers, the thicknesses of the layers and their depths, as well as the seismic velocity of each layer. The wave velocity in each layer is directly related to its material properties such as density and hardness.

A seismic source, geophones, and a seismograph are required to make the measurements. The seismic source may be a simple sledge hammer with which to strike the ground. Explosives and any other seismic, sources may be utilized for deeper or special applications. Geophones implanted in the surface of the ground translate the received vibrations of seismic energy into an electrical signal. This signal is displayed on the seismograph, permitting measurement of the arrival time of the seismic wave. Since the seismic method measures small ground vibrations, it is inherently susceptible to vibration noise from a variety of natural and cultural sources.

At HWS, seismic refraction can be used to define natural geohydrologic conditions, including thickness and depth of soil and rock layers, their composition and physical properties, and depth to bedrock or water table. It can also be used for the detection and location of anomalous features, such as pits and trenches, and for evaluation of the depth of burial sites or landfills. (In contrast to seismic refraction, the reflection technique, which is common in petroleum exploration, has not been applied to HWS. This is primarily because the method cannot be effectively utilized at depths of less than 20 meters.)

Principles and Equipment

Although a number of elastic waves are inherently associated with the method, conventional seismic refraction methods that have been employed at HWS are concerned only with the compressional wave (primary or P-wave). The compressional wave is also the first to arrive which makes its identification relatively easy.

These waves move through subsurface layers. The density of a layer and its elastic properties determine the speed or velocity at which the seismic wave will travel through the layer. The porosity, mineral composition, and water content of the layer affect both its density and elasticity. Table 3 lists a range of compressional wave velocities in common geologic materials. It can be seen from these tables that the seismic velocities for different types of soil and rock overlap, so knowing the velocities of these layers alone does not permit a unique determination of their composition. However, if this knowledge is combined with geologic information, it can be used intelligently to identify geologic strata.

In general, velocity values are greater for:

- o dense rocks than light rocks.
- o older rocks than younger rocks.
- o igneous rocks than sedimentary rocks.
- o solid rocks than rocks with cracks or fractures.
- o unweathered rocks than weathered rocks.
- o consolidated sediments than unconsolidated sediments.
- o water-saturated unconsolidated sediments than dry unconsolidated sediments.
- o wet soils than dry soils.

Figure 67 shows a schematic view of a 12-channel seismic system in use and the compressional waves traveling through a two-layered system of soil over bedrock. A seismic source produces seismic waves which travel in all directions into the ground The seismic refraction method, however, is concerned only with the waves shown in Figure 67. One of these waves, the

TABLE 3. RANGE OF VELOCITIES FOR COMPRESSIONAL WAVES IN SOIL AND ROCK (After jakosky, 1950)

Material	Velocity (meters/sec)
Weathered surface material	305 - 610
Gravel or dry sand	465 - 915
Sand (Wet)	610 - 1,830
Sandstone	1,830 - 3,970
Shale	2,750 - 4,270
Chalk	1,830 - 3,970
Limestone	2,140 - 6. 100
Salt	4,270 - 5,190
Granite	4,380 - 5,800
Metamorphic rocks	3,050 - 7,020

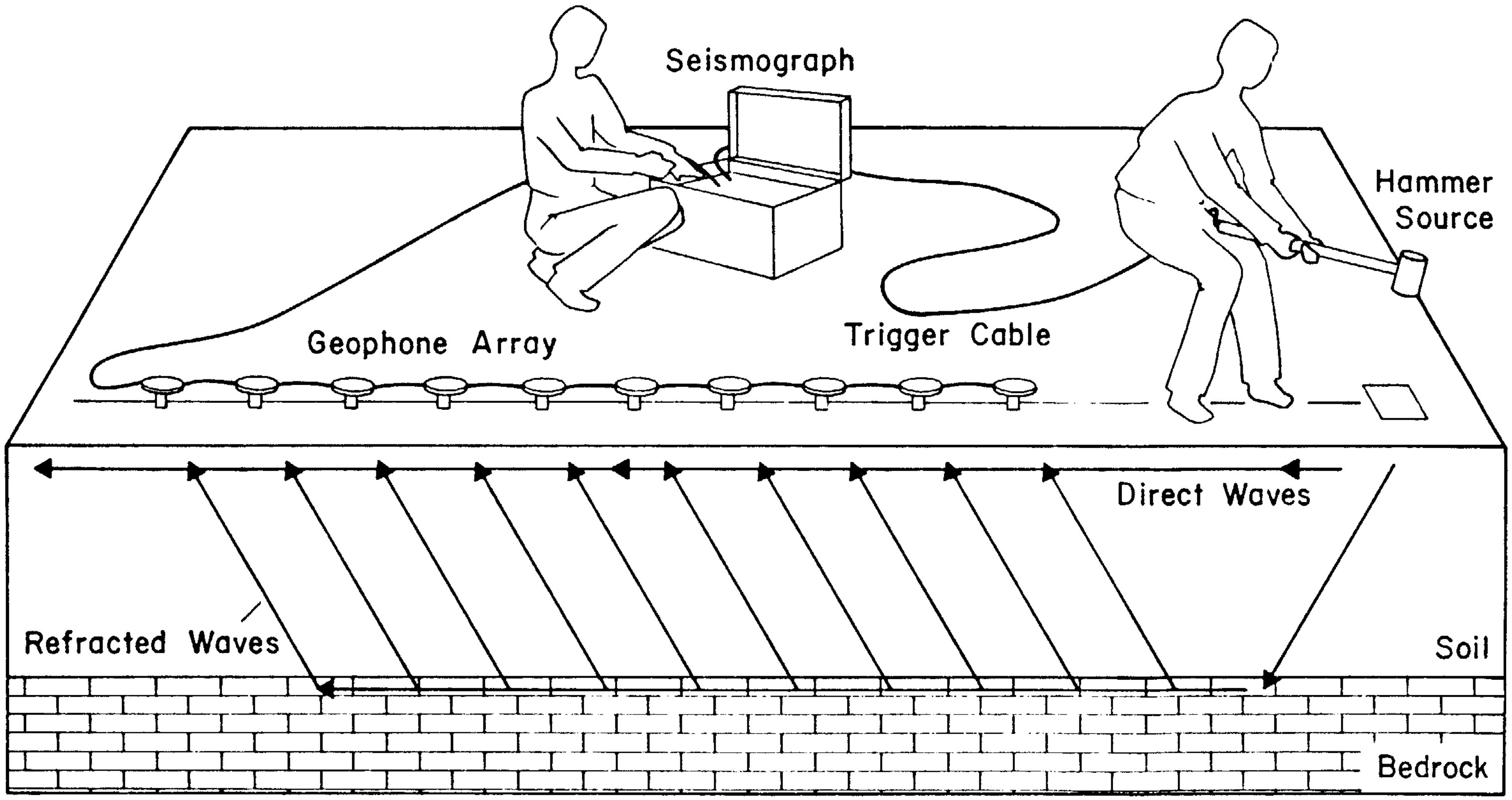


Figure 67. Field layout of a 12-channel seismograph showing the path of direct and refracted seismic waves in a two-layer soil/rock system.

direct wave, travels parallel to the surface of the ground. A seismic sensor (geophone) detects the direct wave as it moves along the surface layer. The time of travel along this path is related to the distance between the sensor and the source and the material composing the layer.

If a denser layer with a higher velocity, such as bedrock, exists below the surface soils, some of the seismic waves will be bent or refracted as they enter the bedrock. This phenomenon is similar to the refraction of light rays when light passes from air into water and is described by Snell’s law. One of these refracted waves, crossing the interface at a critical angle, will move parallel to the top of the bedrock at the higher velocity of the bedrock. The seismic wave travelling along this interface will continually release energy back into the upper layer by refraction. These waves may then be detected in the surface at various distances from the source (Figure 67).

Beyond a certain distance (called the critical distance), the refracted wave will arrive at a geophone before the direct wave. This happens even though the refraction path is longer, because a sufficient portion of the wave’s path occurs in the higher velocity bedrock. Measurement of these first arrival times and their distances from the source permits calculation of layer velocities, thicknesses and bedrock depth. Application of the seismic method is generally limited to resolving three to four layers.

The preceding concepts are based upon the fundamental assumptions that:

1. Seismic velocities of geologic layers must increase with depth. This requirement is generally met at most sites.
2. Layers must be of sufficient thickness to permit detection.
3. Seismic velocities of layers must be sufficiently different to permit resolution of individual layers.

There is no way to establish from the seismic data alone whether a hidden layer (due to 1 & 2 above) is present; therefore, correlation to a boring log or geologic knowledge of the site must be used to provide a cross check. If such data is not available, the interpreter must take this into consideration in evaluating the data.

Variations in the thickness of the shallow soil zone, inhomogeneities within a layer, or irregularities between layers will often produce geologic scatter or anomalies in the data. This data scatter is useful information, revealing some of the natural variability of the site. For example, a zone containing a number of large boulders in a glacial till deposit will yield inconsistent arrival times, due to variable seismic velocities between the boulders and the clay matrix. An extremely irregular bedrock surface as is often encountered in karst limestone terrain, likewise, will produce scatter in the seismic data.

The seismic refraction technique uses the equipment shown in Figure 68. The seismic source is often a simple ten-pound sledge hammer or drop weight which strikes the ground, generating a seismic impulse. Explosives and a variety of other excitation sources are also used for the greater energy levels required for information at deeper layers.

Seismic waves are detected by geophones implanted in the surface of the ground at various distances from the source. The geophone converts the seismic wave’s mechanical vibration into an electrical signal in a manner similar to that of a microphone. This signal is carried by cable to the seismograph.

The seismograph is an instrument which electronically amplifies and then displays the received seismic signal from the geophone. The display may be a cathode ray tube, a single-channel strip chart (Figure 69), or a thermal printer, commonly used on multi-channel systems (Figure 70). The identification and measurement of the arrival time of the first wave from the seismic source is obtained from this presentation. The time is measured in milliseconds, with zero time or start of trace initiated by the source, which provides a trigger signal to the seismograph.

Travel time is plotted against source-to-geophone distance producing a time/distance (T/D) plot (Figure 71).

- The number of line segments indicates the number of layers.
- The slope of each line segment is inversely proportional to the seismic velocity in the corresponding layer.
- Break points in the plot (critical distance, X) are used with the velocities to calculate layer depth.

Factors to be Considered for Field Use

The seismic line must be centered over the required information area and overall line length must be three to five times the maximum depth of interest. Resolution is determined by the geophone spacing. Spacings of 3 to 15 meters are commonly used; however, closer spacings may be necessary for very high resolution of shallow geologic sections.

Figure 68. A portable six-channel seismic refraction system in use. A sledgehammer is being used as a source.

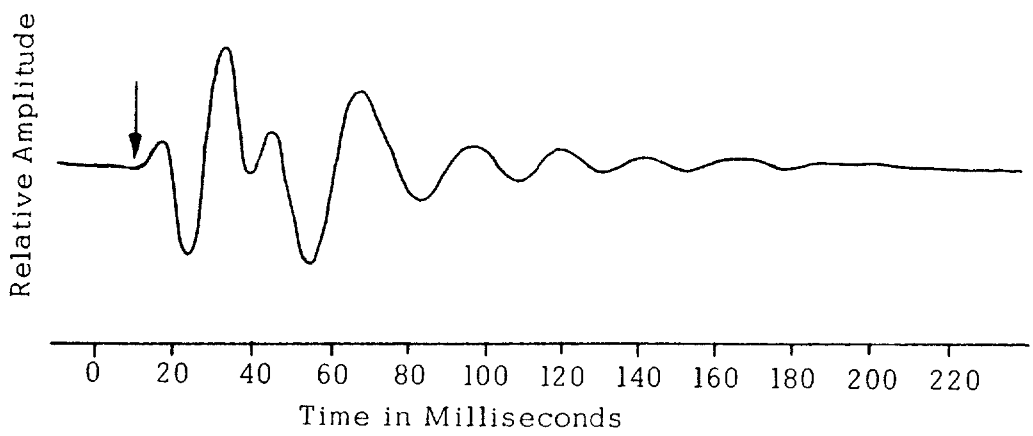


Figure 69. A typical seismic waveform from a single geophone. Arrow marks arrival of first compressional wave.

Repetition of seismic refraction lines along a traverse will reveal lateral variations. Resulting data can be used to indicate trends of dipping layers and to detect anomalous conditions, such as fractures and disturbed zones.

The general concepts presented so far have been for a simple two-layer case with no dip. Since the presence of a dipping layer may not be known, it is accepted practice to run both forward and reverse lines to obtain true velocities and depths, if the geologic beds are not horizontal. A reverse line is simply a second set of seismic measurements with the source located at the opposite end of the same line of geophones (Figure 72).

A modification of the classic seismic refraction method will provide a rapid means of high-resolution profiling. This profiling approach employs a single geophone and a fixed spacing; this array is moved across the site. The distance the station is moved each time is usually short (2 to 10 meters) to provide good resolution of small features. Typically, velocity anomalies (low velocities) will occur as the array crosses a disturbed soil zone such as a trench.

A single channel seismograph is the simplest seismic instrument and is used with a single geophone and usually a hammer source. The geophone is usually placed at a fixed location and the hammer is struck at regularly increasing distances from the geophone. First wave arrival times are identified in the instrument display, logged in a field book, and immediately plotted on a T/D plot. The single waveform will approximate the one shown in Figure 69.

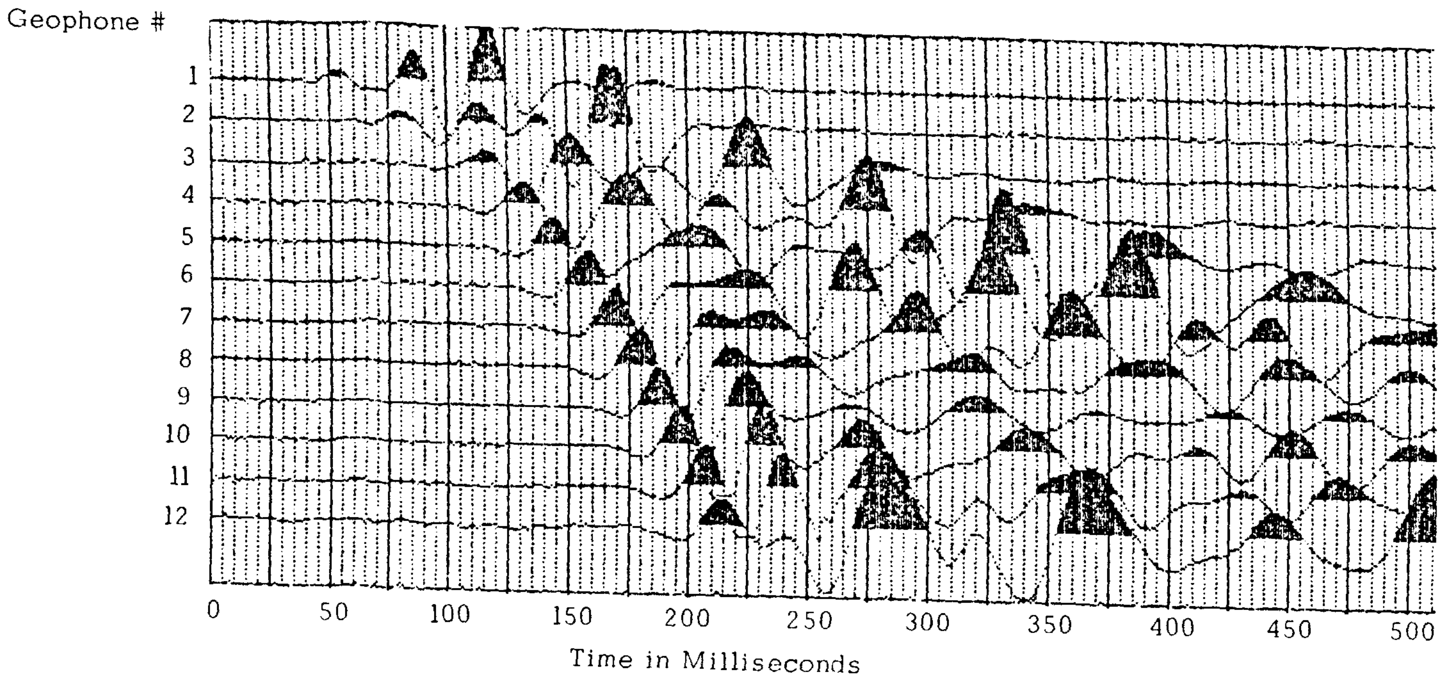
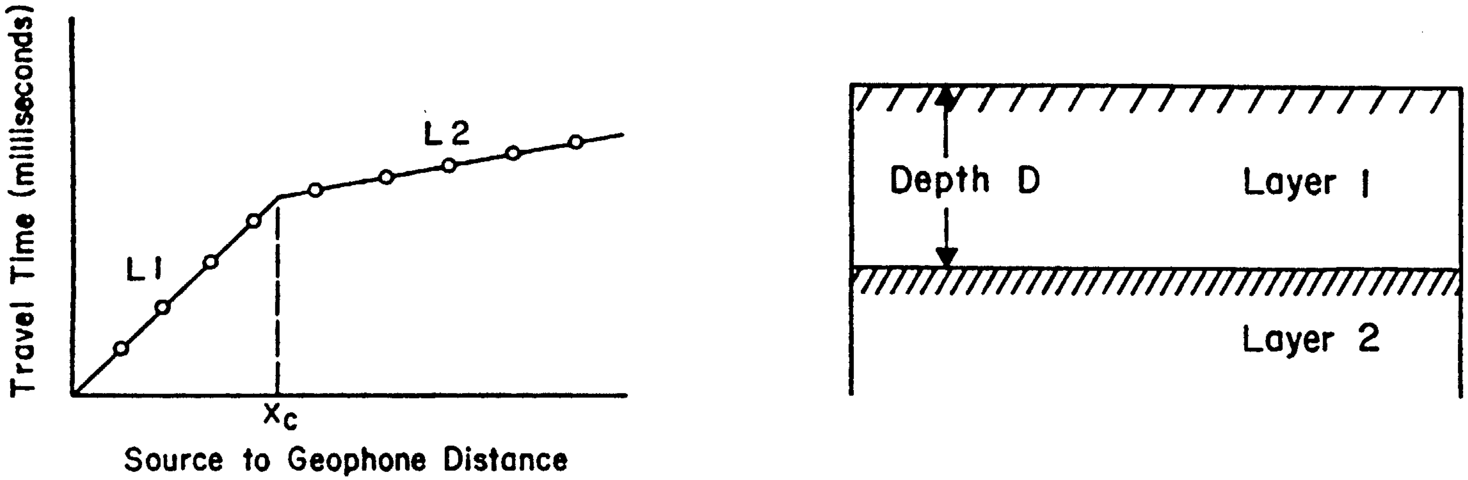


Figure 70. Recording from a 12-channel seismograph. All 12 channels were recorded simultaneously from a single hammer impact.



L I = Layer I

L 2 = Layer 2

V I = Velocity of Layer I = I/Slope of L I

V 2 = Velocity of Layer 2 = I/Slope of L 2

X_c = Critical Distance

$$D = \frac{X_c}{2}\sqrt{\frac{V2 - V1}{V2 + V1}}$$

(For Two Horizontal Layers)

Figure 71. Time/distance plot for a simple two-layer structure. (Equation shown is used to calculate depth of layer.)

Multichannel seismographs increase the rate of data acquisition using an array of 6, 12, 24 or more geophones (Figure 67). All geophone signals are recorded simultaneously after initiation from a single hammer blow (Figure 70). The display of simultaneous waveforms enables the operator to measure arrival time by noting trends in the composite data set. This is especially useful in noisy areas. More sophisticated instruments commonly incorporate a considerable amount of control over gain and filtering of the signals, which is of great use on difficult or "noisy" sites.

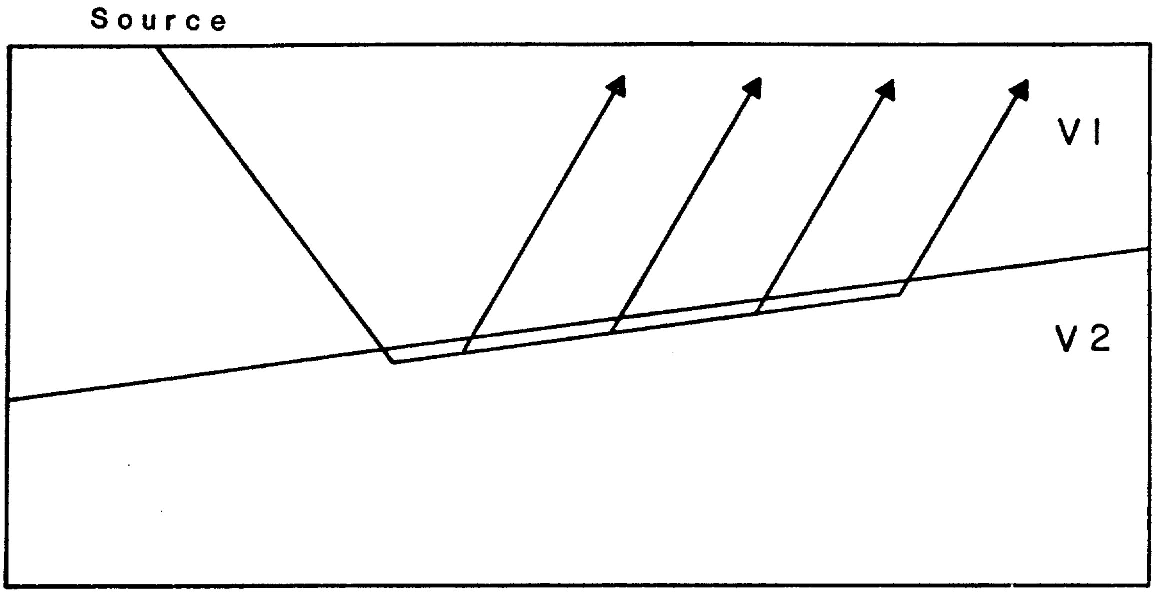
Since the seismic method measures ground vibration, it is inherently sensitive to noise from a variety of sources. Signal enhancement is a significant aid when working in noisy areas and with smaller energy sources. Enhancement capability is available in most single and multi-channel systems. Enhancement is accomplished by adding a number of seismic signals from repeated hammer blows. The coherent seismic signal is increased in direct proportion to the number of blows, while random noise in the seismic signal is increased only by the square root of the number of blows. This causes the seismic signal to "grow" out of the noise level, permitting operation in noisier environments and at greater hammer-to-geophone spacings. The overall results provide a more accurate measurement of the first arrival time.

Depending on site conditions, a hammer is useful for obtaining seismic data to depths of 10 to 15 meters; while a 250-kilogram (500-pound) drop weight is required for depths of 50 to 100 meters. A more powerful seismic source is necessary to obtain deeper data or for work in noisy areas. Many sources are available for meeting specialized needs. If the use of explosives or projectile sources is contemplated, the project manager must consider the safety hazards inherent in such methods, as well as their impact on the hazardous site itself, and the response from the surrounding neighborhood. Local laws, insurance requirements and the increase in project cost associated with compliance may also restrict the use of explosives.

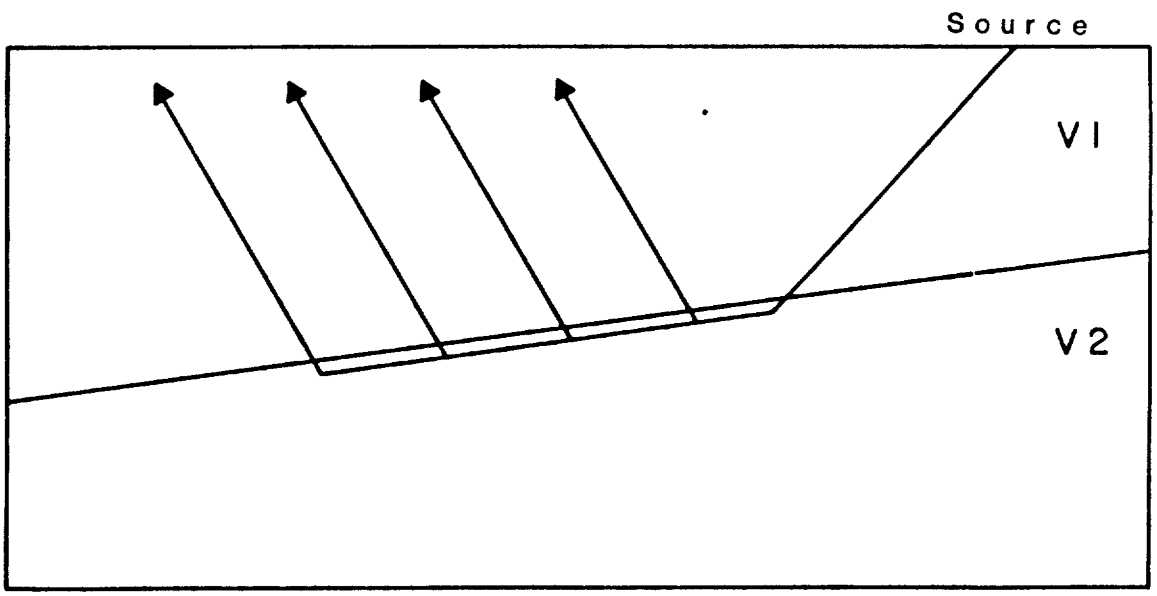
Quality Control

Quality control can be achieved in several ways:

- A check of the seismic signal and noise conditions on the instrument display will verify the proper functioning of geophones and trigger cables and the correct setting of the instrument.
- In cases where paper records are not made, arrival time picks made from the electronic display should be immediately plotted on a T/D graph in the field. Problems with improper picks are often discovered by early inspection of these plots.



Forward Line



Reverse Line

Figure 72. Use of forward and reverse seismic lines is necessary to determine true velocities and depths with dipping horizon.

- If the data is to be used for legal purposes, or if it must be reviewed by persons other than the field party chief, a hard copy of the data must be made. Multi-channel systems provide a much better means of presenting the data than do single-channel units (compare Figures 69 and 70). The individual traces of the single-channel system would have to be clipped and pasted together and would provide a much less acceptable-looking and workable record. For simple, smaller surveys, however, the single-channel units are quite satisfactory if used by experienced personnel.
- Background or off-site data is often required for correlation to known geologic information and to establish clean background data. This information is also useful as a reference for evaluating complex site conditions.

- Boring logs should be obtained to minimize the possibility that low velocity (hidden layers) or thin beds will remain undetected.
- Electronic calibration of the timing circuits of the seismograph may be made in the laboratory. However, this is rarely necessary because these timing circuits are crystal-controlled and have inherently low drift. Normal annual factory maintenance will include such calibration.
- The seismic system may also be run at a standard base station for periodic check of the instrument operation.

Noise

Seismic signals are strongly affected by ground vibration noise; less so by geologic scatter. In addition, the subjective pick of first arrival time can contribute a few milliseconds of error.

Unwanted vibrations which affect the seismic signal at the geophone may be caused by:

- Strong winds which move nearby trees;
- Sounds of airplanes;
- Surface sources, such as moving vehicles on nearby highways and railroads;
- Field crews walking near geophones;
- Nearby blasting or operation of heavy construction equipment.

Geologic scatter may be caused by lateral variation in layer composition or an irregular interface between layers. Such scatter can complicate interpretation of the T/D plot, but is also a valuable indicator of site conditions (see Figure 73). Examples include:

- Variations in the thickness of the "soil zone";
- Boulders in glacial clay or till;
- Zones of increased cementation in sandstone and limestone;
- Lenses of sand in clay layers;
- Variations in saturated water content caused by perched water tables;
- Irregular bedrock surfaces;
- Limestone containing numerous cavities.

Data Format, Processing, Interpretation and Presentation

First arrival times are usually measured from seismic signals in the field and are recorded in field logs and plots. Waveforms may be recorded as hard copy by strip chart records, oscillograph and thermal printers, or by magnetic media for archives, subsequent playback and processing. T/D plots permit calculation of layer parameters. The results may then be interpreted to yield a geologic section of subsurface conditions (Figure 74). Figure 75 shows this sequence of processing and interpretation.

The processing procedure begins with determination of the first arrival time to each geophone. The enhancement technique may be employed to aid in recognizing the first arrivals on the display. Multi-channel seismographs can also assist in identifying this first wave by revealing a trend in the composite received signals (Figure 70).

Once the arrival times are determined for each geophone, the time/distance plot is constructed. Straight line segments are fitted to linear sections of the plot by least square techniques. The number of segments and their slopes correspond to the number of geologic layers and their velocities. These velocities and critical distances (determined by breaks in the line segment) are used to calculate the depth of the layer. Forward and reverse data is needed to provide true velocities, depth, and dip of each layer if layering is not horizontal.

Generally two- or three-layer systems can be analyzed in the field by the use of nomograms and simple calculations. More complicated sites having three to four layers with dip will require a programmable calculator or a small computer to solve the seismic equations.

Single refraction stations can be represented in a similar manner to provide one-dimensional data. The results from a number of refraction stations can be interpreted and combined into a two-dimensional cross section, as shown in Figure 74. If refraction lines are available over a large area or along perpendicular traverse lines, the resulting data can be shown as a three-dimensional section or as a fence diagram.

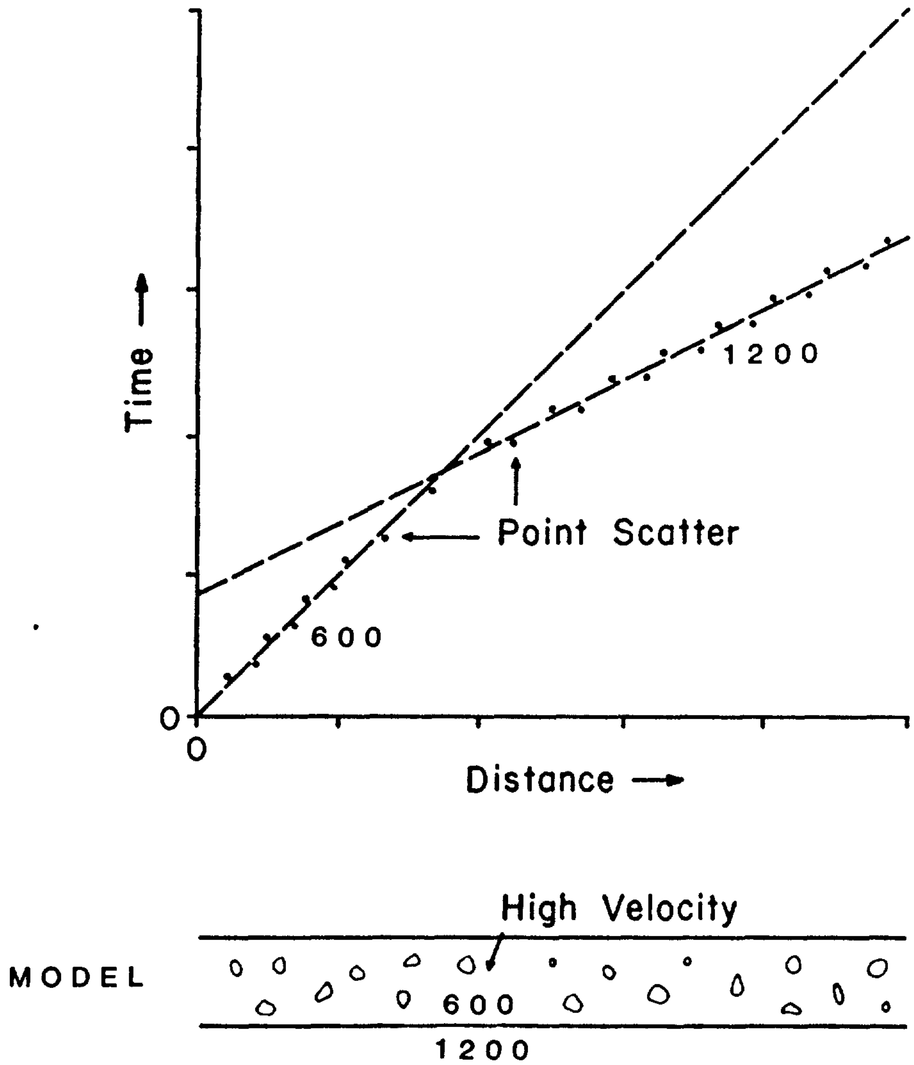


Figure 73. Time/distance plot shows scatter caused by non-uniform soil conditions. such conditions might be caused by differences in local cementation, holders, etc. (velocities shown in meters/sec.)

Time/distance plots may show abnormal slopes or breaks. Such plots reveal that the subsurface is not composed of homogeneous layers of uniform thickness and velocity. Several types of conditions are recognizable from their characteristic T/D plots. For example, Figure 76 shows a T/D plot where a seismic line passes over a deep burial trench. The degree of geologic scatter in the data (Figure 73) is also a good indicator of subsurface conditions.

Many possible pitfalls exist in the acquisition, processing, and interpretation of seismic data. Solutions are not unique and all interpretations must be based on some assumptions about the site, together with independent information on the geohydrological conditions at the site. Velocity inversions and thin bed cases may not be detected. Dipping bedding can cause considerable error in calculations; therefore, both forward and reverse lines must be used.

Summary

The seismic refraction method can be used to aid in defining natural geohydrologic conditions, including thickness and depth of soil aand rock layers, and depth to bedrock or water table. Generally two- or three-layer systems can be analyzed in the field by the use of nomograms and simple calculations. More complicated sites having three to four layers with dip will require a programmable calculator or a small computer to solve the seismic equations.

Since seismic wave velocity is directly related to the material properties of the layer such as density and hardness, lateral variations in composition or an irregular interface between layers will show up as geologic scatter on a T/D plot. This is a valuable indicator of variations in site conditions. The analysis of this data requires that the interpreter be knowledgeable about the method, the conditions under which tune data was obtained, and the geohydrologic conditions.

The seismic line must be three to five times the maximum depth of interest. Lateral resolution in the data is determined by the geophone spacing.

Depending on site conditions, a hammer source is useful for obtaining seismic data to depths of 10 to 15 meters, while a 500-pound drop weight is required for depths of 50 to 1.00 meters‘ Explosives or projectile sources may be used to obtain deeper data.

Since the seismic method measures small ground vibrations, it is susceptible to vibration noise from a variety of natural and cultural sources.

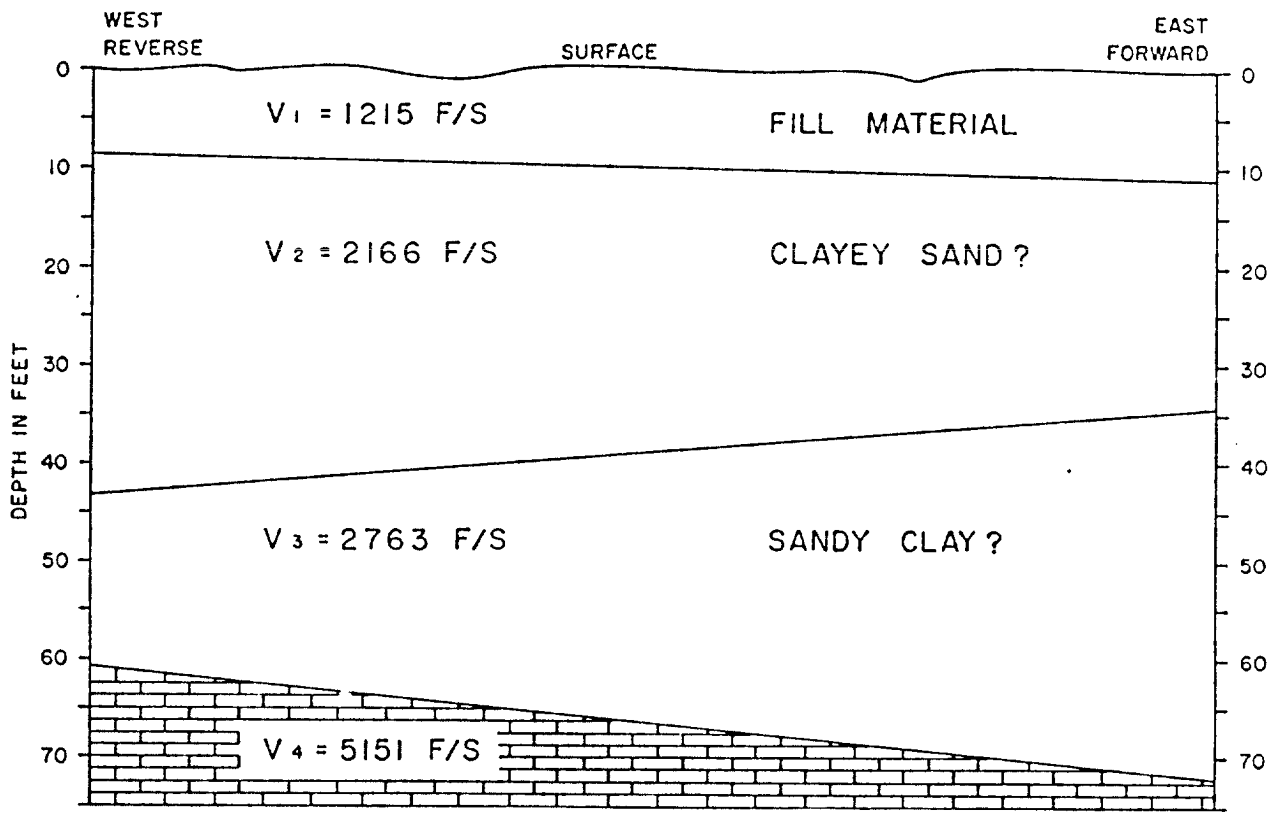


Figure 74. Geologic section interpreted from seismic data (seismic velocities in feet/second).

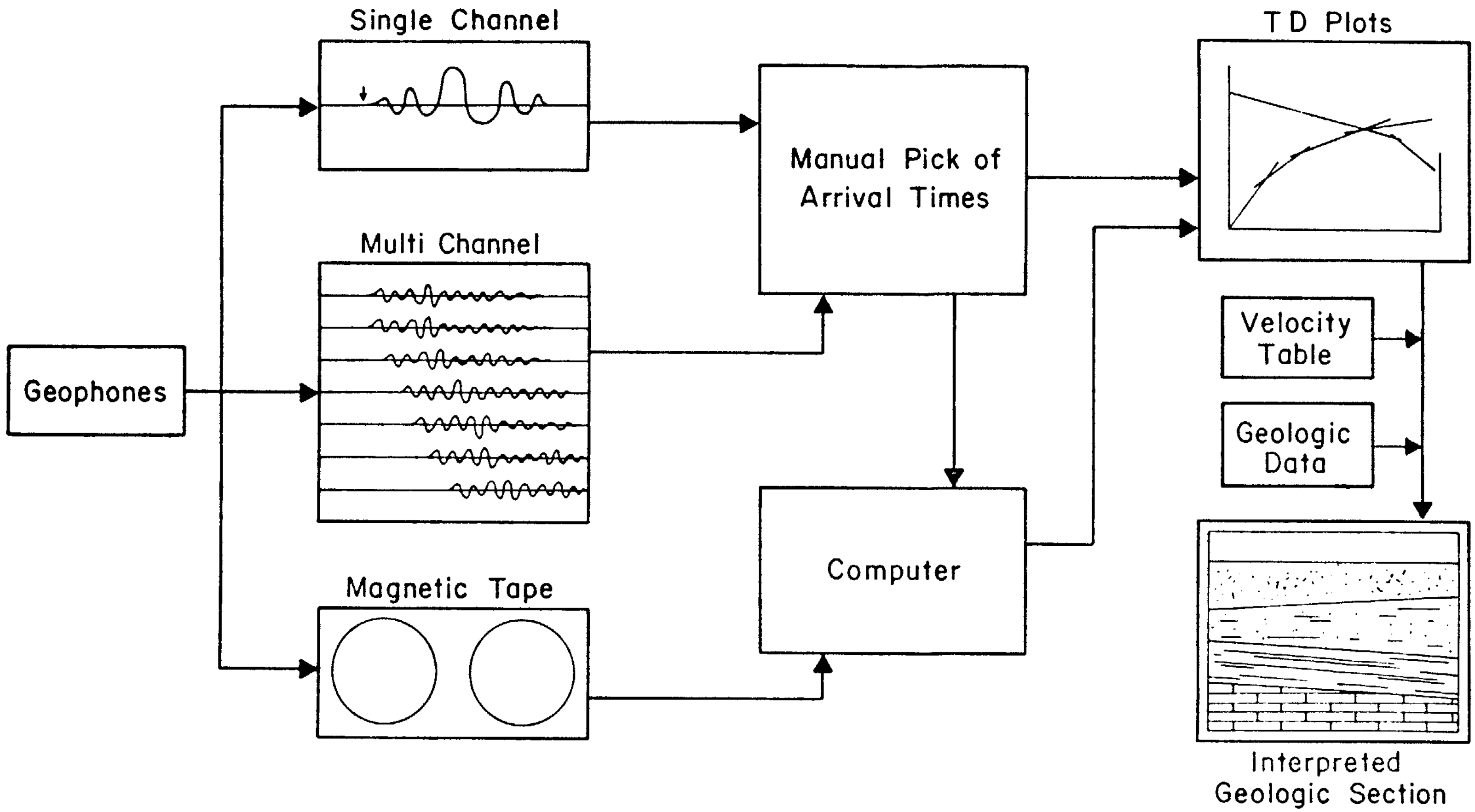


Figure 75. Flow diagram showing steps in processing and interpretation of seismic refraction data.

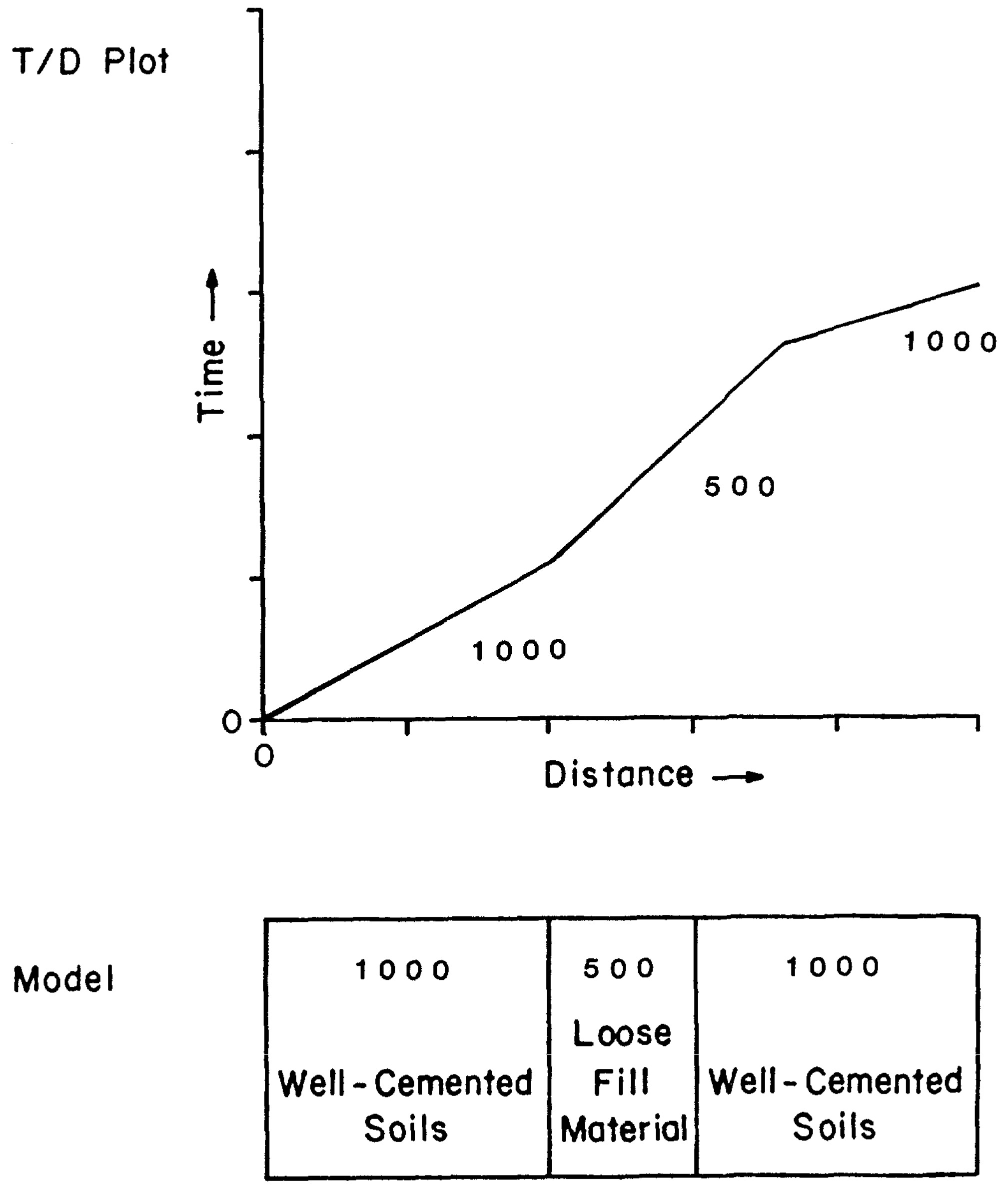


Figure 76. Time/distance plot showing lateral velocity change. Such a plot could be obtained when the refraction line crosses a burial trench. (velocities in meters/see.).

The seismic method is inherently a station measurement because geophones must be implanted in the surface of the ground. This makes the method relatively slow when compared to the other continuous techniques.

Capabilities

- Seismic refraction measurements can provide depth and thickness of subsurface geologic layers including depth to rock and water table.
- Seismic velocity of the layers can be related to their physical properties including composition, density and elasticity.
- Disturbed soil zones can often be detected and mapped, permitting the location and delineation of burial zones at HWS.
- Depth to bottom of disposal areas and landfills may be estimated without drilling.

Limitations

- Seismic data is gathered as a station measurement and involves relatively slow field procedures compared to continuous methods.
- Interpretation requires that site condition be relatively uniform to obtain highly accurate results.
- The seismic method is very susceptible to vibration noise.

Examples

Determining Depth and Thickness of Clay Layer for Proposed Disposal Site

The depth and thickness of a clay layer was required in an evaluation of natural site conditions. A number of seismic stations were located throughout the area of interest.

Figure 77 shows one of the time/distance plots made during this survey. Note that there is very little scatter in the data forming each line segment; this indicates that the each subsurface layer is relatively homogeneous. Both forward and reverse lines were run to evaluate dip, which was found to be insignificant. Since no explosives could be used on this site, a ten pound sledge hammer was employed. This inherently limited the maximum depth of the data and the bottom of the clay was not detected, but a minimum thickness could be established.

Figure 78 shows the localized geologic section constructed from this single refraction measurement. The results of drilling are also shown for correlation. The seismic data had excellent correlation with the major geologic changes, although it did not detect the subtle changes in color which showed up in the boring logs.

Determining Soil Thickness and Bedrock Depth at HWS

A burial trench containing drums of hazardous waste was located in a karst area. The depth of the residual clayey soil over bedrock was of prime concern in the evaluation of possible contaminant migration away from the burial site into the permeable bedrock. The burial trench was known to have been dug by bulldozers and was believed to be less than 2 to 3 meters deep. Drilling was not used because of the risk of opening up a pathway through the clay to the fractured limestone.

Four seismic refraction stations, using forward and reverse lines, were used to determine the depth of the limestone bedrock around the burial trench perimeter. One of these T/D plots is shown in Figure 79. There is considerable geologic scatter in the data, which indicates that there are inhomogeneities within the soil horizon and an irregular soil/bedrock contact.

Analysis of the seismic data revealed a steeply dipping limestone surface from one end of the trench to the other (shown in Figure 80). This was cross-verified by the seismic refraction data taken on the opposite side of the trench, as well as the data from both ends of the trench. This multiple confirmation provided a high confidence level in the assessment of depth to rock without the use of drilling. Depth to limestone varied from four meters to ten meters at the two seismic stations off the ends of the trench. These results showed that there was a minimum of two meters of soil between the deepest trench bottom and the top of the rock; the risk of rapid contaminant migration into the bedrock was judged to be low based upon this data.

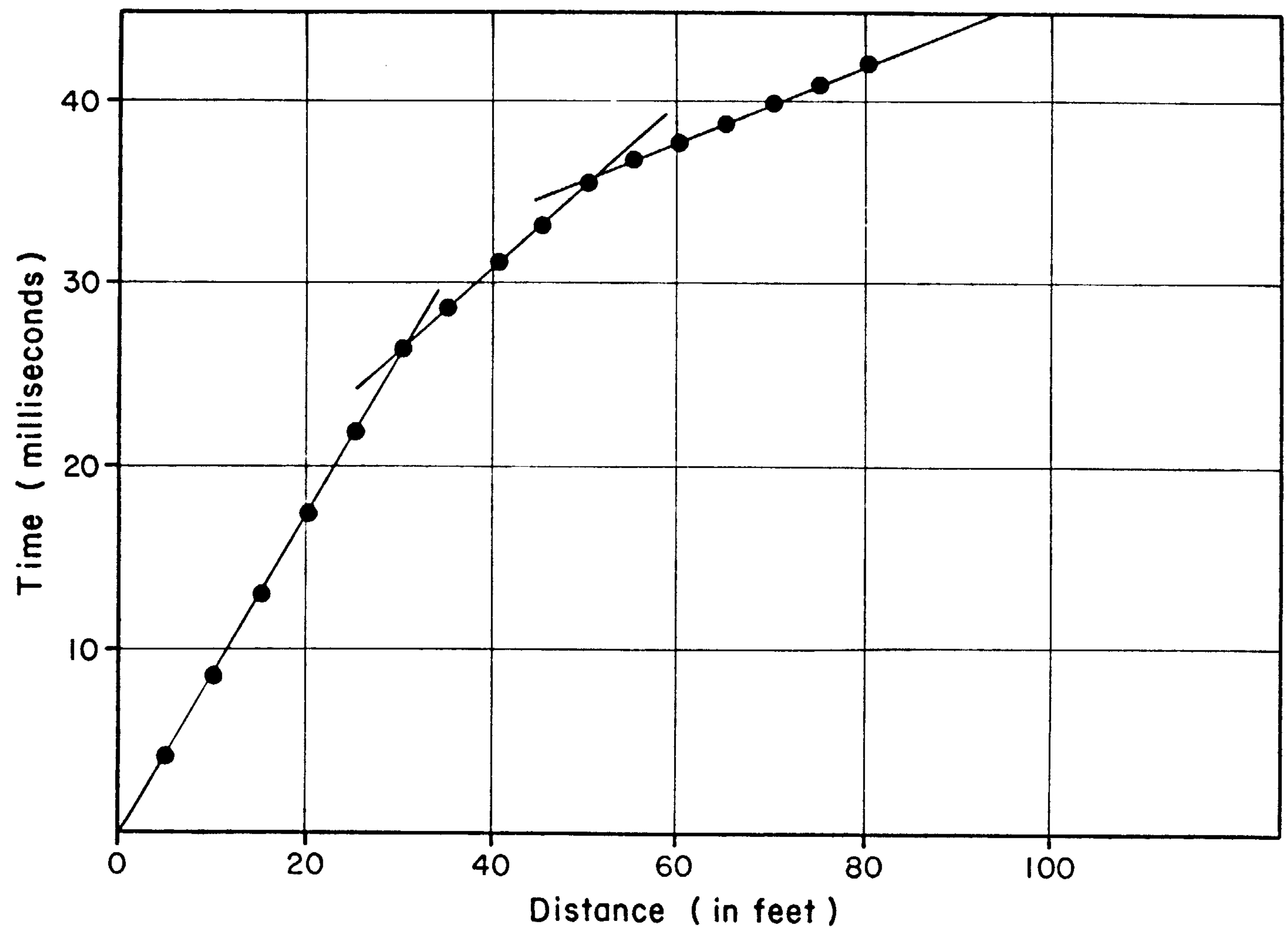


Figure 77. Time/distance plot of field data showing three layer geologic system. (only forward line shown for clarity).

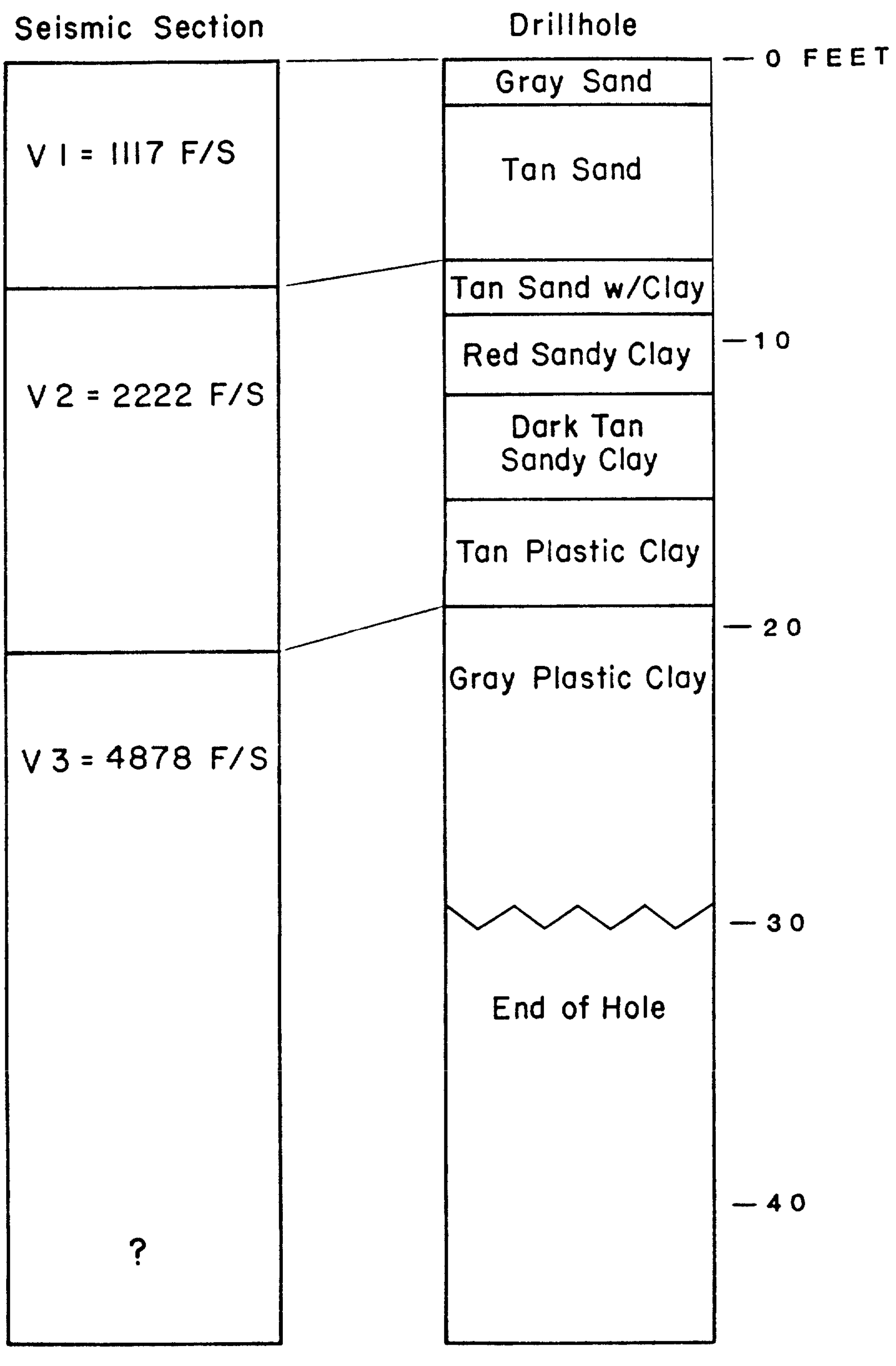


Figure 78. Interpreted seismic data (Figure 77) compared to driller's log.

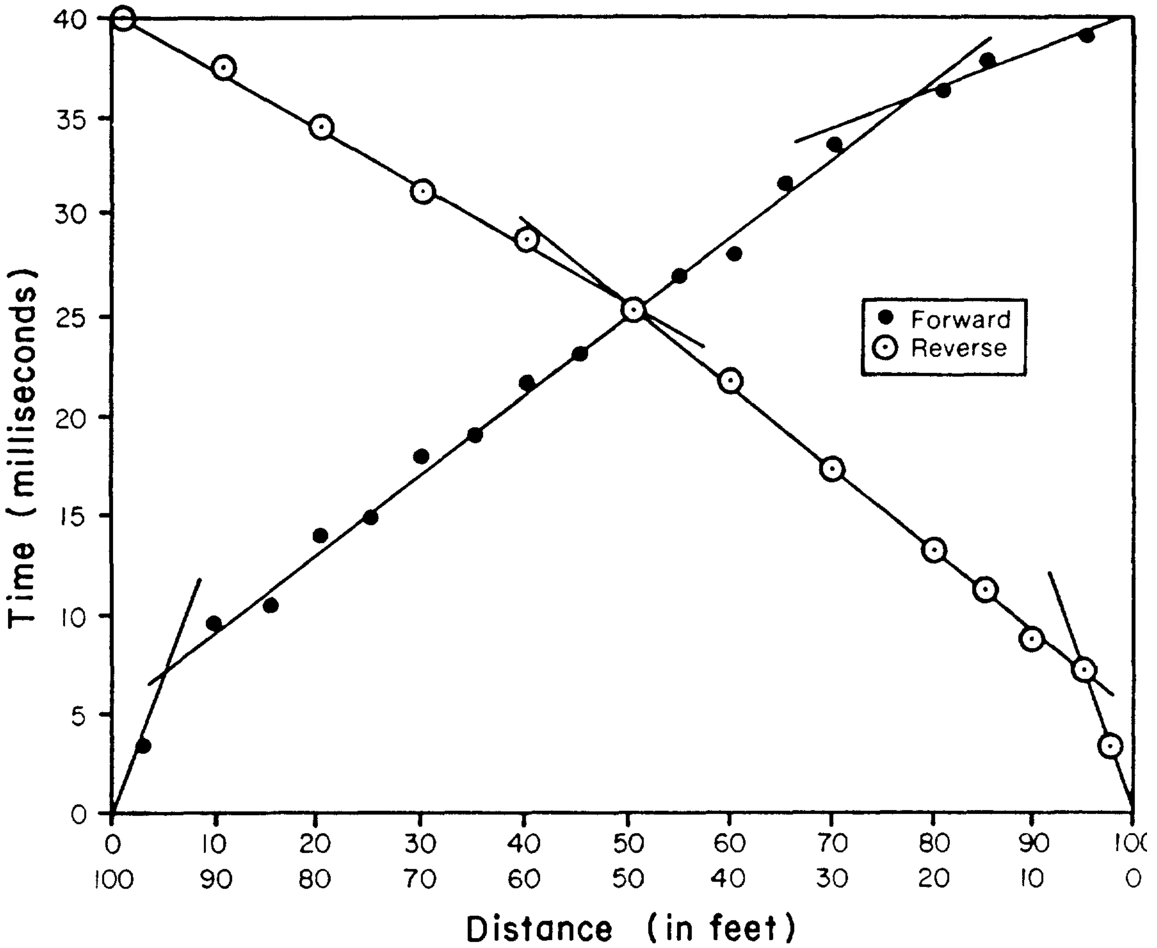


Figure 79. Time/distance plot of field data showing forward and reverse seismic refraction data.

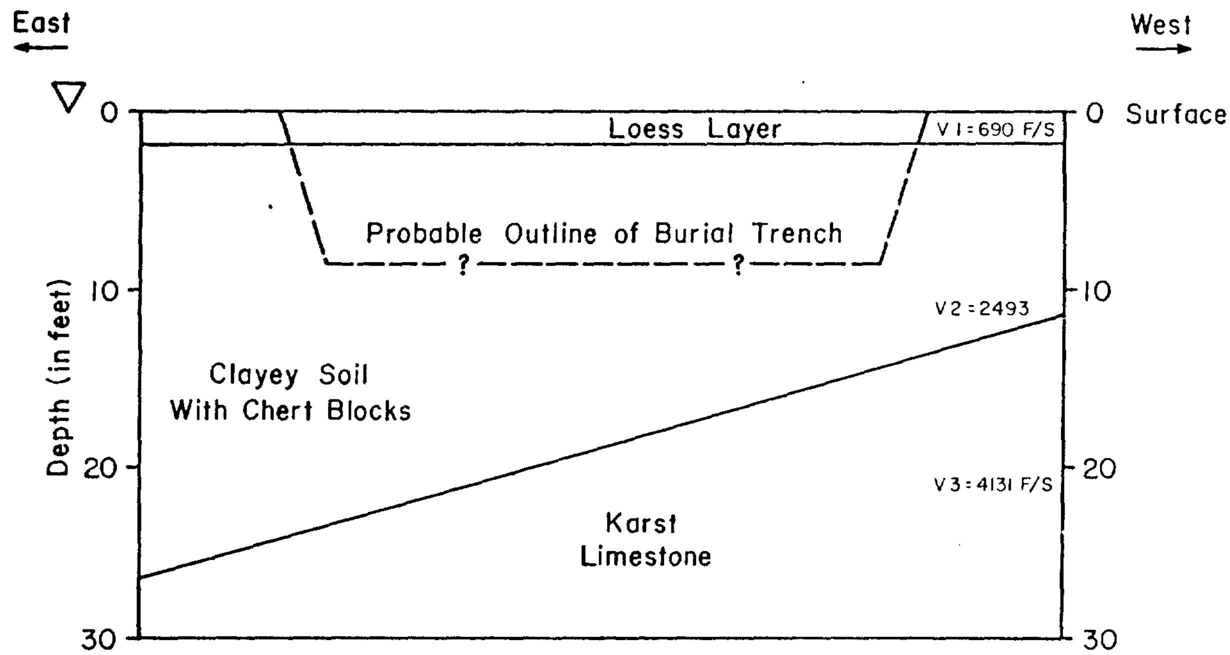


Figure 80. Geologic section resulting from interpretation of seismic data (Figure 79). Estimated outline of trench is shown. (velocities in feet/second)

SECTION VIII

METAL DETECTION (MD)

Introduction

Metal detectors (MD) are designed to locate buried metallic objects. They are commonly used by treasure hunters searching for coins and by utility crews for locating buried pipes and cables. In HWS investigations, MD are invaluable for detecting buried drums and for delineating the boundaries of trenches containing metallic drums.

Metal detectors can detect any kind of metallic material, including both ferrous metals such as iron and steel and non-ferrous metals, such as aluminum and copper. (In contrast, another search device, the magnetometer, discussed in Section IX, responds only to ferrous metals.)

Metal detectors have a relatively short detection range. Small metal objects such as spray cans or quart–sized containers can be detected at a distance of approximately 1 meter. Because the response of a metal detector increases with the target's surface area, larger objects like 55-gallon drums may be detected at depths of 1 to 3 meters. Massive piles of metallic materials may be detected at depths of 3 to 6 meters.

The metal detector is a continuously-sensing instrument which can provide total site coverage and which is well suited for locating buried metal. Experience at HWS investigations has shown that metal detectors can be effectively used to:

- Locate buried metallic containers of various sizes;
- Define boundaries of trenches containing metallic containers;
- Locate buried metallic storage tanks;
- Locate buried metallic pipes;
- Avoid buried utilites when drilling or trenching;
- Locate utility trenches which may provide a permeable pathway for contaminants.

Principles and Equipment

A metal detector responds to the electrical conductivity of metal targets, which is relatively high compared to normal levels of soil conductivity. These targets must, of course, be within the range of the instrument to be detected.

There are many different types of metal detectors available commercially. This document will consider three general classes of equipment:

1. Pipeline/cable locators (Figure 81)
2. Conventional "treasure hunter" detectors (Figure 82)
3. Specialized detectors (Figures 83, 84 & 85)

Numerous pipeline/cable locator metal detectors are commercially available. Besides being effective for locating buried utility cables and pipes, they can be used to detect larger buried targets such as 55-gallon drums, with the added feature that they will not respond to small unwanted surface targets like soda cans. This type of detector is commonly used by EPA Field Investigation Teams (Figure 81).

There is also a wide variety of "treasure hunter" metal detectors on the market (Figure 82). While many of these units are generally designed for locating small coin–sized objects, some of them offer the option of larger sensor coils, which makes them suitable for surveys at intermediate depths. Some of these units are also capable of operating in areas where natural soil conditions (such as large amounts of iron minerals) could adversely affect the instrument's performance.

Specialized detectors have been designed to deal with unique problems. They are expensive, not commonly available, and require an experienced operator. However, these units are quite versatile: working to greater depths, covering a wider area with each pass, producing continuously recorded data (Figures 83 & 84), and operating from a vehicle when necessary (Figure 85). They are invaluable for coping with special field problems such as interference from natural soil conditions and nearby man-made materials.

Figure 86 shows the principle of operation and the functional parts of the typical pipe/cable detector shown in Figure 81. The transmitter of a metal detector creates an alternating magnetic field around the transmitter coil. A balance condition must be achieved to cancel the effect of this primary field at the receiver coil. Shown in Figure 86, the balance or null is accomplished by orienting the planes of the two coils perpendicular to one another. The primary field will induce eddy currents in a metal target within range of the instrument. These eddy currents, in turn, produce a secondary field which interacts with the primary field to upset the existing balance condition. The result will be an output on a meter and/or an audio signal.

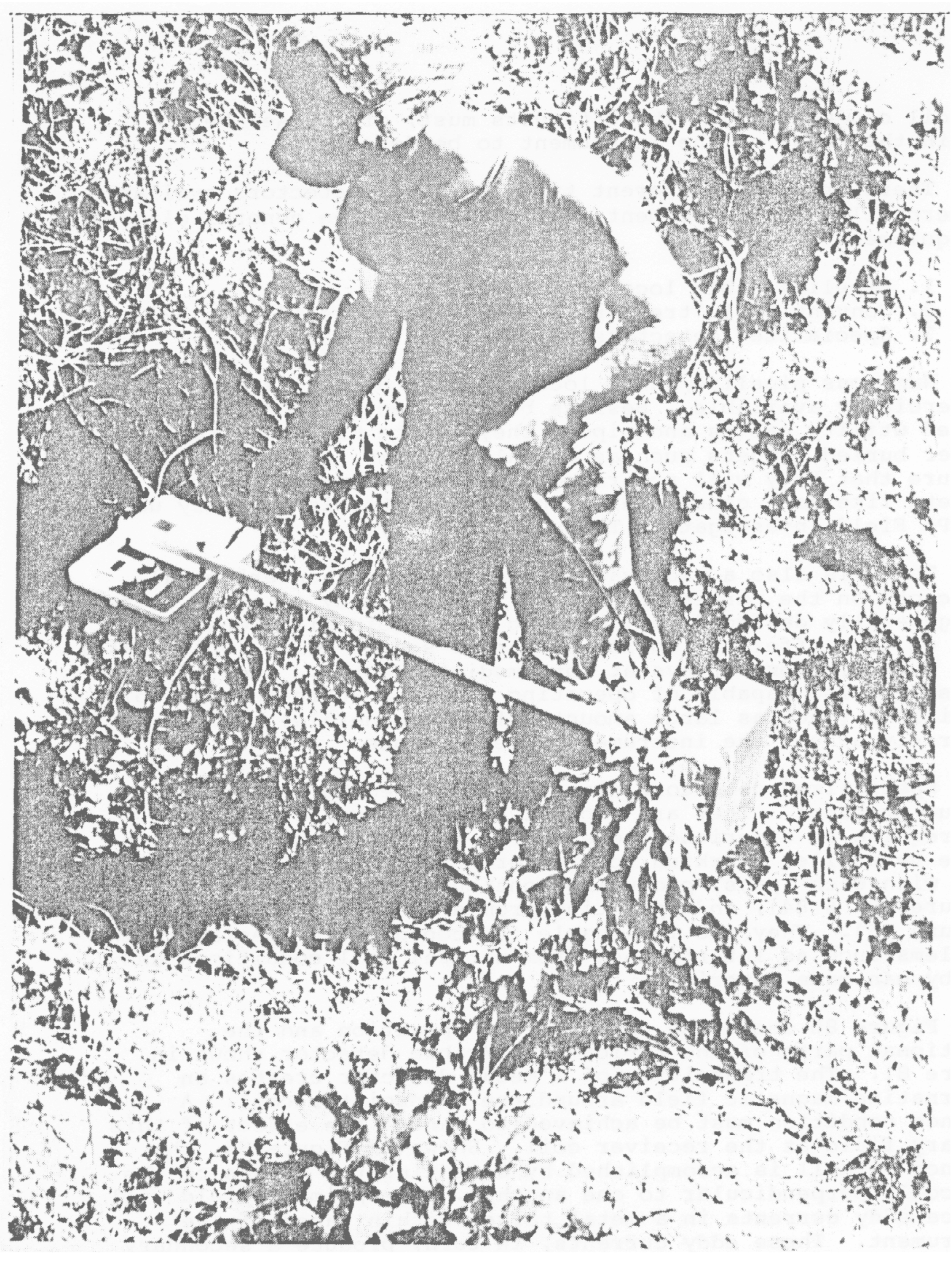


Figure 81. Industrial pipe/cable locator. This type detector is in common use by EPA field investigation teams.

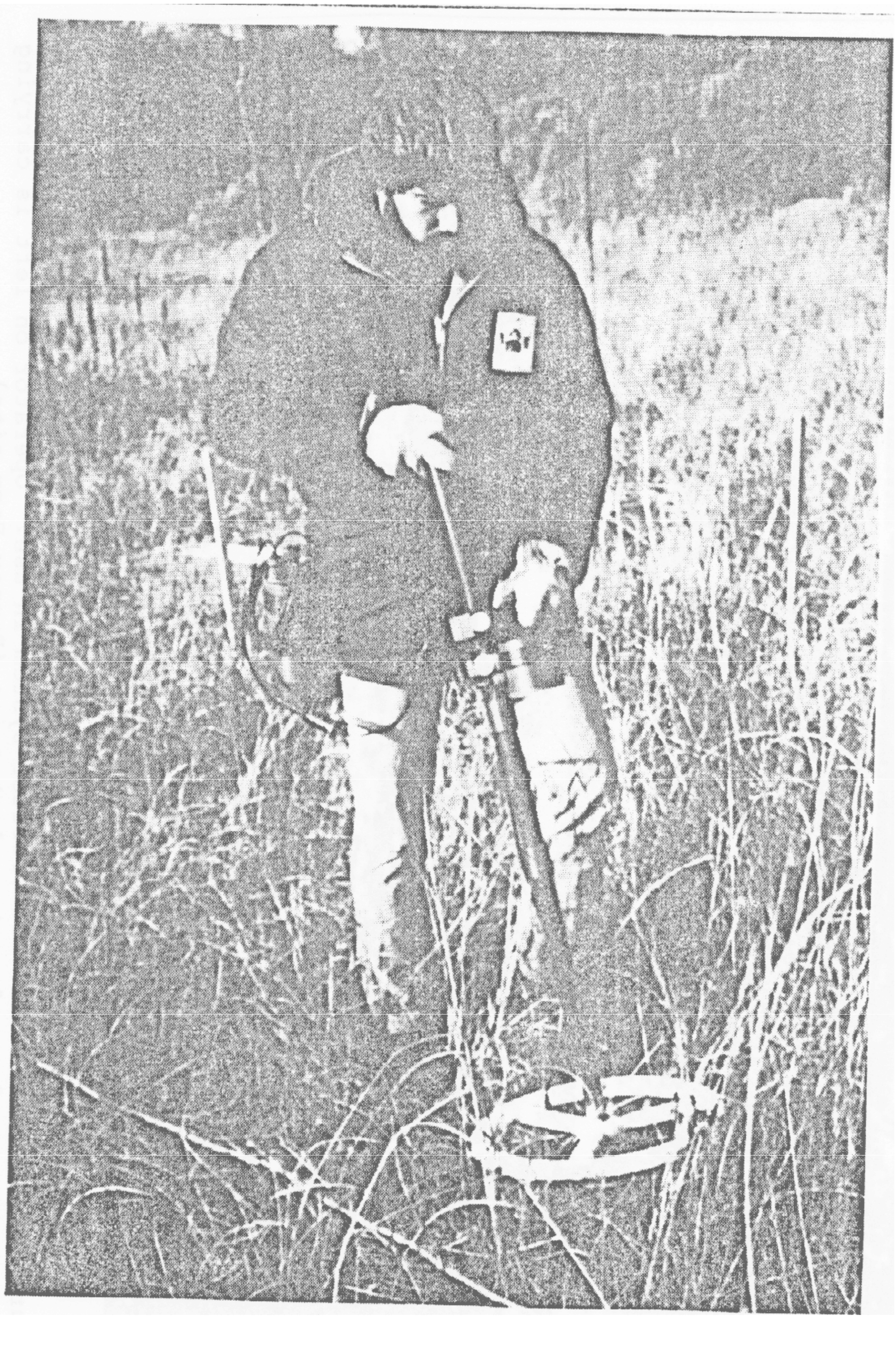


Figure 82. Typical treasure hunter type metal detector with large search coil.

Figure 83. Specialized metal detector system in use. Operator on left is carrying recorder and system electronics (Denney Farm site).

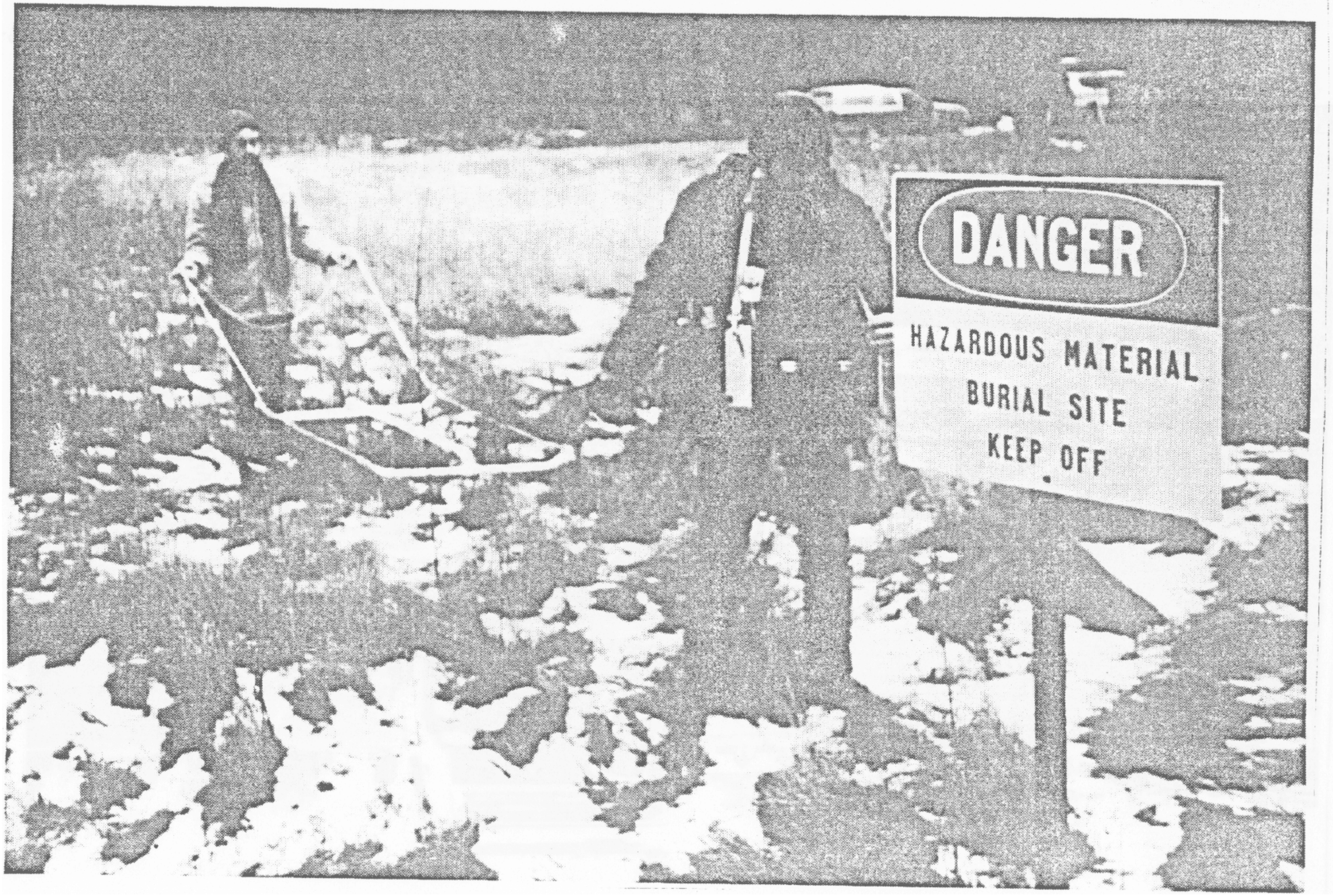


Figure 84. Specialized metal detector system with large search coil. Note strip chart recorder on chest of operator (Savanna Army Depot).

Figure 85. Truck-mounted metal detector system provides rapid site coverage over large areas.

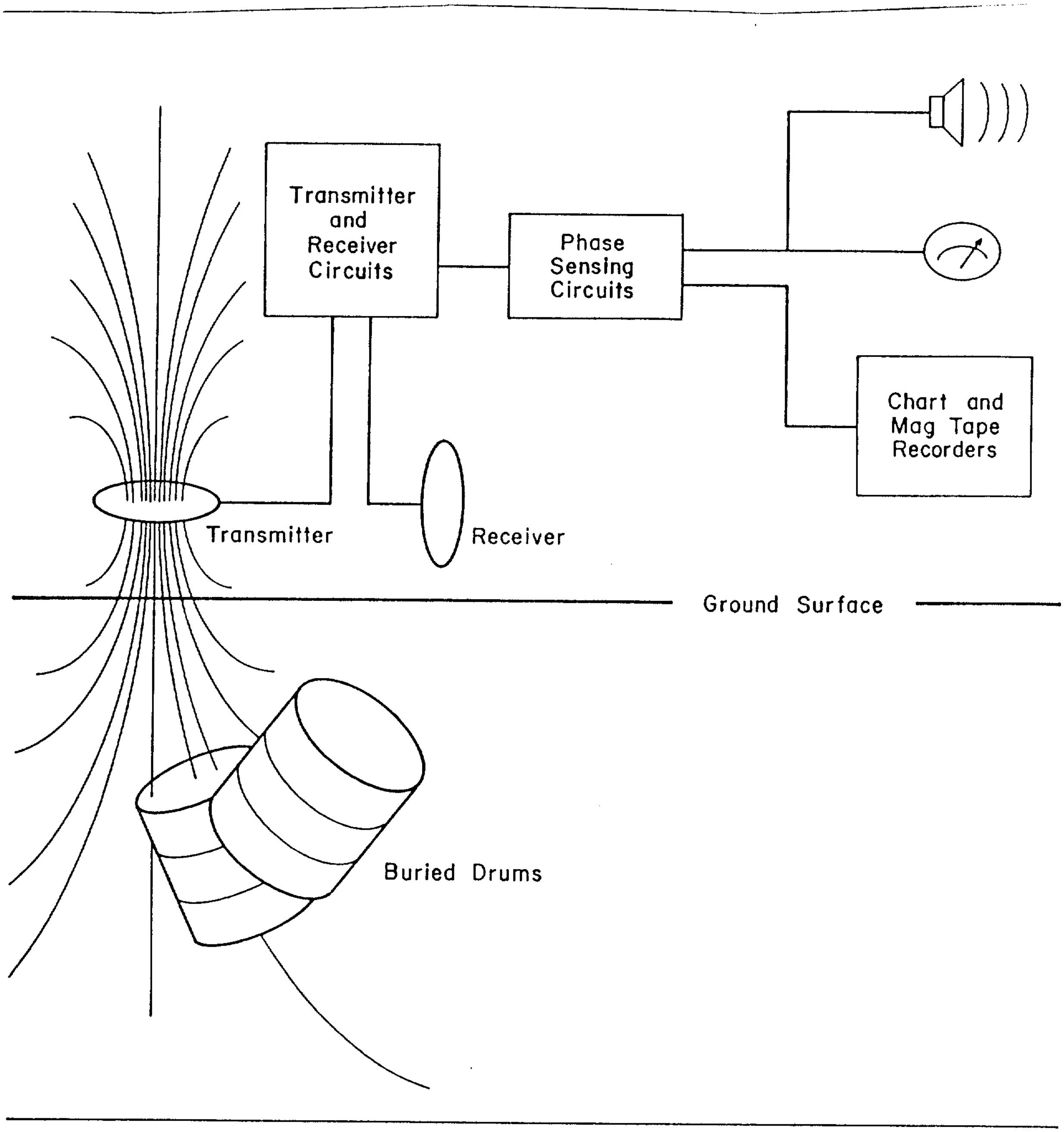


Figure 86. Simplified block diagram of a pipe/cable type metal detector system. Primary field from transmitter is distorted by buried metallic objects causing upset of null at receiver coil.

Other types of metal detectors combine the transmitter and receiver coils into one sensor package, and they may respond to the eddy currents generated in the target in different ways. These eddy currents may be sensed directly by the receiver or they may cause direct loading effects on the transmitter. A discussion of the details of the various types of metal detectors and their electronics is beyond the scope of this document.

Several factors influence metal detector response: the properties of the target, the properties of the soil, and the characteristics of the metal detector itself.

The target's size and its depth of burial are the two most important factors. The larger the surface area of the target, the greater the eddy currents that may be induced, and the greater the depth at which the target may be detected. (Response is proportional to the cube of the area.)

For example, if all the steel in a 55-gallon drum were collapsed into a solid rod of approximately the same length as the drum, the rod would yield a very poor MD response. However, because the steel mass in the drum is in the form of a thin sheet, there is a considerably greater area of metal, in which substantially greater eddy currents may be developed. Consequently, a single 55-gallon drum is an ideal target and may be detected at distances of 1 to 3 meters depending on the specific equipment used.

The MD's response to a target decreases at a rate equal to reciprocal of its depth to the sixth power ($1/\text{depth}^6$). Therefore, if the distance to the target is doubled, the MD response will decrease by a factor of 64. Consequently, the MD is a relatively nearfield device; it is generally restricted to detecting small targets at relatively shallow depths or larger targets at limited depths. Generally, most metal detectors are incapable of responding to any targets, no matter how large, at depths much greater than 6 meters.

Although the shape, orientation and composition of a target will influence the MD response, these factors will have much less influence than will the size and depth of the target. Target deterioration, however, may have significant impact. Metallic containers will corrode in natural soil conditions and this corrosion can be accelerated by unusual conditions at the HWS. If a container is corroded, its surface area will be significantly reduced and this, in turn will degrade the response of a metal detector. Using average corrosion-rates for steel in soil and considering a range of drum metal thicknesses, the life of a buried drum might range from 5 to 20 years under normal soil conditions. Under adverse conditions, however, this corrosion rate could be accelerated by a factor of 5 or more.

High concentrations of natural iron-bearing minerals in the soil will limit the performance of many metal detectors. Similarily, high concentrations of salt water, acids and other highly conductive fluids will also reduce the effectiveness of a metal detector. Search operations conducted in an area with considerable metallic debris will range from very difficult to impossible.

Iron minerals, conductive fluids, and metallic debris will affect the MD in much the same way as a target. A false response will be produced which may confuse the searcher or render the search impossible. In the case of metallic debris, the successful application of a MD will depend on the relative size of the debris and its density. It is obvious that a metal detector survey for buried drums could not be conducted if the surface were to be totally covered with drum lids. In such a case, the detector would respond to the drum lids and deeper targets would be masked.

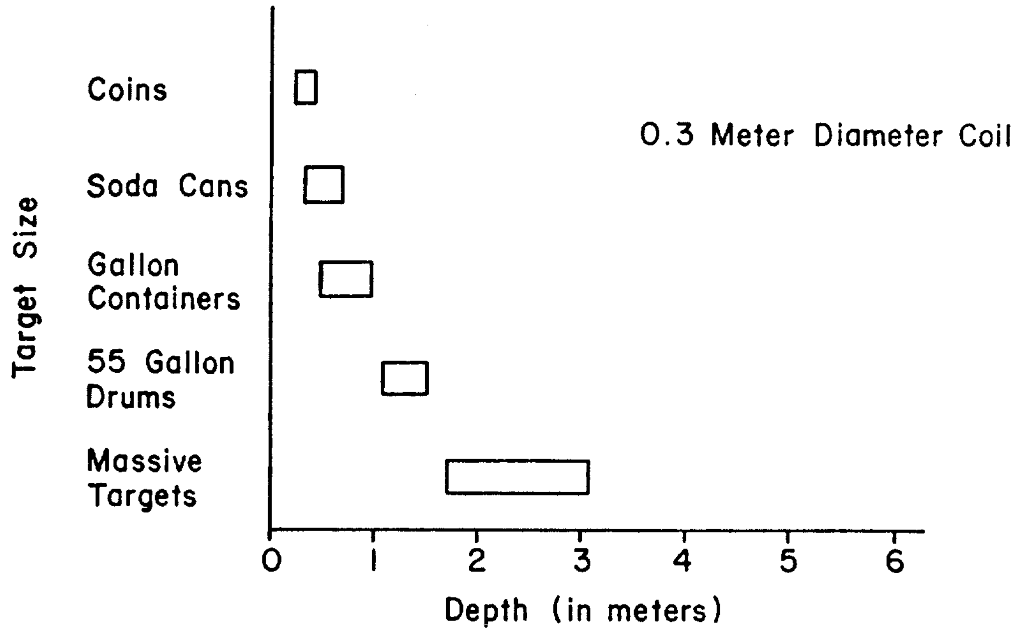
Some compensation for natural soil conditions, metallic debris, and nearby metallic structures can be made by using certain specialized equipment and modified field procedures. These are described in the sections dealing with field usage and noise.

Because the MD's response weakens rapidly with increasing target distance, system gain and instrument stability are important. Coil size is the only variable which can easily be modified on some metaldetectors by the use of interchangeable coils. The influences on system response of target size and coil size are shown in Figure 87. These data shows the detection ranges for various common targets and are presented for two coil sizes. Since the equipment capabilities vary widely, this curve is intended to provide only an approximate guide to metal detector response.

Factors to be Considered for Field Use

Before beginning a metal detector survey, an estimate of the types, sizes and depths of metallic targets should be made. Soil conditions, metallic debris, fences, and the size of the search area should be considered. Finally, the type of MD should be selected to fit the overall survey objectives. This may mean selecting more than one MD to fulfill a project requirement.

The pipeline type of detector has often been used by EPA for locating buried drums. As its name implies, it is also very effective for locating buried utilities; as such, it is a dual-purpose instrument. Because it has an effective coil diameter of about 1 meter (the distance between the transmitter and receiver coils), it is useful in surveys for larger targets and greater depths. Its larger effective coil size also makes it somewhat



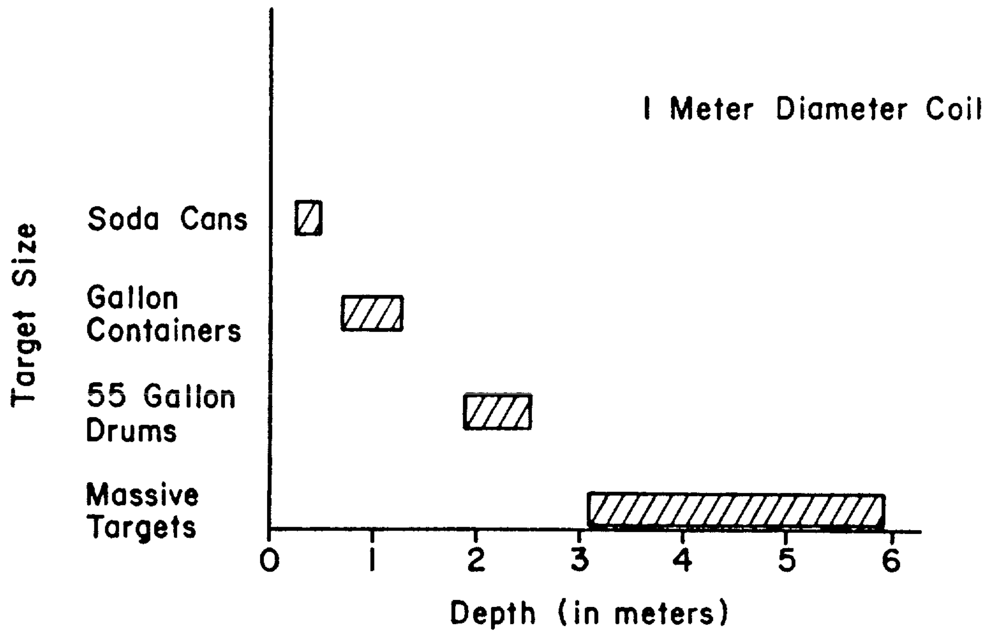


Figure 87. Approximate detection ranges for common targets. Data is shown for two search coil sizes. A-wide variation in detection range occurs because of the many variables involved.

insensitive to small pieces of metallic surface debris, if the detector is elevated above the surface of the ground, as shown in Figure 81.

Metal detectors with coils of smaller diameter (typically less than 0.3 meters), such as those used by treasure hunters, (Figure 82) are much better suited to locating small targets at limited depth. If the field problem is to locate smaller but critical targets, such as individual quart cans of toxic materials, this type of detector is a more logical choice. The detector in Figure 82 is shown with a larger coil which can be useful for detecting single 55-gallon drums at depths of up to 2 meters. These detectors may also be used to evaluate the extent and influence of near-surface trash.

Specialized metal detectors, such as those shown in Figures 83, 84, and 85, are available to handle unusual site conditions or to deal with unique project requirements. These specialized metal detectors can provide:

- Increased depth range;
- Cancellation of interference caused by nearby fences, etc;
- Compensation for unusually difficult soil conditions;
- Continuous recorded data;
- Larger coil configurations to provide greater width of coverage on each pass;
- Vehicle-mounted configurations to cover very large areas;
- Improved semi-quantitative assessments (i.e., estimating the depth and number of drums);
- Classification of targets.

One of the more significant applications of specialized detectors is realized at sites with complex conditions. Here, the MD output can be continuously recorded on a strip chart or magnetic tape for later plotting to provide improved mapping and analysis. Vehicle-mounted sensors are almost a necessity if the area to be surveyed is very large.

A simple reconnaissance investigation for the purpose of detecting the presence of drum-sized targets may satisfy many site survey requirements. On the other hand, remedial action may call for a detailed study to locate burial trenches with high resolution and to provide estimates of the quantity of drums. The lateral resolution capability of MD instruments often permits the successful delineation of closely-spaced multiple trenches, when other techniques fail. If site conditions are relatively simple, a detailed assessment of burial site boundaries may be carried out without recording the data. Stakes may be placed around the burial boundaries as the survey progresses.

More complex sites may require very detailed information and a means of recording many target locations. For such cases, a survey grid of parallel lines should be established at an interval which will provide the resolution required. Typically, such grids may employ spacings of from one meter to more than 10 meters. (Survey stakes should obviously be made of nonmetallic materials.) The coarser grid spacing might be used first to locate larger burial sites, tanks or pipeline crossings; then, selected areas of interest could be surveyed at closer intervals for more complete coverage. Overlap of survey lines may be required at some sites if smaller or discrete targets are important. When data is recorded, the records must be annotated with station locations so that the spot can be located again or for the construction of a location map.

Depending on the size of the area to be covered, hand-carried or vehicle-mounted systems may be used. The vehicle systems can tow wide coils (typically up to 2 to 3 meters wide) for greater coverage. In certain areas, the need for high resolution may require a hand search to provide the necessary details.

The effects of high iron content in the soil or numerous small metallic fragments lying on or near the surface can be minimized by elevating the search coil one to three feet above the ground. This technique is applicable only if the targets are large enough to be detected at the increased distance from the search coil. Figure 84 shows a coil of 1 meter diameter being used in this mode to locate massive concentrations of buried gas canisters, where the surface of the ground is covered with small pieces of metallic debris.

Quality Control

Metal detectors are usually not calibrated. They respond in a relative way; i.e., closer or larger metallic targets create a greater output level than smaller or more distant ones. An experienced operator can usually make a reasonably accurate estimate of target size and depth. However, any attempt at detailed calibration will likely be useless, because of the many variables involved. For example, "calibration" curves relating MD meter response to a steel drum as a function of distance may be accurate under a given test standard condition, but unfortunately these curves are seldom valid, because of the variability and complexity of actual field conditions. Moreover, the operator cannot easily determine the difference between a single drum located at medium depth and several drums lying deeper. What he can report, however, is that drum-sized targets are present in certain specific areas.

Noise

The effectiveness of a metal detector is dependent upon the relative magnitude of the target-signal, the noise produced by the surrounding soil, and other variables. The procedure used to null a metal detector serves to cancel most of the soil interference; however, some level of noise from soil conditions may be present during a survey. As the target response decreases and/or the noise level increases, the target response will eventually be lost in the noise. While it is true that the larger coils will yield better signals from larger and deeper targets, they are also more susceptible to soil effects and other electrical interference. However, the larger coils can be raised, up to about 1 meter off the ground, to minimize both the soil effects and the effects of metal trash near the surface.

When the coil is carried too close to the ground, small shallow targets may easily saturate the system to a full–scale response. When this occurs, other targets, no matter how large, cannot cause a further increase in response and will, therefore, remain undetected.

It is important to understand that a metal detector radiates a field in all directions (Figure 86). However, its most sensitive zones are "focused" directly above and below the plane of the sensor coils. This characteristic can be quite useful in the field. The focused response characteristic of the MD will allow the operator to work relatively near some metallic items, so long as they are far enough to the side of the sensor coil. In addition, the focused response provides good definition of the edges of trenches containing buried drums.

The operator must exercise care to avoid interference from nearby fences and vehicles, as well as from buildings and buried pipes. For example, by running a survey line parallel or oblique to one or more unknown pipelines, the operator can cause invalid data to be produced. Certain welded fence materials and the mesh used for concrete reinforcement will provide a very good MD response, despite the fact that they are not solid metallic surfaces.

Precaution must also be taken to remove metal from the operator, or to minimize its effects. Steel-toed boots, respirators and air bottles can all cause considerable problems with noise.

Data, Processing, Interpretation, and Presentation

Unrecorded Data--Most commercial metal detectors have both audio and meter indicators, with no provision for directly recording the information output. Reconnaissance-level surveys with relatively simple site conditions can be handled effectively with these instruments. MD responses or target locations can be noted in a field log or site map; stakes or paint marks can be placed over target centers or around their boundaries as the survey proceeds. This is the approach commonly used to locate buried utilities. Since MD results are generally self-evident, further analysis and processing are unnecessary.

An experienced operator using these simple field procedures, commercial equipment, and unrecorded data might be able to provide the following:

- The location and delineation of buried metallic objects;
- A crude approximation of depth;
- A crude approximation of size of discrete targets.

Recorded Data--Metal detectors with recording capability should be considered if:

- There is a need for coverage of large areas;
- Complex distribution of burial areas exists;
- Semi-quantitative results are required;
- Difficult soil conditions prevail;
- Documentation is necessary.

The output from some specialized MD can be recorded directly on strip charts for interaction in the field or on magnetic tape for later playback and/or processing. Such recorded data is invaluable in locating and mapping the boundaries of metal in randomly-oriented trenches and burial pits. Data acquired along grid or parallel survey lines can be assembled into an accurate composite map of the site.

Both strip chart and magnetic tape data lend themselves to computer graphics and processing. Corrections for profile linearity and scale/range changes can be made Filtering may be applied to all or part of the profile data. High-frequency noise from small local targets such as soda cans may be removed to improve the analysis and display of massive burial sites. Finally, the results can be plotted in contour maps or as 3-dimensional views of the combined data set. Semi-quantitative assessments, such as the determination of the number of drums and their burial depth, are not easily accomplished using the MD method alone. It is commonly necessary to use other techniques in conjunction with the MD survey in order to derive this expanded level of information.

Summary

At HWS, metal detectors are primarily used to determine the presence, location and definition of trench boundaries. They can also be used to assist in the process of selecting a site for drilling, so that metallic containers and underground utilities are not accidentally struck during the drilling operations. Buried tanks and pipes which may be sources of leaks can be located; and in addition, the location of utilities may serve to define areas representing more permeable passage-ways in which contaminants may flow.

Metal detectors will detect any kind of metallic material, including ferrous metals, such as iron and steel, and non-ferrous metals, such as aluminum and copper. (In contrast the magnetometer, discussed in Section IX, responds only to ferrous metals.)

The metal detector is a continuously-sensing instrument which can provide total site coverage, and which is well suited for locating buried metal within its depth range. The lateral resolution capability of MD instruments often permits the successful delineation of closely-spaced multiple trenches when other techniques fail.

Metal detectors have a relatively short range. They can detect quart-sized containers at a distance of approximately one meter. The response of a metal detector increases with the target's surface area; therefore, larger objects like 55-gallon drums may be detected at depths up to 3 meters, and massive piles of metallic materials may be detected at depths up to 6 meters. Specific performance is highly dependent upon the type of metal detector used. Generally, most metal detectors are incapable of responding to any targets, no matter how large, at depths much greater than 6 meters.

An experienced operator can usually make a reasonably accurate estimate of target size and depth. However, any attempt at detailed calibration will likely be useless, because of the many variables involved.

Metal detectors are very susceptible to noise caused by some natural soil conditions, unwanted metallic debris, pipes, fences, vehicles, buildings, etc.

There are many different types of metal detectors available commercially, each. with its own advantages and limitations. The choice of a MD should be determined by the type of targets to be located, their depth, the nature of the soil, the size of the search area, site conditions and other project requirements.

Capabilities

- MD respond to both ferrous and non-ferrous metals;
- They will detect single 55-gallon drums at depths of up to 1 to 3 meters;
- They will detect large masses of drums at depths of up to 3 to 6 meters;
- MD provide a continuous response along a traverse line;
- A wide range of commercial equipment is available most of which is relatively easy to use;
- MD provide very good definition of boundaries in burial trenches and pits containing metal;
- Limited semi-quantitative information may be obtained from the use of commercial detectors;
- Specialized equipment is available for recording data, coping with unique site conditions, or obtaining semi-quantitative information.

Limitations

- Metal detectors are inherently limited in depth capability;
- They are susceptible to a wide range of noise including that introduced by natural soil, metallic debris, pipes and cables, and nearby fences and metal structures;
- The performance of many commercially-available detectors is marginal for use at HWS;
- They are limited in providing quantitative data concerning the number and depth of targets;
- Specialized MD instruments are uncommon and require experienced personnel;
- Complex site conditions will demand increased levels of skill; special equipment; the recording, processing and plotting of data; and experienced interpreters.

<u>Examples</u>

Selecting a Safe Drilling Site

When work is being done in a hazardous area, drill sites should be positioned with care to avoid drilling into disposal pits, drums, pipes or cables. Figure 82 shows a proposed drill site 7x7 meters in area which was selected for a monitor well.

The site was immediately adjacent to an area known to contain extremely hazardous buried materials. The area was surveyed by two metal detectors to provide a high confidence level in selecting the precise well location. A large coil system was used to detect larger, deep targets; a small coil system was used for the smaller, shallower targets. Data was not recorded; targets were noted as the survey progressed. They were immediately marked with wooden stakes, then reverified after placement of the stakes to eliminate possible position errors.

The use of a rope grid permitted a very rigorous and complete survey of the site to be completed in a relatively short time. After completion of this search procedure, the largest clear area was again resurveyed to verify that it was, indeed, free of metal. The exact well location was then positioned in the center of this clear area.

Location of a Single Burial Trench

An area suspected of containing a trench with buried drums was investigated using a specialized MD system with a recorded data output. The first survey line was run perpendicular to the obviously disturbed soil area and yielded the profile shown in Figure 88. This profile shows a very strong response over a distance of about 10 feet. Additional parallel MD lines were run across the remaining disturbed area. These profiles when plotted together (Figure 89) show a linear trench-like feature composed of a strong central response and very distinctive boundaries. Such results are characteristic of a trench filled with a large number of steel drums. The same profile data may also be presented in a plan view, as seen in Figure 90. This format permits exact location of the edges of the burial trench, and subsequent calculation of its area. Using depth estimates from other data, the investigator can calculate the volume of the trench and arrive at an estimate of the number of buried drums.

Location of Multiple Burial Trenches and Pits

A large singular burial pit containing canisters of extremely hazardous materials was known to exist in a field (100 x 180 meters) that had been overgrown by bushes and weeds. Several MD reconnaissance lines were run across the general area to locate the burial site. Within an hour, this unrecorded reconnaissance survey revealed that the entire area was a complex maze of metallic targets and, possibly, contained multiple burial sites. (At this point, the exact location of the large burial pit was uncertain.) Many of the smaller targets could be attributed to metal debris lying on or just below the surface of the ground.

It was determined that a high-density recorded MD survey was necessary to properly evaluate the site. A detailed survey was designed using multiple parallel lines of 15 meter spacing. A specialized detector system was selected which provided a chart-recorded output and a search coil one meter in diameter. The additional depth capacity of the large coil permitted it to be elevated above the ground to minimize the effects of small fragments of metallic debris at the surface (See Figure 84). The results of this survey produced the data shown in Figure 91. This presentation clearly indicates the overall complexity of the site. Although only one large burial trench was believed to exist on the site, this detailed MD survey revealed the existence of smaller pits and trenches within the survey area. This evaluation would have been very difficult, or impossible, without the use of the specialized MD system and

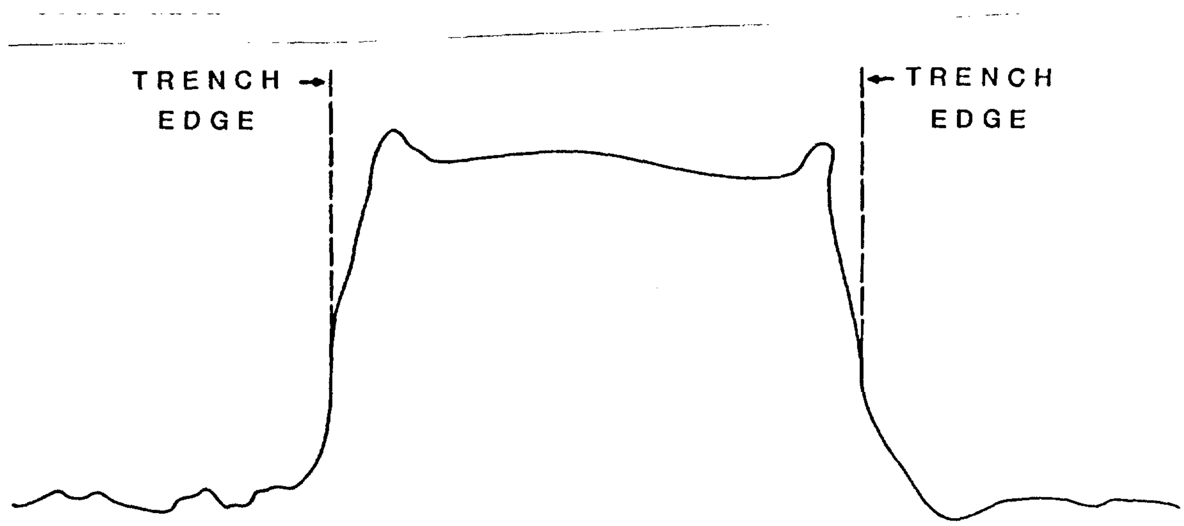


Figure 88. Continuously-recorded metal detector data over a trench with buried drums. Note good resolution of trench edges.

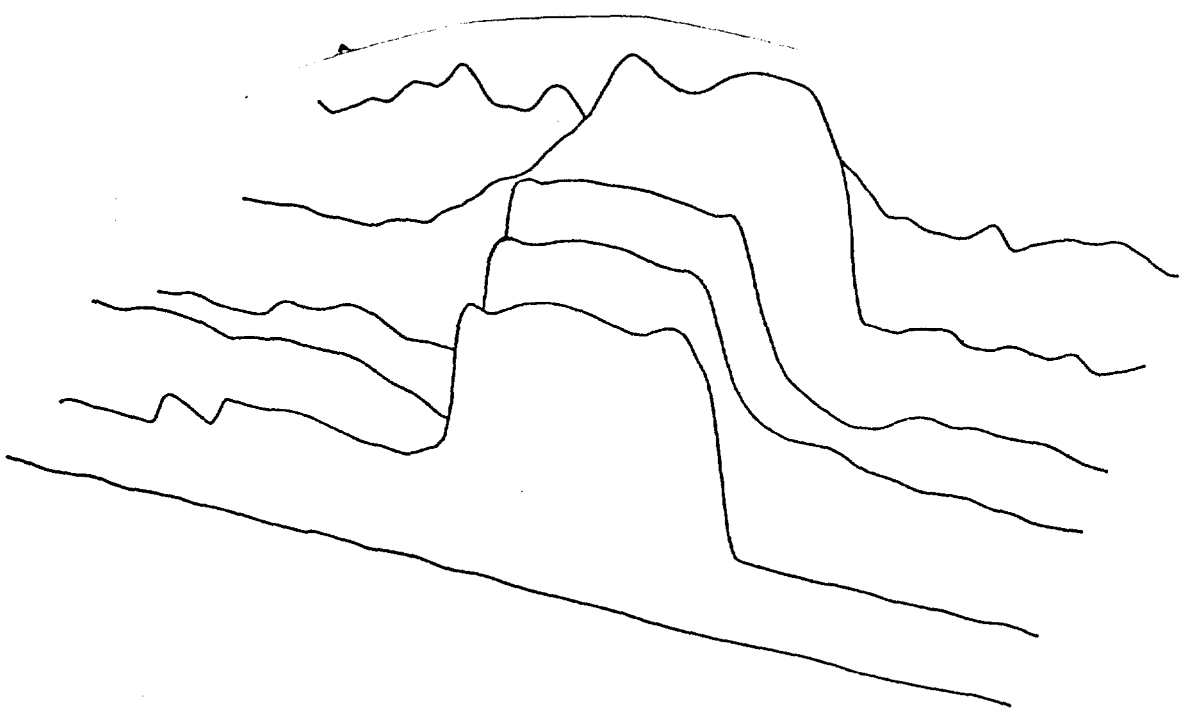


Figure 89. Three-dimensional perspective view of metal detector data from parallel survey lines over a single trench.

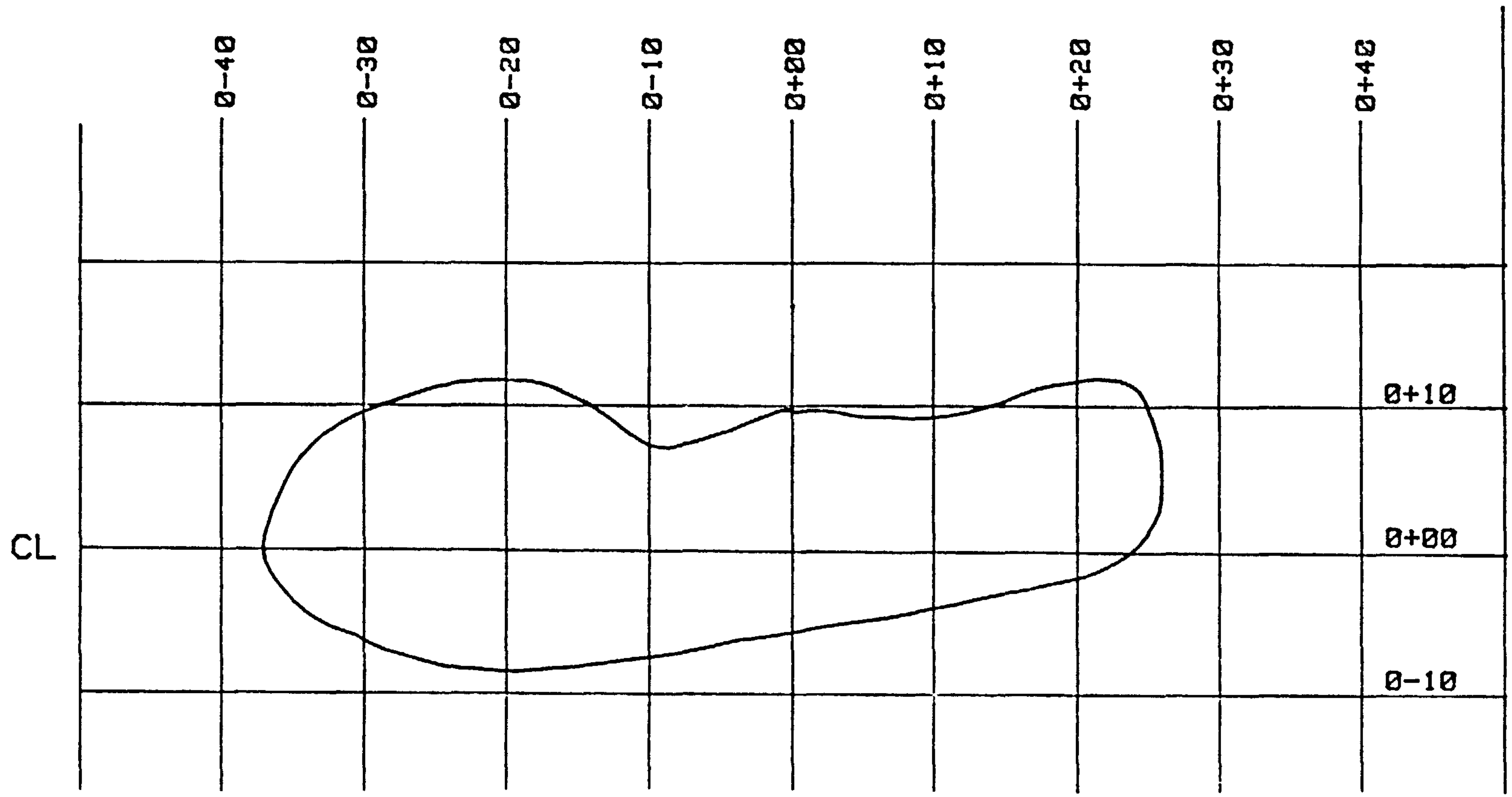
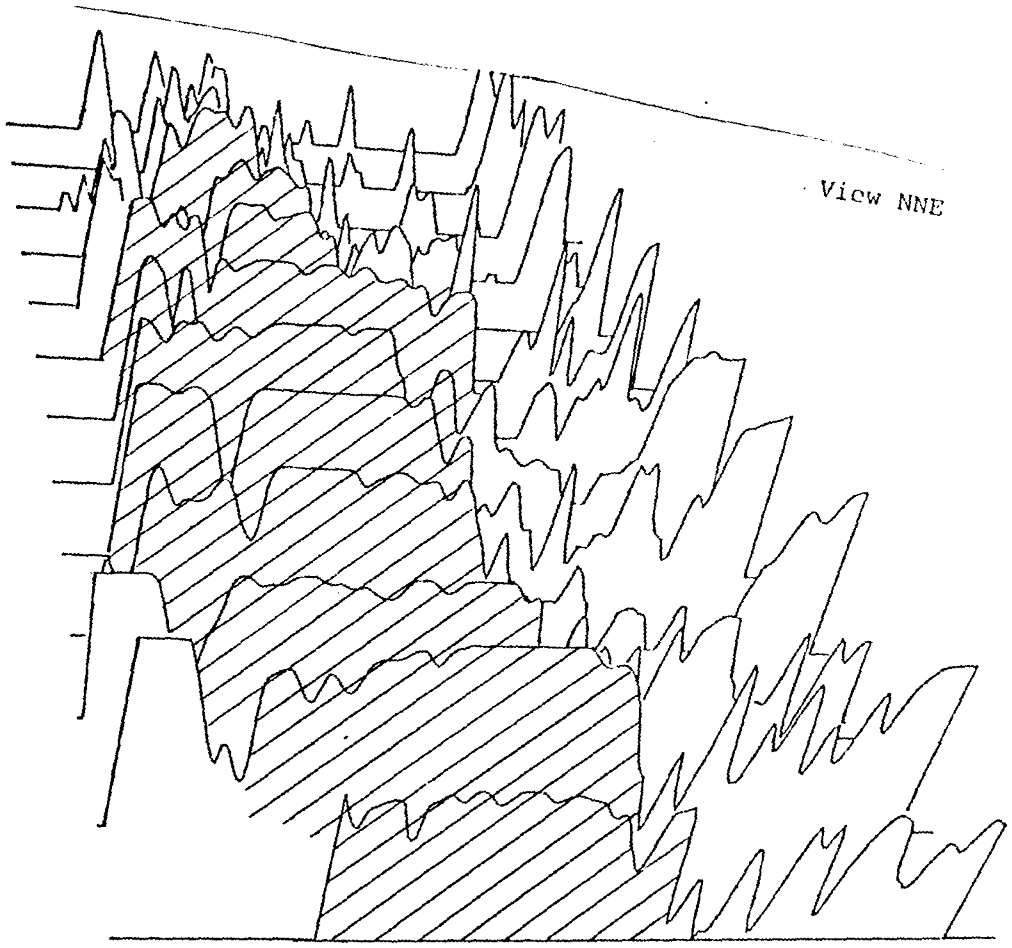


Figure 90. Plan view map of burial trench boundaries based upon metal detector data in figure 89.



TECHNOS INC, MIAMI

Figure 91. Perspective view of survey lines shows a metal detector data from trench containing metal complex burial site. side of the data (shaded) can be seen in the left-hand

SECTION IX

MAGNETOMETER

Introduction

Magnetic measurements are commonly used to map regional geologic structure and to explore for minerals. They are also used to locate pipes and survey stakes or to map archeological sites. They are commonly used at HWS to locate buried drums and trenches.

A magnetometer measures the intensity of the earth's magnetic field. The presence of ferrous metals creates variations in the local strength of that field, permitting their detection. A magnetometer's response is proportional to the mass of the ferrous target. Typically a single drum can be detected at distances up to 6 meters, while massive piles of drums can be detected at distances up to 20 meters or more.

Some magnetometers require the operator to stop and take discrete measurements; other instruments permit the acquisition of continuous data as the magnetometer is moved across the site. This continuous coverage is much more suitable for high resolution requirements and the mapping of extensive areas.

The effectiveness of a magnetometer can be reduced or totally inhibited by noise or interference from time-variable changes in the earth's field and spatial variations caused by magnetic minerals in the soil, or iron and steel debris, ferrous pipes, fences, buildings, and vehicles. Many of these problems can be avoided by careful selection of instruments and field techniques.

At HWS, magnetometers may be used to:

- Locate buried steel containers, such as 55–gallon drums;
- Define boundaries of trenches filled with ferrous containers;
- Locate ferrous underground utilities, such as iron pipes or tanks, and the permeable pathways often associated with them;

- Select drilling locations that are clear of buried drums, underground utilities, and other obstructions.

<u>Principles and Equipment</u>

A magnetometer measures the intensity of the earth's magnetic field. Variations in this field may be caused by the natural distribution of iron oxides within the soil and rock or by the presence of buried iron or steel objects. (The magnetometer does not respond to nonferrous metals such as aluminum, copper, tin, and brass.)

The earth's magnetic field behaves much as if there were a large bar magnet embedded in the earth. Although the earth's field intensity varies considerably throughout the United States, its average value is approximately 50,000 gammas.* The angle of the magnetic field with respect to the earth's surface also varies. In the U.S., this angle of inclination ranges approximately 60 to 75 degrees from the horizontal.

The intensity of the earth's magnetic field changes daily with sunspots and ionospheric conditions which can cause large and sometimes rapid variations. With time, these variations produce unwanted signals (noise) and can substantially affect magnetic measurements.

If the magnetic properties of the soil and rock were perfectly uniform, there would be no local magnetic anomalies; however, a concentration of natural iron minerals, or a buried iron object, will cause a local magnetic anomaly which can be detected at the surface (Figure 92).

An example of a magnetic anomaly indication over buried drums is shown in Figure 93; the exact shape of which may vary considerably. Typical magnetic anomalies at HWS will range from one to hundreds of gammas for small discrete targets, depending on their depth. Massive piles of buried drums will result in anomalies of from 100 to 1000 gammas or more.

---

* The unit of magnetic measurement is the gamma. Recently, the gamma unit has been renamed the Nano Tesla. At this time, most instruments are still labeled in gammas as are specification sheets, existing literature and field data; hence, all references to magnetic data in this document are expressed in gammas.

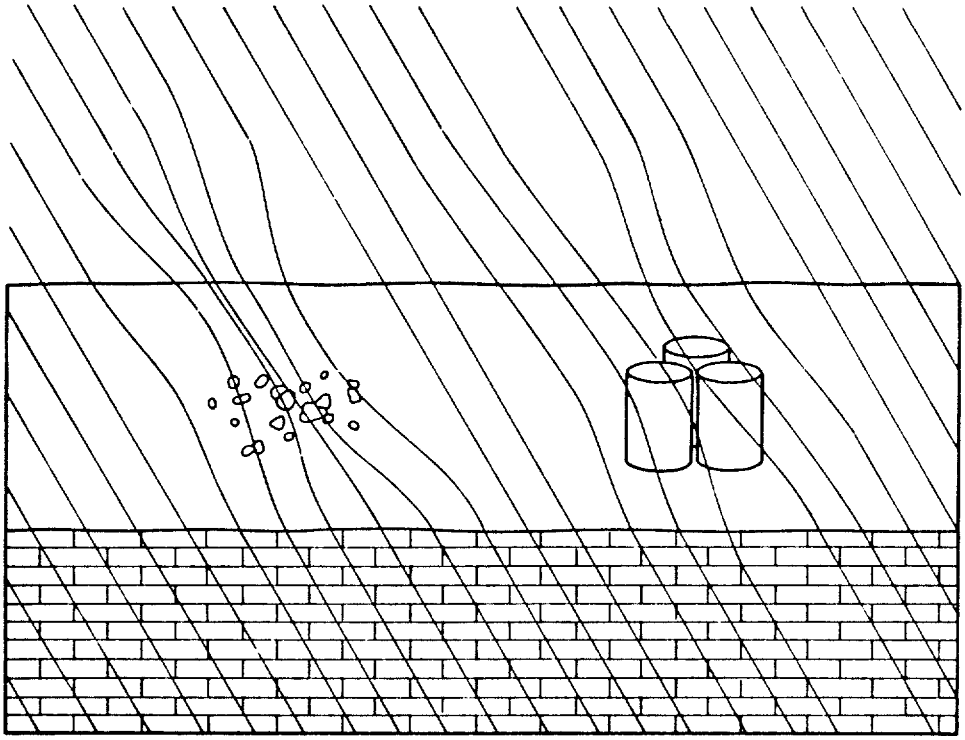


Figure 92. Distortions in the earth's magnetic field due to concentrations in natural soil iron oxides (left) and buried iron debris (right).

There is a wide variety of magnetometers available commercially; two basic types commonly used at HWS are the fluxgate and the proton magnetometer. Typical equipment is shown in Figures 94 through 97. A simplified block diagram of a magnetometer is shown in Figure 98. In a fluxgate magnetometer, the sensor is an iron core which undergoes changes in magnetic saturation level in response to variations in the earth's magnetic field; differences in saturation are proportional to variations in field strength. The electronic signals produced by these variations are amplified, then fed to an amplifier, whose output drives a meter or a recorder.

The signal output of a single element fluxgate magnetometer is extremely sensitive to orientation. To overcome this problem, two fluxgate elements can be rigidly mounted together to form a gradiometer. This gradiometer measures the gradient of a directional component of the earth's magnetic

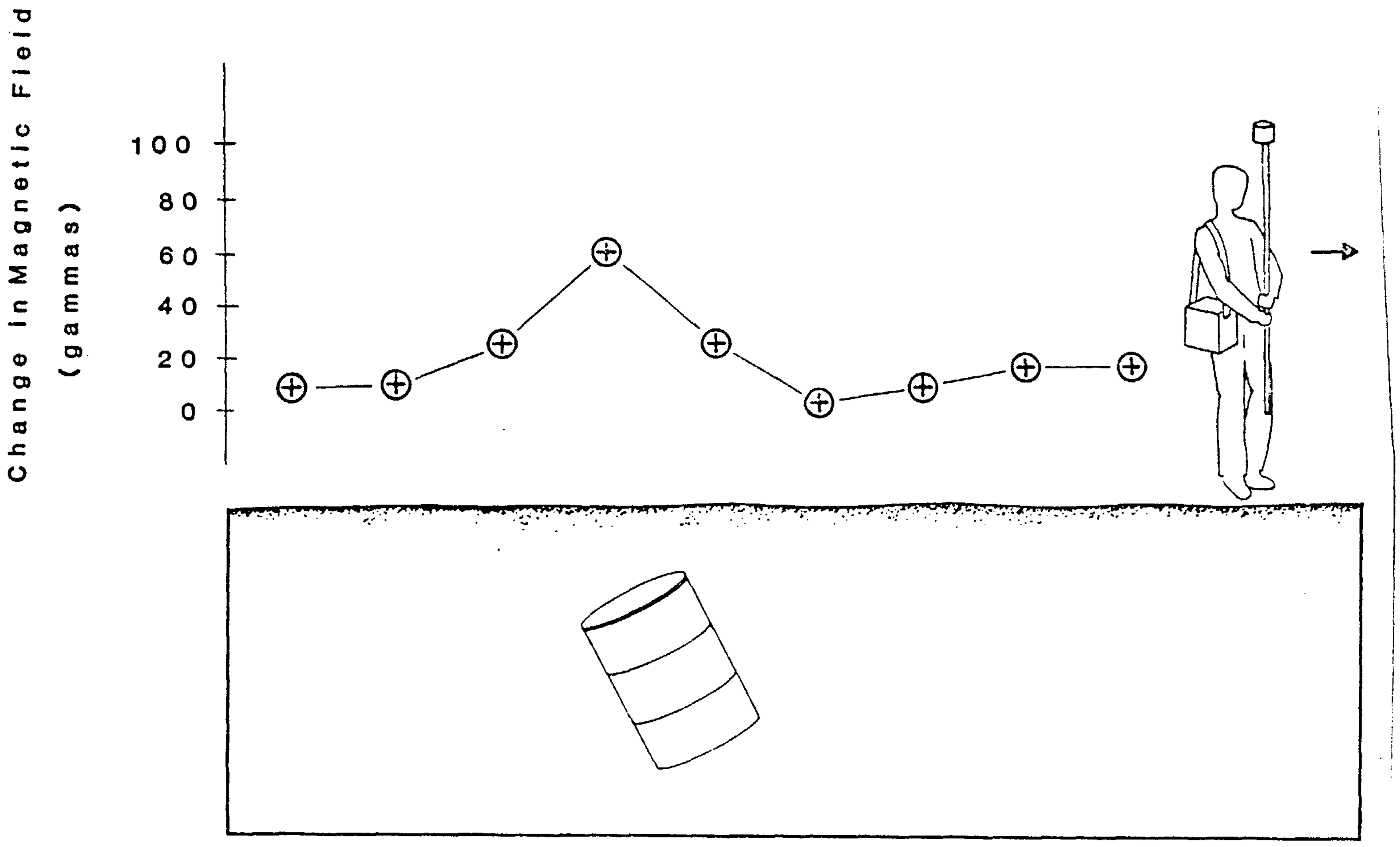


Figure 93. Station measurements of a magnetic anomaly caused by a buried steel drim.

field. The gradiometer configuration of the fluxgate magnetometer, one which measures the vertical component of the field, is the instrument that is discussed in this document (see Figures 95, 96, and 97).

In a proton magnetometer, an excitation voltage is applied to a coil around a bottle containing a fluid such as kerosene. The field produced reorients the protons in the fluid; when the excitation voltage is removed, the spinning protons reorient to line up with the earth's magnetic field. By nuclear precession they generate a signal, the frequency of which is proportional to the strength of the field. The signal is amplified and the precession frequency measured by the use of counter circuits. The frequency is electronically translated into gammas and the output is fed to a digital display, a digital memory, or a strip chart recorder. Proton magnetometers measure the earth's total field intensity, and they are not sensitive to orientation. However, the proton magnetometer will cease to function when it is used in areas with very high magnetic gradients (above 5,000 gammas/meter) which may be found in junk yards or near steel bridges, buildings, vehicles, etc.

Portable cesium magnetometers may have application to HWS investigations as recognized by the authors, but at the time of this writing they are unaware of any such successful application and have not included them.

All types of magnetometers can be used for taking station measurements in the manner shown in Figures 93 and 94. The operator stops, takes a reading, records it, and moves on to the next station. A great many of these station measurements are required to cover an area. Recent improvements in portable proton magnetometers have incorporated a built-in microprocessor, so that the variables of time, station number, location, and magnetic intensity can all be recorded in memory for later playback into a printer or a portable computer for processing. This new system enables station measurements to be made more rapidly. However, the minimum sample time for these ground-portable proton magnetometers still ranges between 2 and 4 seconds. Because it requires many station measurements to cover a site adequately, the station-by-station approach is not often used at HWS.

An alternative to the station measurement method is to use a continuous measurement magnetometer system, as shown in Figures 95, 96, and 97. These units provide continuous measurement of the gradient of the magnetic field as the operator moves along a traverse line, and they provide considerably more detail than can be obtained by station measurements. By proper selection of the spacing between survey lines, total site coverage may be obtained at reasonable cost.

Figure 94. High sensitivity (0.1 gamma) total, field proton magnetometer being used for station measurements. (Photo courtesy Geometric.)

Figure 95. Fluxgate gradiometer. A continuous-sensing low sensitivity 20 gammas/meter magnetometer for shallow search.

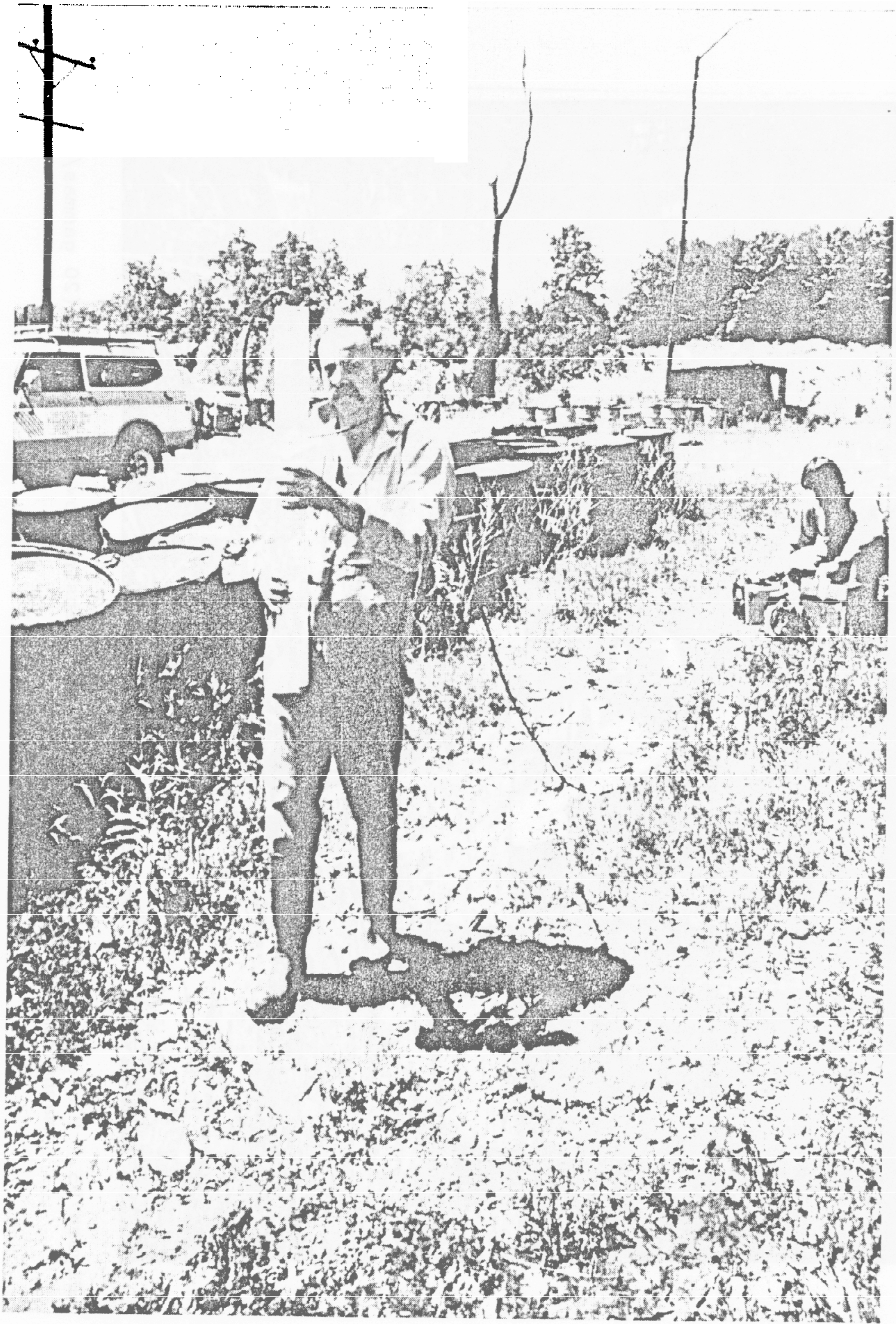


Figure 96. Fluxgate gradiometer: a continuous -sensing high sensitivity (1 9amma/meter) magnetometer (Valley of the Drums, Kentucky).

Figure 97. Fluxgate gradiometer. A vehicle-mounted continuous-sensing high sensitivity (1 gamma/meter) magnetometer (Love Canal, New York).

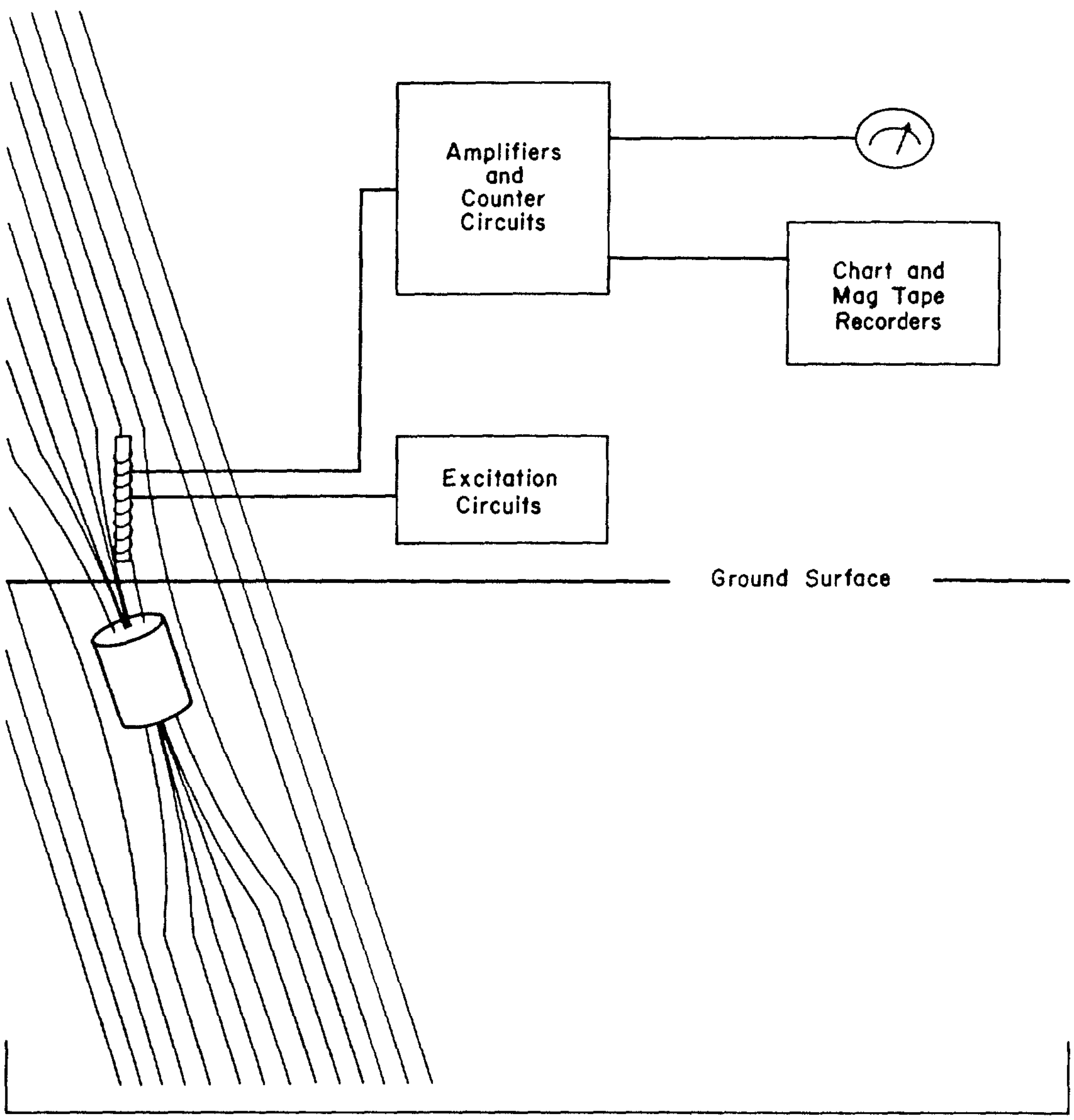


Figure 98. Simplified block diagram of a magnetometer. A magnetometer senses change in the earth's magnetic field due to buried iron drum.

Two types of magnetic measurements may be made. A total field measurement is made with a proton magnetometer by observing the value of the magnetic field at a selected point (Figure 99a). A gradient measurement is the difference between measurements taken at two different points (Figure 99b).

Figures 99b and 99c show two methods of taking a gradient measurement. A total field proton magnetometer can be used to take two total field readings: the difference between them is the gradient of the total magnetic field (Figure 99b). The gradiometer is a magnetometer composed of two separate sensors, either fluxgate or proton. Both sensors respond to the total field at their respective locations; the difference between them is obtained electronically to provide a gradient reading. Although the gradient may be measured in any direction, it is commonly the vertical gradient that has been measured at HWS, as shown in Figure 99c. For purposes of this document, total field measurements will imply measurement using a proton magnetometer, while gradient measurements will be accomplished by either proton or fluxgate systems.

Several factors influence the response of a magnetometer. The mass of a buried target is one factor; it will affect the magnetometer's response in direct proportion to the amount of ferrous metal present. The depth of the target is an even more significant factor, as response varies by one over the distance cubed ($1/d^3$) for total field measurements; this means that the response will decrease by a factor of 8 if the distance between the target and the magnetometer is doubled. If a gradiometer is used, the response falls off even faster, at the rate of one over the distance to the fourth power ($1/d^4$). If sensors of identical sensitivity are used, the total field system provides the greater working range.

Another factor which will influence the response of a magnetometer is the permanent magnetism of the target. Ferrous objects will have two superimposed magnetic values; one due to induced magnetism and one due to permanent magnetism. The permanent magnetism of an object is like that of a bar magnet. Its value may be many times that of the induced magnetism, which may add to or reduce the resulting anomaly. As a result, the value of a magnetic anomaly may vary over a wide range, making the quantitative analysis of magnetic data difficult.

In addition, the target's shape and orientation together with its state of deterioration also affect the magnetometer's response. (See corrosion rates for drums, in Section VIII.)

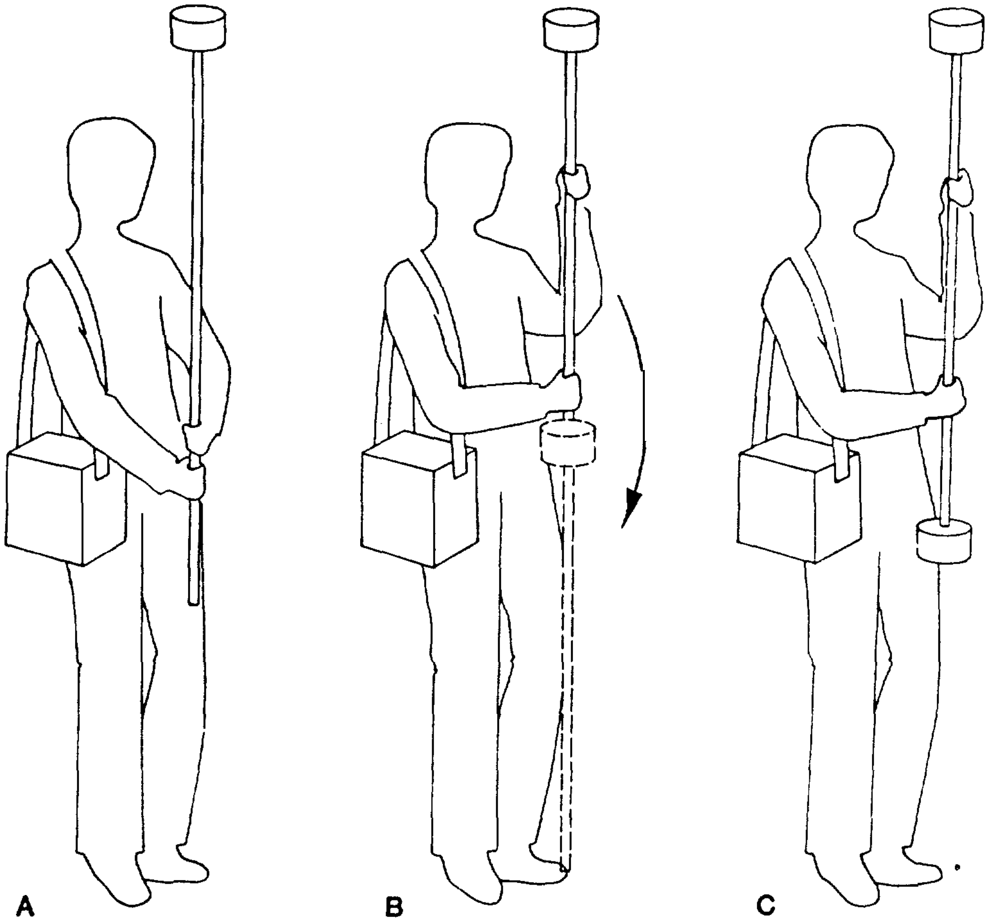


Figure 99. Comparison of total field and gradient measurements.
A. Total field measurement.
B. Gradient measurement consisting of 2 total field measurement
C. Gradient measurement made with 2 sensors simultaneously.

Some magnetometer characteristics are summarized in Table 4. The maximum sensitivities (0.1 gamma for total field measurements, and 0.05 gamma/meter for gradient measurements) shown in the table are rarely required at HWS. In fact, excessive sensitivity can be a severe handicap and may even inhibit acquisition of usable field data if the instrumentation does not have available the necessary useful dynamic range.

Factors To Be Considered For Field Use

Project objectives, site conditions, equipment and field procedures will all influence the technical results and the cost of a search and location mission. Some aspects of the project which should be considered are: site access, level of search (reconnaissance or detail), estimate of mass or quantity of targets, maximum depth of search, and safety requirements. Equipment features, including sensitivity, susceptibility to noise, capability for recording, total field or gradient measurement, continuous or station measurement, recording capability, and hand or vehicle mode of operation must be matched to the job.

Although a reconnaissance investigation provides less than total site coverage, it is often more than adequate to provide a sampling of site conditions. Detailed surveys with a high density of survey lines provide a greater degree of spatial resoluton. The level of site coverage may be increased by degrees until total site coverage has been obtained. The use of a continuous gradient magnetometer is preferred, as it will provide the highest level of lateral resolution and will minimize unwanted responses so that anomalies may be more easily detected.

If a high-resolution survey is required over a large area, the benefits of using continuous sensors (Figures 95 & 96) and vehicle-mounted systems (Figure 97) are self-evident.

The most difficult magnetometer survey task will be to quantify the depth and number of 55-gallon drums or other ferrous targets. Theoretically, the total number of drums may be calculated from the amplitude of the magnetic anomaly (Figure 100), and their location and depth may be obtained from the shape and width of the anomaly (Figure 101). However, because of the number of variables associated with target, site conditions, and calculations, such results should be considered only approximations. Actual results may vary by a factor of 2 to 10. Factors such as the target’s magnetic properties, its geometry, orientation, deterioration, and permanent magnetism are not considered in the nomograph of Figure 100. Furthermore, Figures 100 and 101 address only discrete targets such as single 55-gallon drums; the effects of large numbers of randomly distributed drums are not considered. Because of these many variables, high levels of accuracy should not be expected in evaluations of the depth and quantity of drums. To be realistic, quantities and depths should be stated in terms of a range of values.

TABLE 4. SUMMARY OF MAGNETOMETER CHARACTERISTICS

	TOTAL FIELD MEASUREMENTS Most Sensitive Susceptible to Noise		GRADIENT MEASUREMENTS Less Sensitive Insensitive to Noise Improved Location		
	Station	Continuous	Station	Continuous	Typical Sensitivity
FLUXGATE	NA	NA	YES	YES[1]	0.1 gammas/meter to 20 gammas/meter gradient
PROTON	YES[1]	NO[2]	YES	NO	.1 gammas total field .1 gammas/meter gradient

NA - Not applicable
1 - Commonly used mode of operation
2 - Maximum sample time for portable proton ground magnetometers presently range from 2 to 4 seconds.

The magnetometer shown in Figure 95 is extremely insensitive to nearby fences, cars or buildings; it can provide an effective reconnaissance survey for shallow 55-gallon drums, but would be ineffective for deeply buried drums. In the latter case, a magnetometer with greater sensitivity should be selected (Figures 94 or 96). However, using an instrument with greater sensitivity than necessary can lead to excessive noise in the data, which, in turn, will make analysis difficult.

If a magnetometer sensor is carried too close to the ground, it becomes susceptible to noise produced by variations in the magnetic characteristics of the soil. Raising the sensor 3 to 6 feet off the ground can reduce or eliminate this noise (Figures 94 & 96), but at the same time it may appreciably reduce the target signal. Therefore, to minimize noise, a proper balance must be struck between instrument sensitivity and operating height.

Quality Control

The precision (repeatability) of a magnetometer survey may not be a matter for concern if the survey is conducted over a short period of time and the results are not to be compared with subsequent surveys. Errors may be present due to changes in the earth’s field ocurring over the day of measurement or during the time interval between surveys.

Total field measurements may be corrected for these time variations by employing a reference base station magnetometer; changes in the earth’s field are removed by subtracting fixed base station readings from the moving survey data. Gradiometers do not require the use of a base station, as they inherently eliminate time variations in the data.

Accuracy: If semi-quantitative or quantitative results are not needed in a survey (such as when merely locating an object or defining trench boundaries), accuracy is of little concern. However, if estimates of the depth and number of drums are to be made, instrument calibration is very important. Quantitative analysis requires that field data be fitted to a model for interpretation; therefore, the values of the magnetic anomalies must be sufficiently accurate to do so.

Proton magnetometer sensors are inherently calibrated, as their operation is based on nuclear precession; only their crystal-controlled counters may require occasional factory calibration. On the other hand, fluxgate magnetometers are not calibrated; they will require calibration if accurate results are to be obtained. (A laboratory calibration of any magnetometer can be accomplished by using a standard magnetic field created by a set of coils carrying a known current.) However, a much more practical approach is a reference magnet,

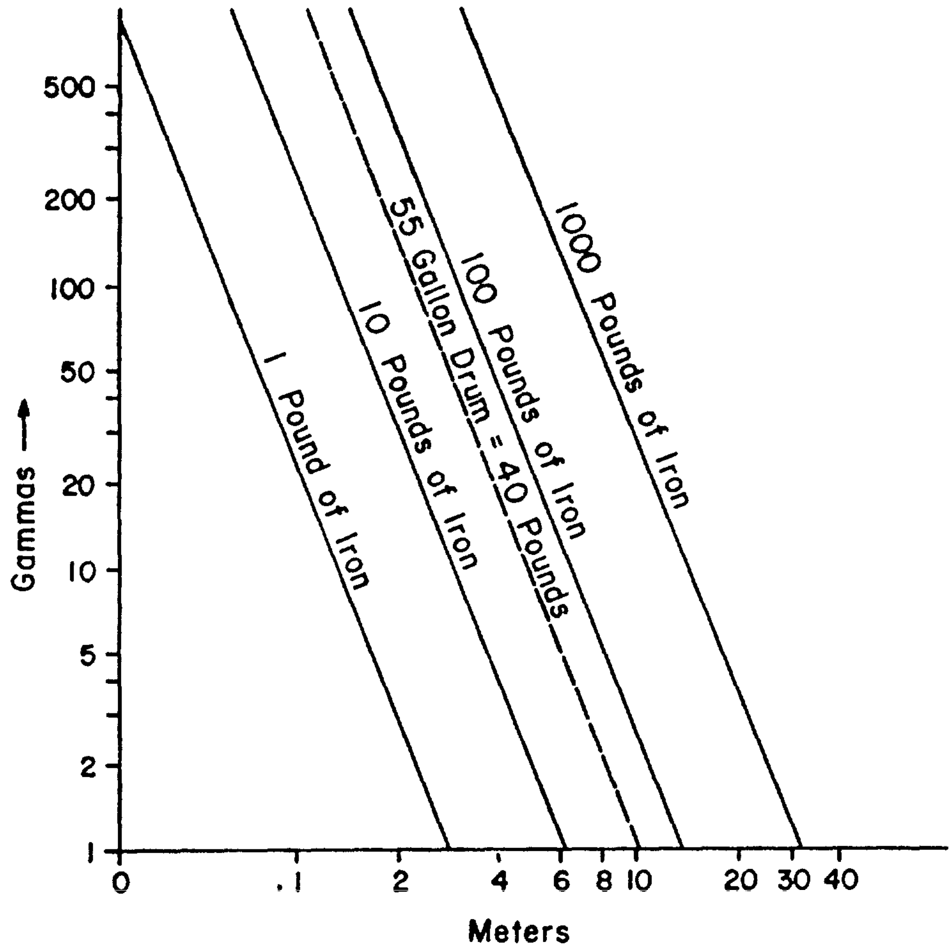


Figure 100. Total field magnetometer response (in gammas) for different target distance and mass. Due to the many uncertainties associated with magnetic anomalies, the estimates shown in this graph may vary up to an order of magnitude. (Modified from S. Breiner).

which is an invaluable aid in the field. It provides a quick way to verify instrument operation and to perform an in-field calibration. This reference magnet will itself require calibration to absolute standards at periodic intervals.

Noise

Noise is any unwanted signal or response, and a large signal-to-noise ratio is desirable. Noise may be caused by time variations such as the natural changes in the earth's field and by spatial variations. Spatial noise may be associated with changes in local soil conditions or produced by passing over ferrous debris.

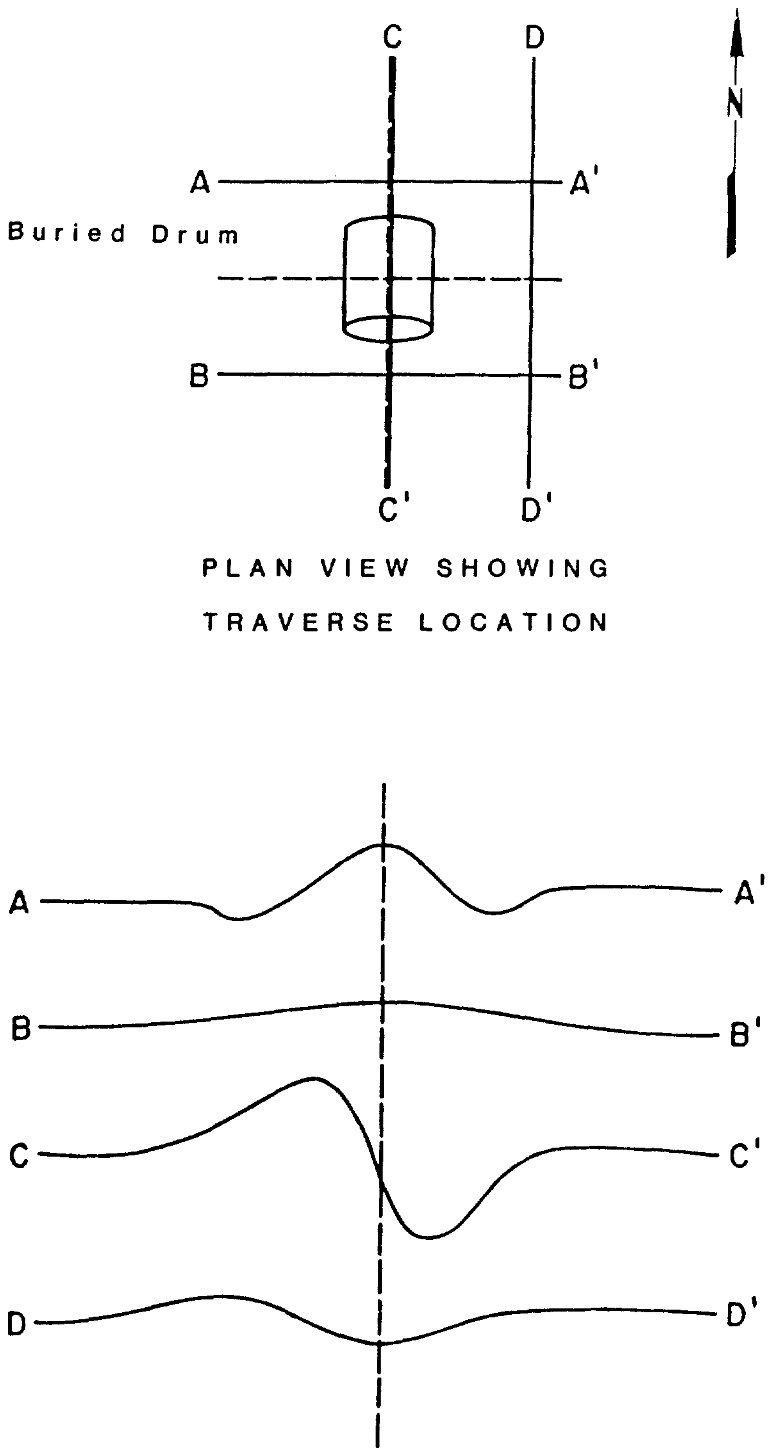


Figure 101. Magnetometer response will vary considerably depending upon traverse location and direction with respect to the target.

The effects of time changes in the earth's field can be eliminated from total field measurements by using a second magnetometer as a base station. The time changes sensed by the fixed base station are removed from the values obtained by the roving search magnetometer. The result of this process is a series of measurements showing only the spatial changes in the magnetic field. (A gradiometer accomplishes this process automatically.)

By lifting the sensor up off the ground and carrying it at some distance above the surface, as shown in Figures 94 and 96, the noise due to natural soil and rock variations and small particles of metal debris can be minimized. At the same time, the increased target-to-sensor distance will not appreciably reduce the instrument's response if the target, for instance, is a massive pile of 55-gallon drums. However, if the target is only one steel drum, the sensor's response may fall off dramatically as a result of its increased distance from the target. In this case, the advantage of reducing noise must be weighed against the accompanying disadvantage of decreasing the instrument's sensitivity.

Cultural features can cause large unwanted anomalies in magnetic data. For example, a buried pipe may be the cause of a large magnetic anomaly, but it can often be identified as such and be separated from other targets. However, if a single 55-gallon drum is buried next to a large iron pipe, the drum probably will not be identified as a separate target and could remain undetected.

Noise interference from personal effects and clothing may also be a problem. The solution is to eliminate all ferrous material from the operator's person. Steel-toed boots and some respirators are sources of noise, but they may be required safety measures at certain locations. Noise from this equipment must be minimized by keeping the sensor as far from the operator as possible.

If the magnetometer is mounted on a vehicle, the sensor must be as far from the vehicle as possible, and/or it must be compensated for the presence of the vehicle. Some influence can always be expected from the vehicle; to minimize its effects, survey lines should be straight, and they all should run in the same direction to eliminate the directional effects of the vehicle and provide for simple visual analysis of the field records.

Data Format, Processing, Interpretation and Presentation

A magnetometer's output will depend upon the instrument used. Audio signals, analog meters, digital numeric displays and recorders, and strip chart recorders are all commonly used.

Proton magnetometers provide a numerical value which can be recorded in a field notebook or directly on a map. Newer equipment has an internal memory which stores field data. This data may be retrieved as a printed tabulation or plot, or fed directly to a computer for processing and plotting. Raw values may be plotted directly on a map or profile line to provide in-field quality control and initial interpretation. Final presentation of data is typically limited to profile lines locating anomalies or contour maps showing the location of buried. material.

The simple hand-held magnetometer shown in Figure 95 provides only an audio signal to the operator. This type of instrument has a continuous response and can he swept from side to side across a traverse line. The audio response indicates the presence of a target, which can be marked with a non-ferrous stake as the survey progresses. Locations of anomalies may be recorded in field notes, but no output from the magnetometer is recorded or noted directly.

The location of an anomaly can be determined in this manner with reasonable accuracy. However, the angle of the earth's field must be considered, as the target may be offset, not necessarily lying under the largest portion of the anomaly (Figure 102). Further, the shape of a magnetic anomaly can be complex, and in the vicinity of the target, it may vary from one traverse to another (Figure 101).

A magnetometer with continuous recording capabilities can be used to produce a strip chart or a digital record of the field data. Such magnetometers provide the field party with a graphic profile of the data and assist in assessing signal-to-noise ratio, anomaly shape, and target location; such records, thereby, provide a means of exercising quality control over field data. The raw records can be used in the field to locate buried drums, to define boundary limits, and to provide estimates of the depth and mass of targets. The same records may be replotted into final profile lines with corrections for instrument range changes and spatial position variations.

A number of processing options may be carried out on magnetic data. They include:

- Corrections for instrument drift;
- Corrections for changes in the earth's field;
- Filtering to remove noise;

- Enhancement or removal of surface targets, or deeper targets as required.

Data can be interpreted quantitatively to provide anomaly locations along a profile line or burial areas on a map. Semi-quantitative data for depth and mass (number of drums) can be obtained by the use of a model (see Figure 100) and calibrated instruments. However, error factors of 2 to 10 may occur in such calculations.

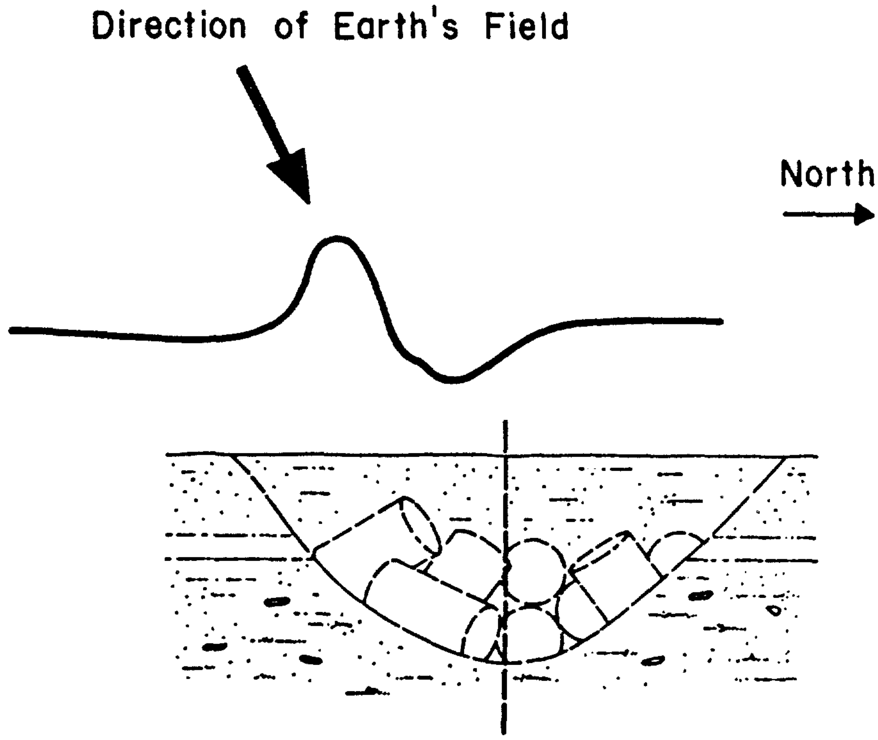


Figure 102. Diagram of magnetic anomaly over burial trench. Note that the peak anomaly may not necessarily lie over the center of the trench due to the angle of the earth's field.

Raw magnetic data, such as a strip chart record of a profile line, may be sufficient for final presentation (Figure 103) Simple maps may be drawn to show the concentrations of suspected buried drums (Figure 104). If 'high resolution data is available, a map can be contoured to provide more detailed information. A graphic presentation may be made by compiling parallel profile lines into a three-dimensional image of the magnetic data (Figure 105).

Summary

A magnetometer responds to the presence of buried ferrous metals. At HWS, magnetometers may be used to:

- Locate buried 55-gallon drums;
- Define boundaries of trenches filled with ferrous containers;
- Locate ferrous underground utilities, such as iron pipes or tanks, and the permeable pathways often associated with them;
- Aid in selecting drilling locations that are clear of buried drums, underground utilities, and other obstructions.

While several factors influence the response of a magnetometer, the mass of a buried target and its depth are the most important. A magnetometer’s response is directly proportional to the mass of ferrus metal present and varies by one over the distance cubed ($1/d^3$) for total field measurements. If a gradiometer is used, the response falls off even faster, as one over the distance to the fourth power ($1/d^4$). With sensors of equal sensitivity, the total field system provides the greater working range. Typically, a single drum can be detected at distances up to 6 meters, while massive piles of drums can be detected at distances up to 20 meters or more. There is a wide variety of magnetometers available commercially; specific performance is highly dependent upon the type of magnetometer and the field conditions. While the number of drums may be calculated, such results should be considered only approximations because of the number of variables associated with targets, site conditions and calculations. Actual results may vary considerably.

A magnetometer with continuous recording capabilities can be used to produce a strip chart of the field data, which is helpful in assessing signal-to-noise ratio, anomaly shape, and target location, and provides a means of exercising quality control over field data. This continuous coverage is much more suitable for high-resolution requirements and the mapping of extensive areas.

The effectiveness of a magnetometer can be reduced or totally inhibited by noise or interference from time-variable changes in the earth’s field and spatial variations caused by magnetic minerals in the soil, or iron and steel debris, ferrous pipes, fences, buildings, and vehicles. Many of these problems can be avoided by careful selection of instruments and field techniques.

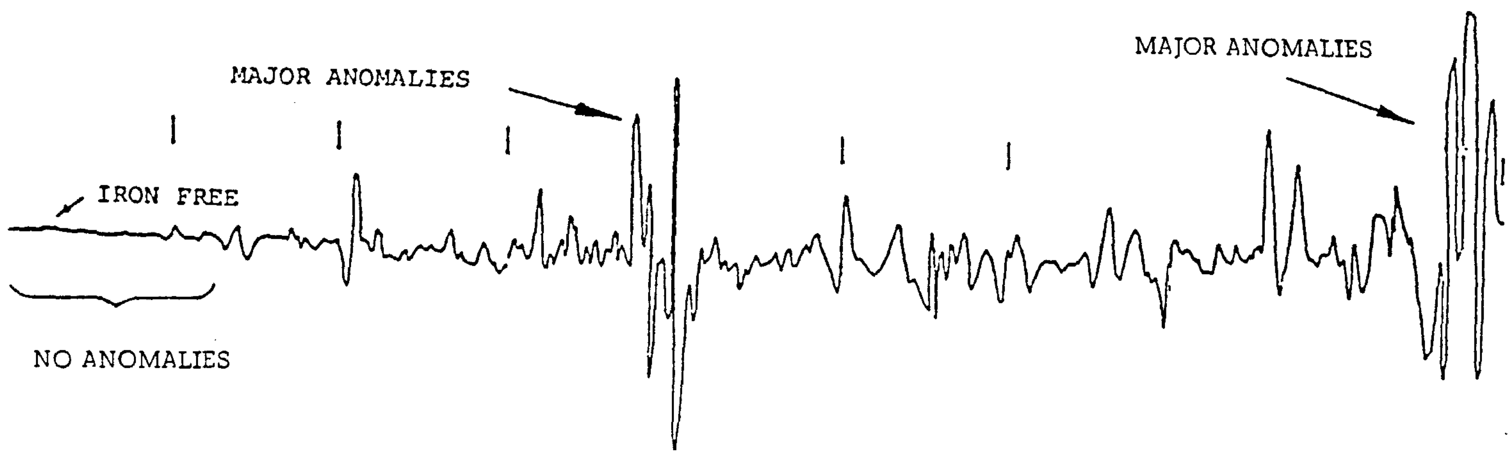


Figure 103. A single magnetic profile line showing a wide range of magnetic anomalies.

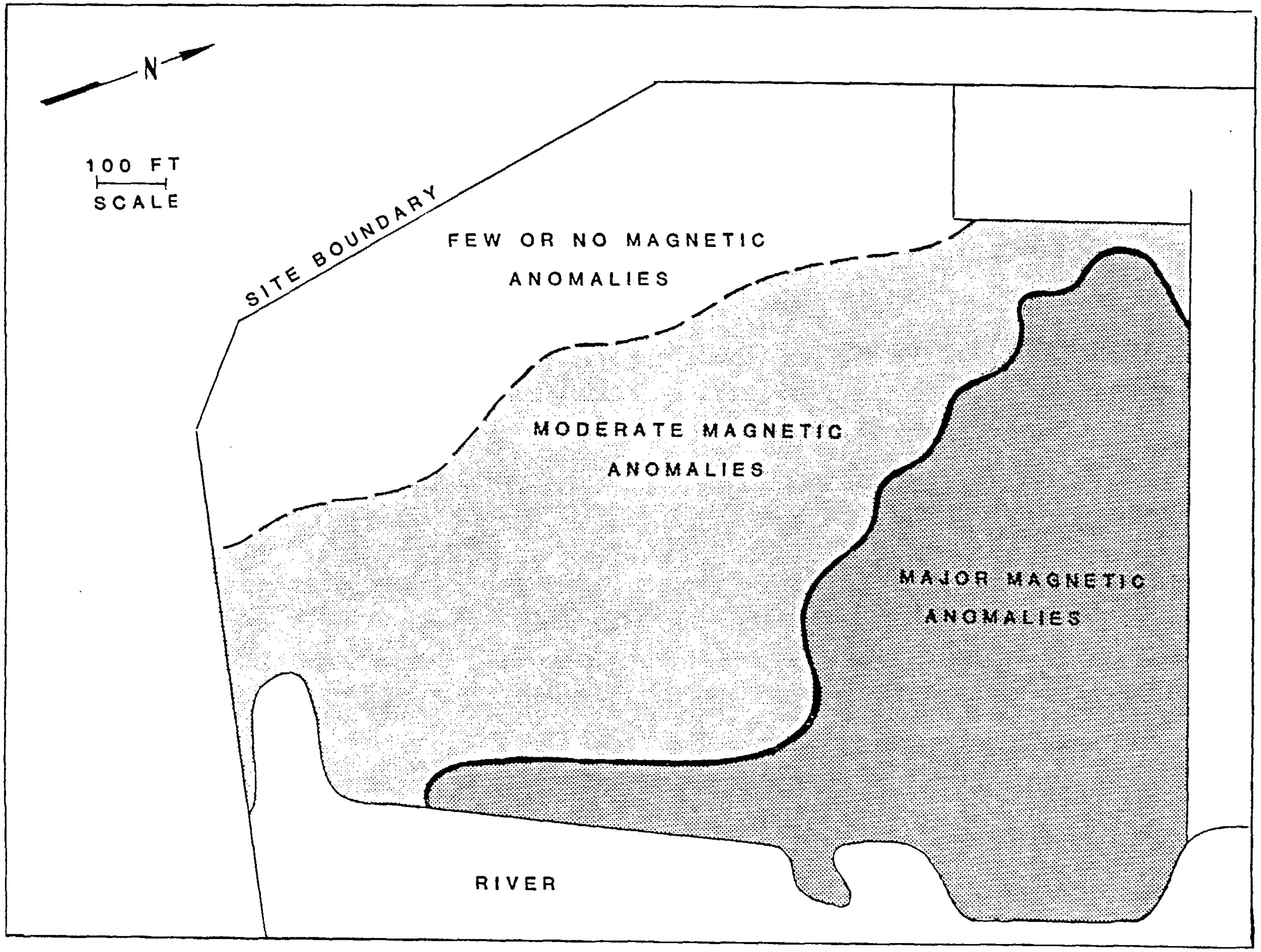


Figure 104. Simple contour map of magnetic anomalies shows relative concentration of buried drums (buried 55-gallon drums are inferred).

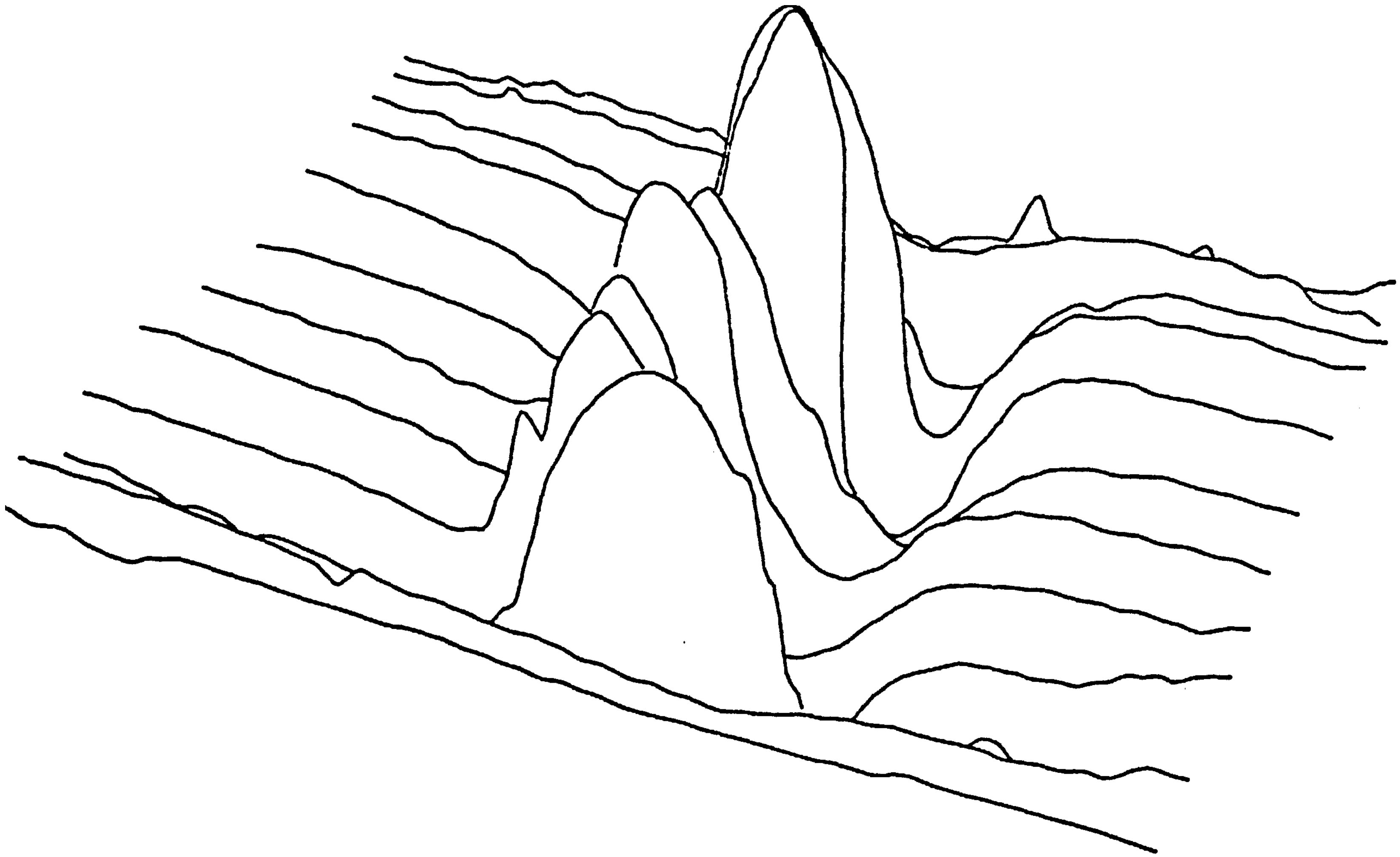


Figure 105. Three-dimensional perspective view of magnetic profiles over a trench containing buried drums.

Capabilities

- Magnetometers respond to ferrous metals (iron or steel.) only.
- Individual drums can be detected at depths up to 6 meters.
- Large masses of drums can be detected at depths of 6 to 20 meters.
- Magnetometers can provide a greater depth range than metal detectors.
- Interpretations of their data may he used to provide estimates of the number and depth of buried drums.
- They can provide a continuous response along a traverse line.
- They may be mounted on vehicles for coverge of a large site.

Limitations

- In general, magnetometers are susceptible to noise from many different sources, including steel fences, vehicles, buildings, iron debris, natural soil minerals and underground utilities.
- Low cost units are limited in depth range (but their limitations make them insensitive to many of the above sources of noise).
- Total field instruments are also sensitive to fluctuations in the earth's magnetic field which can seriously affect data.
- Data is of limited use in determining the number and depth of targets.
- Complex site conditions may require the use of highly skilled operators, special equipment, and the recording and processing of data, along with skilled interpretation.

Examples

Determination of Drum Distribution--

An old covered dump in a marshy area was suspected of containing drums of hazardous waste. Location of the areas containing major concentrations of drums was necessary in order to undertake a ground water sampling program. The area (300 x 400 meters) was surveyed, using a continuously-recordi.ng gradiometer. Approximately 70 lines spaced 10 meters apart were used to cover the site. The lo-meter spacing was selected because only large groups of drums were of interest.

Magnetic data from a typical profile line is shown in Figure 103. Note the many strong magnetic anomalies on the right portion of the line, indicating the presence of numerous ferrous targets in this area. The anomaly-free area to the extreme left shows that little or no dumping had taken place there.

Analysis of the remaining magnetic profiles yielded. the magnetic anomaly contour map shown in Figure 104. The subsequent ground water sampling program was designed using this information.

Note that in such a survey the presence of drums is inferred, not determined conclusively, from the magnetic data alone. However, drums were observed on the surface and had been encountered in limited subsurface sampling therefore the overall map is a good indicator of drum distribution.

Burial Trench Location--

Officials suspected that hundreds of drums containing a highly toxic substance had been dumped into a burial trench in a rural area. A chain link fence, 30 meters by 30 meters, was erected around the site. Estimates concerning trench location and the depth and quantity of drums were needed for a sampling program and to make recommendations for remedial. action.

Multiple parallel passes were made perpendicular to the suspected trench using a continuous gradiometer magnetometer. The end survey lines were within 3 meters of the steel chain link fence, a situation which affected the magnetometer data. The resulting profiles, shown in Figure 105, were spatially-corrected for variations in walking speed along the traverse, amplitude corrected for the effects of the chain-link fence, and plotted by computer. These results confirmed suspicions that the trench was totally filled with steel drums; the data was instrumental in determining trench boundaries and estimating the quantity of drums.

SECTION X

APPLICATIONS

Summary of the Six Geophysical Methods

This section presents a summary of the six geophysical methods discussed in this document. The following tables highlight features of each method and are intended as general guidelines to provide the reader with a capsule summary of the capabilities and limitations of the six methods, including factors which may affect their measurements. These tables are based on extensive field experience, and they present data which will be applicable in most cases. However, the reader should use them as guidelines, recognizing that exceptions may occur because of the wide range of site conditions and project objectives.

Table 5 - summarizes the primary technical characteristics of the six methods, including: mode of measurement, depth of penetration, relative resolution, and data format.

Table 6 - outlines primary (more suitable or more commonly used) and secondary (less commonly used or less effective) applications of each method.

Table 7 - lists sources of noise which may affect the performance and utilization of each method.

No single method, whether traditional direct sampling or one of the contemporary geophysical techniques, will solve all site investigation problems. All the methods discussed are founded on sound scientific principles and can be extremely effective in the field; but any of them may fail, when improperly applied or when applied to the wrong objective. The methods and approach discussed in this document have been successfully applied to a number of site investigation problems as outlined in Table 6. A large number of sites have been evaluated throughout the United States with a diverse set of both hazardous waste and geohydrologic conditions. In addition, the approach has been used repeatedly in evaluation of new disposal sites, and to evaluate conditions after clean up or remedial action has occurred. By selecting the most suitable methods, combining methods, and utilizing the synergistic benefits of an integrated

TABLE 5 CHARACTERISTICS OF THE SIX GEOPHYSICAL METHODS

METHOD	RESPONDS TO CHANGE IN	MODE OF MEASUREMENT	DEPTH OF PENETRATION	RESOLUTION	RAW DATA FORMAT
1. Ground Penetrating Radar (GPR)	Complex Dielectric Constant of soil, rock, pore fluids, and man-made objects	Continuous Profile .4 Km/hr. detail - 8 Km/hr. reconnaissance (Ground contact not necessary)	One to ten meters typical-highly site specific. Limited by fluids and soils with high electrical conductivity and by fine grain materials.	Greatest of all six geophysical methods	Picture-like graphic display. Analog tape Digital tape
2. Electromagnetics (EM)	Bulk electric conductivity of soil, rock and pore fluids (Pore fluids tend to dominate)	Continuous Profiles to .5 to 15 meters depth. Station measurements to 15 to 60 meters depth. Some sounding capability (Ground contact not necessary)	Depth controlled by system coil spacing .5 to 60 meters typical	Excellent lateral lution. Verticle resolution of 2 layers. Thin layers may not be detected.	Numerical values of conductivity from station measurements. Stripchart and/or magnetic recorded data yields continuous profiling.
3. Resistivity Sounding (RES)	Bulk Electrical resistivity of soil, rock and pore fluids (Pore fluids tend to dominate)	Station Measurements for profiling or sounding (Must have ground contact)	Depth controlled by electrode spacing.[1] Limited by space available for array. Instrument power and sensitivity become important at greater depth.	Good vertical resolution of 3 to 4 layers. Thin layers may not be detected.	Numeric values of voltage, current and dimensions of array. Can plot profile or sounding curves from raw data.
4. Seismic Refraction	Seismic velocity of soil or rock which is related to density and elastic properties.	Station Measurements (Must have ground contact)	Depth limited by array[1] length and energy source.	Good vertical resolution of 3 to 4 layers. Seismic velocity must increase with depth - thin layers may not be detected.	Numeric values of time and distance. Can plot T/D graph from raw data.
5. Metal Detector (MD)	Electrical conductivity of ferrous and non-ferrous metals	Continuous (Ground contact not necessary)	Single 55 gal. drum up to[2] 3 meters Massive piles 55 gal. drums up to 6 meters	Very good ability to locate targets	Relative response from audio/visual indicators (may record data)
6. Magnetometer (MAG)	Magnetic susceptibility of ferrous metals	Continuous Total Field or gradient measurements. Many instruments are limited to station measurements. (Ground contact not necessary)	Single 55 gal. drum up to[2] 6 meters Massive piles 55 gal. drums up to 20 meters	Good ability to locate targets	Non-quantitative response from audio/visual indicators. Quantitative instruments provide meter or digital display (may record data)

1. Depth is also related to equipment capability.

2. Depth is very dependent upon instrument used.

TABLE 6 TYPICAL APPLICATIONS OF THE SIX GEOPHYSICAL METHODS

Application	Radar	EM	Res	Seismic	MD	MAG
NATURAL CONDITIONS -						
Layer thickness and depth of soil and rock	1	2	1	1	NA	NA **
Mapping lateral anomaly locations	1	1	1	1	NA	NA **
Determining vertical anomaly depths	1	2	1	1	NA	NA
Very high resolution of lateral or vertical anomalous conditions	1	1	2	2	NA	NA
Depth to Water table	2	2	1	1	NA	NA
SUB-SURFACE CONTAMINATION LEACHATES/PLUMES -						
Existence of contaminant (Reconnaissance Surveys)	2 *	1	1	NA	NA	NA
Mapping contaminant boundaries	2 *	1	1	NA	NA	NA
Determining Vertical extent of contaminant	2 *	2	1	NA	NA	NA
Quantify magnitude of contaminants	NA	1	1	NA	NA	NA
Determine flow direction	2 *	1	1	NA	NA	NA
Flow rate using 2 measurements at different times	NA	1	1	NA	NA	NA
Detection of organics floating on water table	2 *	2*	2*	NA	NA	NA
Detection & Mapping of contaminants within unsaturated zone	2	1	1	NA	NA	NA
LOCATION AND BOUNDARIES OF BURIED WASTES -						
Bulk Wastes	1	1	1	2	NA	NA
Non-Metallic containers	1	1	1	2	NA	NA
Metallic Containers						
- Ferrous	2	1	NA	NA	1	1
- Non-ferrous	2	1	NA	NA	1	NA
Depth of burial	2	2	1	2	2*	2*
UTILITIES -						
Location of pipes, cables, tanks	1	1	NA	2	1	1
Identification of permeable pathways associated with loose fill in utility trenches	1	1	NA	2	1	1
Abandoned Well Casings	NA	NA	NA	NA	1	1
SAFETY -						
Pre-drilling site clearance to avoid drums, breaching trenches, etc.	1	1	2	NA	1	1

1 - Denotes primary use
2 - Denotes possible applications, secondary use; however, in some special cases 2 may be the only effective approach due to circumstances.
NA - Not applicable
* Limited applications
** Not applicable in the context used in this document.

TABLE 7. SUSCEPTIBILITY OF GEOPHYSICAL METHODS TO "NOISE"

This table shows the susceptibility of the geophysical methods to various forms of "noise" which may influence field operation, resulting data and subsequent interpretation.

SOURCE OF NOISE	RADAR	EM	RESISTIVITY	SEISMIC	MD	MAG
Buried Pipes	will detect, but may affect data	1 only if close to pipe	1 only if survey is parallel and close by	2 only if survey is directly over	1 any metal pipes	1 steel pipes only
Metal Fences	NA	1 only if close to fence	2 only if survey line is parallel & close to fence	NA	2 only if nearby	1 steel fences only
Overhead Wires (powerlines)	2 only if unshielded antennas are used	1	NA	NA	NA	2 some mags respond
Ground Vibrations	NA	NA	NA	1	NA	NA
Airborne Electro-magnetic Noise	NA	2	2	NA	2	1 to 2 (Earth's Field Changed)
Ground Currents and Voltage	NA	NA	2	NA	NA	NA
Trees	2 only if unshielded antennas are used	NA	NA	2 (Wind noise)	NA	NA
Metal from Buildings, Vehicles, etc.	2 only if nearby & unshielded antennas are used	2 only if nearby	2 only if nearby	NA	2 only if nearby	2 only if nearby
Small Metallic Debris on Surface or Near Surface (nails, wire coathangers)	2	NA	NA	NA	1	1 ferrous metal only
Large Metallic Debris on Surface or Near Surface (Drums, Drum Covers, etc.)	2	2	2	NA	1	1 ferrous metal only
Susceptible to noise from ground contact/ Electrode problems	2	NA	1	2	NA	NA

1 - Very Susceptible
2 - Minor Problem
NA - Not Applicable

systems approach, high levels of accuracy and cost-effectiveness can be achieved in subsurface investigations of HWS. The following discussion will illustrate some of the trade-offs or compromises that may be required in applying the methodology to HWS investigations.

Detecting and Mapping Conductive Plumes

Table 8 compares the capabilities and limitations of the EM and resistivity methods for detecting and mapping conductive plumes. Table 6 indicates that radar is a less effective or less commonly used means of measuring contaminant plumes. This does not mean that radar cannot be used to map the top of a shallow, electrically-conductive plume; it can. Most of the time, however, it will be more productive to use EM or resistivity for that purpose. Even so, if information concerning shallow soils/ cementation and other variables is considered to be an import-ant factor in assessing the migration of contaminants, the radar method might be used to complement EM or resistivity data.

Furthermore, both EM and resistivity may be rendered totally ineffective by noise from a variety of sources; for example, the presence of nearby railroad tracks or buried pipes may be found to make measurement impossible. In that case, the radar method might be used with great success, where the other methods had failed.

The final decision as to which method to use should be made only by those with a comprehensive understanding of the entire array of methodologies. In many cases the program should be designed to be flexible with respect to the decision-making process, so that a final determination can be made in the field, after conditions have been examined first–hand.

In weighing the use of resistivity versus EM on a particular project, it must be decided whether profiling or sounding data are needed, and how much of either will. he required to produce a statistically valid measurement. The required level of detail, quantification of results, and data format should be established before work is begun.

The resistivity and EM methods are compared in Table 8. Both resistivity and EM are capable of vertical sounding: however, the vertical resolution of the EM method is limited. The depth to which sounding data can be obtained with resistivity is virtually unlimited: depths of 100 meters or more are easily obtained. EM, however, is limited to approximately 60 meters depth, based upon the equipment discussed in this document. Therefore, the resistivity sounding technique is the preferred approach if detailed vertical information such as depth to

TABLE 8. COMPARISON OF RESISTIVITY AND ELECTROMAGNETIC METHODS

	RESISTIVITY	ELECTROMAGNETICS
Vertical Sounding Capability	Yes	Yes (limited number of depths available)
Depth of Sounding Measurement	Not Limited	60 meters maximum with equipment discussed
Profile Station Measurements	Yes	Yes - to 60 meters depth
Continuous Profile Measurement	No	Yes - to 15 meters depth and at speeds up to 8 Km/hr
Relative Lateral Resolution	Good in Profile Mode	Good in profile mode with station measurements. Excellent in continuous profile mode.
Relative Speed of Measurement	Good	Very Rapid
Total Site Coverage	Not Generally Economical	Feasible at reasonable cost
Susceptible to Noise and Buried Pipes/Cables	Yes	Yes (continuous measurement aid identification of pipes and cables)
Electrode Contact Problem	Yes	No (operates through dry sands, concrete blacktop, etc.)
Overall Length of Wenner Array or Coil Separation for given Sounding Depth	6 - 12 times Depth * of Interest	Less than 2 times depth of interest *
Length of Array or Coil separation for given profile	Typically 4.5 to 6 times depth* (Minimum of 3 times depth)	2/3 Depth *

* Comparison of depths of resistivity and EM measurements are only approximations because of differences in contributions from various depths inherent in each methods.

bedrock, depth to water table, or depth and thickness of the soil/rock layers is required; or when data deeper than 60 meters is required.

Although both resistivity and EM can be used for profiling work, EM is limited to about five discrete profiling depths to 60 meters. This limitation of EM is more than made up for by its capability for rapid measurements, and continuous profile measurements at up to 15 meter depths. Continuous profiling measurements have extremely high lateral resolution and can be run at speeds from 1.5 to 8 km per hour, depending on the detail required. The resistivity method is not capable of producing these continuous profiling measurements, due to the need to set electrodes in place to make contact with the ground.

Both resistivity and EM measurements can miss a subsurface feature or contaminant plume if the station or profile line is in the wrong location; however, with the capability of continuous EM profiling, a site can be covered by a number of lines with very close spacing, to approach total site coverage. While the high lateral resolution inherent in a continuous EM measurement can be approximated by a higher-density resistivity survey, cost and time considerations do not make this a very practical approach. EM measurements are preferred for profile work, particularly where continuous sampling can be employed.

Both resistivity and EM methods are susceptible to noise due to buried pipes, cables, fences and other metallic cultural features. They are also susceptible under some conditions to electromagnetic noise created by powerlines. Because the number of resistivity stations is usually less than is used for EM, it is difficult to assess if cultural noise is affecting a particular resistivity station measurement. This leaves a degree of uncertainty as to the validity of that data. When using EM many more stations are used or continuous data is acquired which aids in evaluation of noise interference. When noise can be recognized, it is often possible to remove it or take it into account in data interpretation.

The requirement of ground contact in the resistivity method creates additional problems not encountered with the EM method. Because electrodes must be driven into the ground, conducting a resistivity survey over a concrete or blacktop surface or hard soil can be a difficult task. If the surface material is resistive (dry sand), the electric current will be difficult to inject. Furthermore, the resistivity method is disproportionately affected by resistivity variations in the surface soils near the electrodes.

Another factor that influences the choice and applicability of the methods and their spatial resolution is the physical length of resisitivity arrays, or the EM coil separation, required to make a measurement to a given depth. The overall resistivity array length will typically be 6 to 12 times the depth of interest with a Wenner configuration. Information to a depth of 20 meters will, therefore, require an array of 120 to 240 meters in overall length. Finding accessible space on a site to place this long array may be difficult. Further, longer arrays are more likely to be influenced by noise factors and electrode contact problems. On the other hand, the overall length of the EM coil separation will be less than two times the depth of interest. Again, in the case of data to 20 meters depth, the EM coil spacing will be between 20 and 40 meters, as compared to 120 to 240 meters for resistivity.

Array length or coil spacing also determines the volume of subsurface that is sampled; the resistivity method integrates a larger volume than does the EM method. The EM method will, therefore, provide an improvement in lateral spatial resolution, as well as the capability to work in tighter quarters.

In summary, the resistivity method is the preferred tool for obtaining vertical sounding information; the EM method provides the better tool for profiling. If high-resolution to depths of no more than 15 meters is required, EM is, preferred over the resistivity method because of its continuous profiling capabilities.

Each technique is susceptible to noise from a variety of sources and there will be instances where one technique will fail to function at a site due to noise, while the other technique will function perfectly. For example, both methods have been used successfully under high-voltage transmission lines, and each method has at one time or another failed under such conditions. To be successful in carrying out a field investigation under such conditions requires that both resistivity and EM options be available to the field party.

Comparison of Methods to Detect Buried Metals

A comparison of metal detector and magnetometer techniques for use at hazardous waste sites is shown in Table 9. A metal detector will respond to both ferrous and non-ferrous metals, while a magnetometer will respond only to ferrous metals. Therefore, it is necessary to determine what metals may be present in order to select the proper instrument.

The metal detector is a continuous-sensing device and may be used on continuous traverse lines, or may be swept from side to

TABLE 9. COMPARISON OF METAL DETECTOR AND MAGNETOMETER METHODS

	METAL DETECTOR	MAGNETOMETER
Detects Ferrous Metals	Yes	Yes
Detects Non-ferrous Metals	Yes	No
Responds to	Surface area of target	Mass of target
Provides continuous coverage	Yes	Yes (some equipment limited to station measurement)
Define boundaries of buried materials (lateral resolution)	Very good	Good
Depth of detection	Relatively shallow Single Drum up to 3 meters Massive piles of drums up to 6 meters	Shallow to deep, depending upon sensitivity and configuration Single Drum up to 6 meters Massive piles of drums up to 20 meters
Noise problems	Susceptible to metallic pipes, fences, vehicles and surface trash, as well as some soil conditions	Susceptible to ferrous pipes, fences, vehicles and surface trash as well as some soil conditions
Ability to quantify data	Very limited capability	Limited estimates of depth and quantity

side to cover an area. Some magnetometers are also capable of this continuous coverage, while many commonly available magnetometers are limited to taking discrete station measurements. Recent improvements in magnetometers allow fairly rapid station measurements to be taken. However, for small, discrete, critical targets, continuous magnetometer coverage may be required to provide sufficient resolution and greater probability of detection.

Metal detectors have relatively shallow depth–sensing capability. A single 55-gallon steel drum may be detected at depths up to 3 meters, while massive piles of steel drums may be detected at depths up to 6 meters, depending upon equipment sensitivity. Magnetometers can sense a single steel drum to a depth up to 6 meters and a massive pile of steel drums to a depth up to 20 meters.

Metal detectors provide reasonably good spatial resolution to pinpoint the location of a target. Magnetometers, however, do not provide the same level of definition of target location because they are affected by the dip of the earth's magnetic field, and the shape of the magnetic anomaly is more complex.

Both metal detectors and magnetometers are highly susceptible to interference from nearby metallic cultural features such as pipes, fences, vehicles, metallic surface debris and even some soil conditions. Any of these factors can produce an erroneous response from the metal detector, a response which may be incorrectly interpreted as a subsurface target. Because metal detectors are relatively short-range devices, they can be operated closer to such sources of noise than can most magnetometers. Proton magnetometers are susceptible to interference from high magnetic gradients and nearby power lines, whereas fluxgate gradiometers do not suffer from these shortcomings.

The metal detector outputs are usually qualitative and, therefore, have limited capability to evaluate the size and depth of targets. Magnetometers, because their output can be calibrated and equations are available, can provide data for estimating the depth and number of drums. Due to the wide range of variables which may influence these instruments, any estimate from metal detector or magnetometer data regarding the depth and especially the quantity of drums should be considered an approximation.

In summary, both the metal detector and magnetometer respond to ferrous metals, but only the metal detector will respond to non-ferrous metals as well. The metal detector is normally limited to detecting metal objects lying at relatively shallow depths, but the magnetometer can detect metallic objects buried at deeper levels. The MD is capable of pinpointing the location of a buried object with somewhat greater accuracy than the magnetometer. Careful measurement and use of combined data from both MD and magnetometer will aid in estimating the depth and quantity of buried drums, and will often allow reasonably accurate estimates to be made.

In planning metal detector and magnetometer surveys, an estimate must be made of what it is the investigator is looking for, and its estimated depth of burial. For example, looking for single isolated drums at depths of 10 meters is an unreasonable survey requirement, due to the depth limitations of both instruments. The area to be surveyed and the spatial resolution required should be considered in deciding how best to provide a statistically valid measurement. If the objective of the program is to provide a first-approximation assessment for large burial trenches, the sampling grid spacing can be increased. In an extremely critical situation where buried materials might interfere with a drilling operation, the survey grid will be tightened up so that overlap between the survey lines occurs, to provide a measurement with a high margin of safety.

Use of GPR to Locate Buried Drums

Radar can be and has been used to locate buried steel drums (Figure 106). However, if soil conditions are not favorable for radar penetration, or if the relationship between the orientation of the buried drums and the radar antenna is not optimal, or if too much noise or too many subsurface reflections from other sources are present in the data, the drum(s) will not be detected. Furthermore, there are many sources (other than drums) which produce hyperbolic reflections. The presence of a hyperbola, therefore, does not inherently imply the existence of drums. If the site contains a buried pile of drums, the composite reflections will be very difficult to identify as drums. However, it will certainly be possible to say that an anomalous condition exists. Since there are other methods and instruments, such as metal detectors and magnetometers, to detect buried drums with much greater certainty, even when soil conditions are bad, it would seem prudent to consider these two methods first. On the other hand, if site conditions (such as proximity to a steel building) make the use of a metal detector or magnetometer impossible, radar does provide a secondary alternative. If the depth of a drum, or depth to the top of a pile of buried drums is required, radar may provide estimates with a high level of accuracy than could be derived from metal detector or magnetometer data.

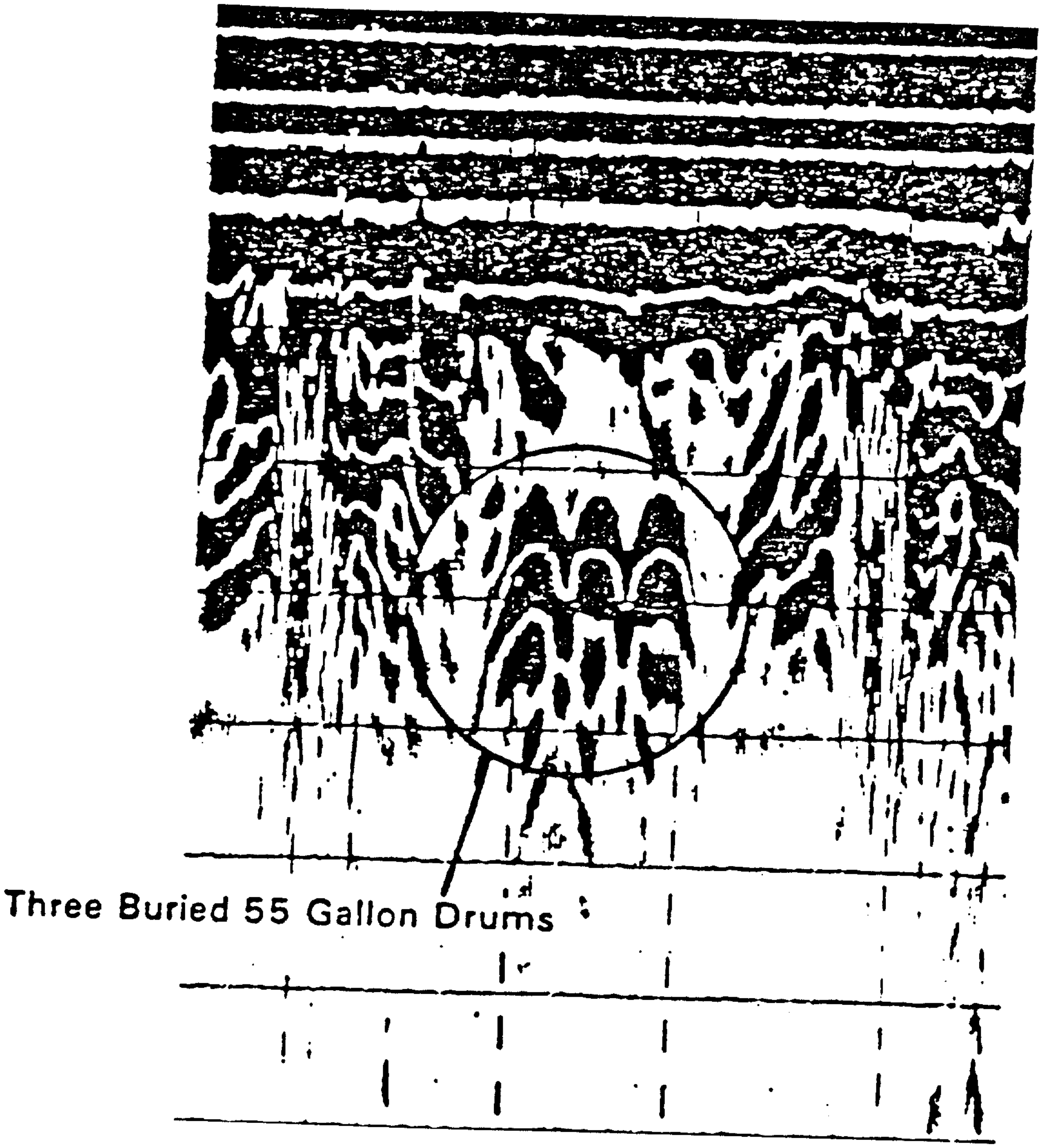


Figure 106. Radar record over three buried 55-gallon steel drums.

Site Investigation Considerations

This section outlines some procedural steps and variations in conducting a geophysical survey of a hazardous waste site. Figure 107 shows some important resources and tools which may he used effectively for the HWS investigation.

While this document deals with only six of the contemporary surface geophysics methods shown in the lower center portion of Figure 107, background information, traditional methods, computer and analytical capabilities, technical experience and professional and technical personnel are all important factors. Just as the geophysical methods provide synergistic support to each other, all of these factors provide synergism to the project. In addition to these technical components, other factors affecting the hazardous waste site assessment plan are shown in Figure 2. Factors such as budget, natural site conditions, cultural features, hazardous waste type, access, positioning, safety considerations, logistics, legal requirements, social/economic considerations--all will influence the planning, execution and results of a hazardous waste site investigation.

Some site investigations may be relatively straightforward, consisting of only a few days of on-site effort, while others may be more complex, requiring many weeks. The following example (addressing the geophysical effort only) illustrates some considerations which may be required for various levels of effort.

Small or Simple Site Investigation

A simple site investigation may require only reconnaisance-level geophysics with little if any subsequent interaction. Such an investigation (outlined below) might consist of three phases: (1) planning, (2) field operations, and (3) analysis and report.

The field investigation may consist of:

- Initial site characterization (establishing background values and evaluating cultural features, noise, etc.)
- Establishing survey grids
- Data acquisition and quality control
- Direct sampling (not required on all projects)
- Analysis and report.

A more extensive effort may be required for a large or complex project, an example of which is shown below.

Major Site Investigation

Planning

- Establish objectives
- Review existing data (aerial photos)

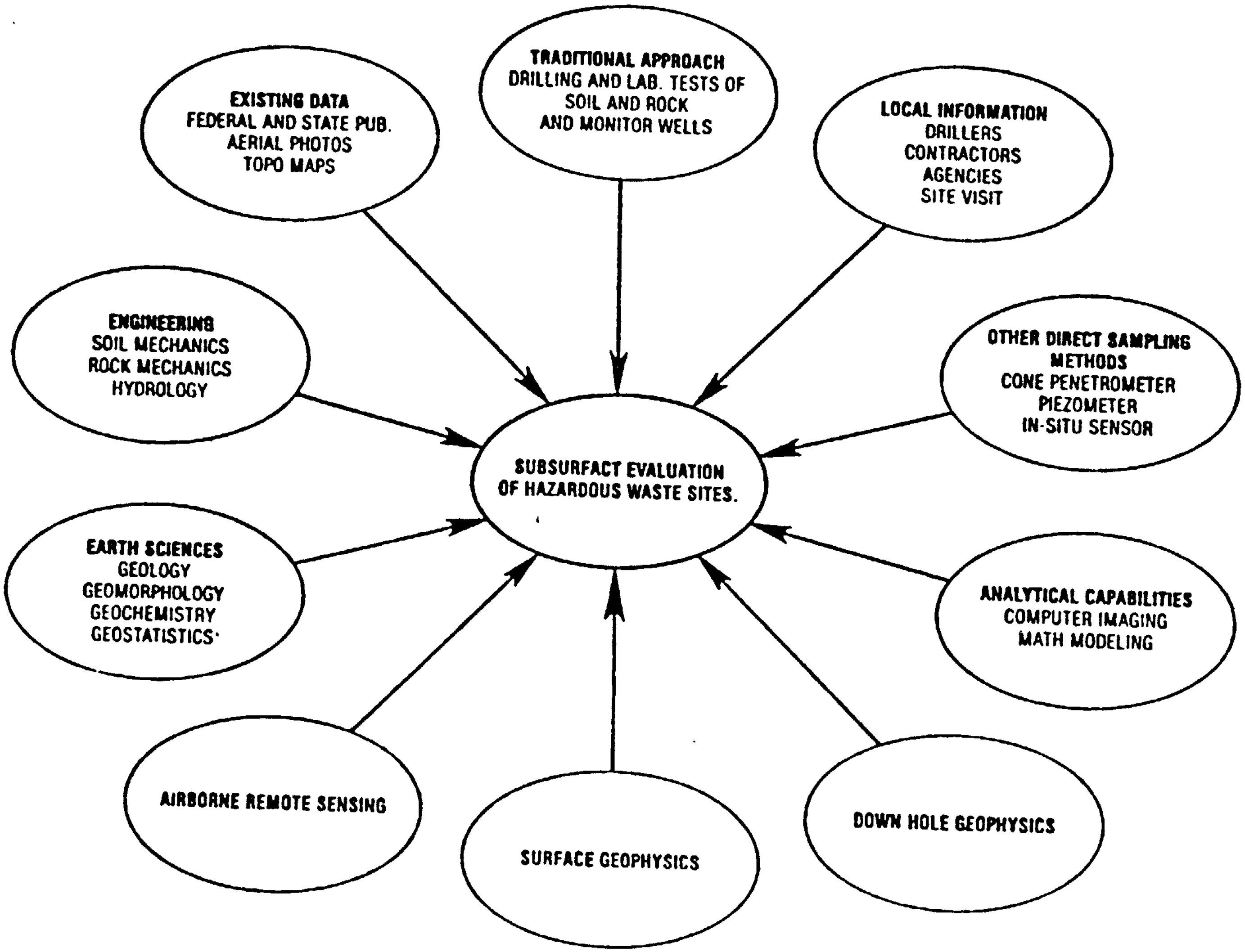


Figure 107. Technical resources and tools which may be applied to subsurface investigations at hazardous waste sites.

- o Visit site
- o Establish field survey requirements
  - Coverage considerations
  - Depth and resolution
  - Determination of techniques to be employed
  - Accessibility
  - Safety
  - Logistics and coordination

Field Operations

- o Reconnaissance
  - Safety considerations
  - Site familiarization
  - Initial site characterization (establish background values, and evaluate cultural features, noise, etc.)
  - Check fit of plan to actual conditions
- o Survey
  - Establish survey grids
  - Data acquisition and quality control
  - Initial direct sampling (soil and/or water samples)
  - "Fill-in" data acquisition (geophysical/direct) based upon preliminary findings
- o Design and execution of major direct sampling and laboratory analysis program
- o Review and integration of all data with analysis

Final Analysis and Report

It is essential to clearly establish and periodically review the objectives of a project. Initial efforts in the planning phase would include review of existing data as a critical part of establishing the objectives, especially in major site investigations. Generally, a considerable amount of information is available and can be obtained from a variety of sources, such as topographic maps, aerial photos, local USGS office publications, and government soil publications. Many of these readily available documents contain a wealth of information and are worth the time it takes to obtain and review them.

A site visit provides information for use in optimizing the field investigation plan and in safety planning. Those personnel. involved in planning the field operations should participate in the site visit whenever possible.

The area to be included in the site investigation and the density of site coverage are important factors to be considered when establishing survey requirements. It is often imperative to survey an area larger than the actual site itself in order to establish background values, local trends, and develop the overall "picture". Coverage of an area much larger than the site itself is common in plume measurements and is an important factor to be considered in planning, logistics and budgeting.

The resolution requirement will determine the density of the site coverage. A survey of insufficient density may miss desired information, whereas an excessively high-density survey results in unnecessary expenditures.

The accessibility of a site will affect the time it takes to conduct a survey. Trees, brush, trash piles and property fences can all cause serious delays for a survey team. If accessibility is a problem, trees and brush can sometimes be removed, or surveys can occasionally be designed around them. Permission to enter the property should be acquired prior to on-site activities to ensure optimum utilization of the field party's time.

Providing for personal safety is always of utmost importance when designing a field survey. A safe plan of investigation must be preceded by a thorough evaluation of existing data and an on-site reconnaissance to reveal safety hazards requiring special attention. Depending on the outcome of this evaluation, proper protective headgear, eyewear, footwear, clothing and respiratory equipment should be utilized. If safety precautions are necessary, they will certainly slow down field operations, particularly in hot weather. Decontamination procedures will also add time to a field survey. Other factors to consider are the safety hazards involved in use of the geophysical equipment, such as the high voltage and currents associated with resistivity measurements, or the danger of injury from explosives, if they are used in a seismic survey. None of the safety hazards associated with the use of geophysical equipment poses a serious problem to an experienced field crew, but they all may become critical considerations if inexperienced persons are in the field.

After the field requirements have been established, the actual field operation begins with a reconnaissance effort incorporating general familiarization with the site, a review of safety considerations, and a check of the "fit" of the plan to actual site conditions. The survey work can then begin. Initially, the geophysical survey should establish both nearby and background values from off the site to aid in Understanding the setting and to have values for comparison. In addition, the potential for cultural interference must be evaluated. By means of this initial reconnaissance, the on–site geophysical project manager can usually obtain a quick overview of natural site conditions and cultural activities which might affect subsequent operations.

Some site investigations require that geophysical survey lines be referenced to the legal land boundaries, while other investigations do not require establishing any survey base. For example, the boundaries of a burial trench delineated by a metal detector may be marked in the field without relating the trench location to legal land boundaries. The necessity to have a geophysical survey grid tied into a formal land survey ususally depends upon the technical and legal requirements of the project.

Even though a formal land survey may not be required, all on-site work should be tied to local references, so that any part of the survey can be checked or repeated, or an anomaly located, with sufficient accuracy. In many cases, however, the total cumulative error in positioning can easily be large enough so that the location of a single drum, or the definition of the edge of a trench, may not be accurately indicated. This will require that the geophysical team support any remedial action work, or stake it out in the field directly, so that exact locations may be obtained.

Sampling of spatially varying data may be accomplished by discrete, as well as continuous measurements. If we can establish the size of the smallest feature in the data that will be of interest, we can indeed design a survey so that adequate resolution can be obtained by discrete station measurements. Before the survey, however, we will not often be able to accurately estimate the minimum sample distance. Hence, if our estimate is sufficiently in error, our data will be in error. (Review concepts of discrete and continuous measurements in Section 111, Figure 17.) To minimize the possibility of making such errors, to achieve maximum resolution, and to minimize project costs, continuous methods are recommended whenever possible.

Basic quality control for the field survey involves a number of factors including:

° Checking that instrumentation is working properly;
° Assuring that the positioning of stations is sufficiently accurate;
° Noting stations accurately on recorded data;
° Noting unusual conditions;
° Monitoring signal-to-noise ratios;
° Plotting data in the field;
° Evaluating initial results for reasonableness.

Quite often, only the relative values from the geophysical data are needed to identify a potential problem area. In such cases we may not be concerned with the repeatability or accuracy of the measurements, but only with the finding that an anomaly exists (e.g., high conductivity). From such information we can further evaluate the anomaly by resistivity sounding, drilling, trenching, or whatever method is appropriate to the mission.

When more than one geophysical method is being used, and if surveys are to be repeated at a later date, quality control and repeatability of the measurements also becomes an important consideration. In some cases it may be desirable to establish a background test site so that all instruments on subsequent surveys may be referenced to this standard. Then if changes in seasonal conditions (temperature, snow cover, frost, rainfall, etc.) have occurred, the extent of their influence can be evaluated and compensated for by corrections to instruments or data. Time level of quality control required at a site will vary considerably depending upon project requirements. There is little need for a high-level quality control program if the project objectives are straightforward, such as a metal detector survey to identify burial site boundaries. Overkill here will. simply add needless cost to the program. But when legitimately required, an in–field quality control program should be established, ensuring that only those procedures that are considered necessary will be performed.

Correlation with existing data (drill logs, ground water chemistry, etc.) may be done before, during, or after the geophysical survey. Sufficient data may already be available from existing monitor wells or soil analyses. In some cases, additional direct sampling may be required in anomalous areas identified by geophysical methods. Many times, however, the geophysical survey will he carried out with little or no existing site information; in those instances, geophysical data can be used effectively to locate monitor wells or other direct sampling stations.

In some cases, technical, safety, and legal considerations may preclude direct sampling and it is frequently necessary to determine subsurface conditions without their benefit. For example, the survey objective may be to define the location and boundaries of buried materials without drilling because of the high safety risk involved. When this situation occurs, a systematic survey using multiple geophysical. methods often provides the investigator with the ability to semi-quantify subsurface conditions without direct sampling. In many instances, a highly accurate evaluation has been made without direct sampling; in others, virtually no conclusions can be drawn without further direct investigation. The results of surveys made without actual direct sampling are, of course, more speculative, and the limits of accuracy from such a survey should be clearly recognized by all concerned. When direct sampling is required, considerable care must be exercised to avoid creating problems such as might result from drilling into hazardous waste or drums. Of course drilling operations for the evaluation of natural subsurface conditions will usually present no safety hazards.

Preliminary data analysis is often done in the field. The analyses will often indicate the need for additional measurements, and will aid in the selection of additional geophysical methods. Final analysis will usually be done in the office with the support of manual and computer calculations.

Although data analysis can yield a solution from a geophysical measurement, the solution is not unique. Other information must be integrated to arrive at an assessment which portrays, in geological rather than physical terms, actual site conditions. This process requires a trained and experienced interpreter. The more complex the site conditions or the overall problem, the greater the level of skill that will be required. In many cases, experienced personnel can accomplish this integration and interpretation process quite rapidly and effectively.

While experienced personnel may be able to interpret much of the required information directly from the raw data, computer processing can be a significant aid in its analysis. Processing is also used to improve the presentation of the data, so it may be better understood by persons not familiar with geophysics. Computer processing generally is used to:

- Assist in handling larger quantities of data.
- Apply corrections to the data (e.g., for non-linearities and calibration).
- Compensate continuous data for spatial non-linearities due to variations in speed when traversing the survey line.
- Remove cultural responses such as pipelines, etc. This cleans up data which may otherwise be extremely complex to interpret.
- Perform modeling calculations to aid interpretation of the data (e.g., forward and inverse calculations for resistivity sounding interpretations).
- Evaluate data amplitude, frequency, or phase.
- Process the data to improve technical aspects or visual presentations.
- Correct or exaggerate vertical or horizontal scales to present data in the best visual format.
- Plot stacked profile lines.
- Contour data.
- Create three-dimensional plots, with various viewing directions and angles.
- Filter data to eliminate unwanted "noise".

- Overlay multiple sets of data, such as maps, site plans, geophysical data, etc.
- Analyze multiple data sets, for correlation and statistical trends.

Finally, all existing and new field data is reviewed and a final report written. Since there is generally no unique solution to be found in a given set of geophysical data, the mere acquisition of data (through the use of geophysical methods) does not in itself provide the solution to a site assessment problem. Interpretation of the data is required, and the accuracy of the interpretation will depend on the training and experience of the interpreter. The more complex the problem, the greater are the demands on this skill.

Examples of Field Investigations

The following examples describe the use of geophysical methods at a variety of hazardous waste sites. The examples are taken from actual site investigations. These five cases include:

1) Investigation of Natural Setting Prior to Construction of a Disposal Site.
2) Mapping and Characterization of Bulk Buried Wastes.
3) Delineation of Trench Boundaries.
4) Mapping and Assessment of Landfill Leachate Plume.
5) Locating Monitor Wells at an Uncontrolled Hazardous Waste Site.

Investigation of Natural Setting

In selecting a site for waste disposal, an evaluation was required of a natural clay layer believed to exist over limestone bedrock. Data on the lateral extent, continuity and thickness of the clay layer was needed to evaluate the effectiveness of the clay in preventing contamination of the underlying limestone aquifer.

Seismic refraction and resistivity sounding surveys were conducted over the area. Samples from several augured holes were obtained to determine the physical and chemical properties of the clay, and to correlate with the geophysical data. Seismic refraction and resistivity produced a faster, more reliable survey at lower cost than could have been achieved with just monitoring wells. Borings could not be made through the clay layer; for if improperly sealed, they would have created potential pathways for the migration of contaminants.

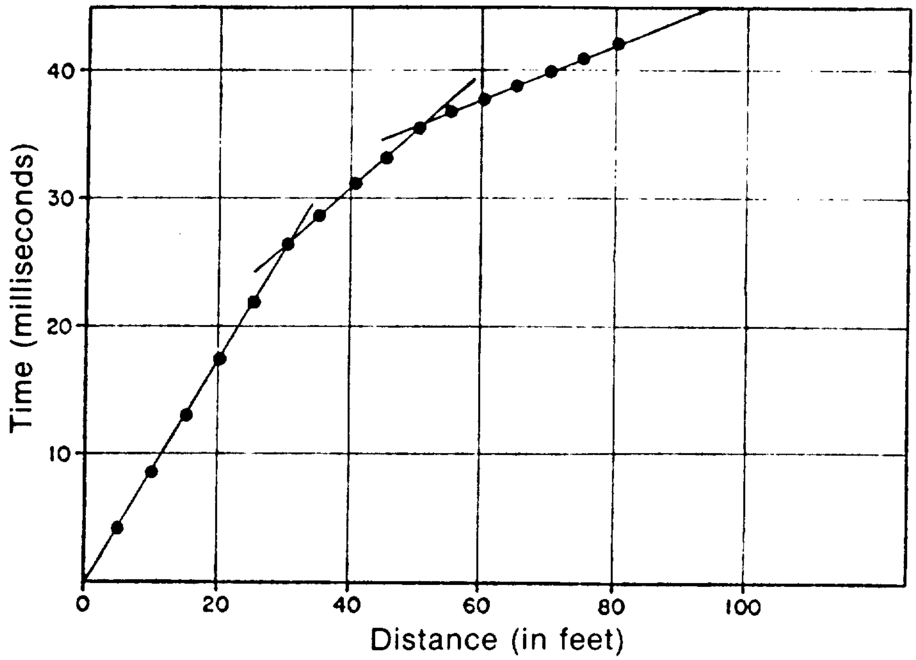
Ten seismic refraction lines were located over the 25-acre site to obtain adequate coverage. Since explosives were prohibited at this site, a hammer was selected as a seismic source for the shallow work. The use of a sledge hammer source limited the seismic station lines to a length of approximately 30 meters, providing information to a depth of 10 to 12 meters Five-foot geophone spacings were used to obtain detailed information regarding site variability. Initially, forward and reverse seismic lines were made to check for possible dip of the underlying strata. From the first few seismic lines, it was found that the bedding was horizontal and the remaining stations were run without the reverse line, in order to reduce costs.

The seismic data in Figure 108(a) indicated a three-layer system which was tentatively identified as sand, sandy clay and massive clay (this data is shown in detail in Figures 77 and 78). The length of the seismic line was not sufficient to detect the top of the limestone because a small hammer was used; however, calculations provided the minimum depth to the top of the limestone, and a minimum thickness of the overlying clay layer was obtained. The lack of geologic scatter in the seismic data indicated that the materials were fairly uniform.

Five resistivity sounding stations overlapped the seismic stations. Wenner array soundings were carried out to 100-meter electrode, or "A" spacing, and sounding data was obtained to a depth of “A" approximately 30 meters. The resistivity data was of "text book" quality with virtually no geologic noise.

The interpreted resistivity data indicated a four-layer system (Figures 63 & 64). The first three layers corresponded to the sand, sandy clay and massive clay layers identified by the seismic method. The fourth layer was identified as limestone. The depth to top of limestone was calculated at 12 meters and the massive clay layer was determined to be ahout 8 meters thick; these results are summarized in Figure 109.

The geophysical survey results were confirmed by use of five shallow auger borings which also provided samples for laboratory mineral and permeability analysis. The auguring log also provided detailed information about the color of sand samples, which were not discernible in the seismic and resistivity results. The borings were limited to 10 meters so that the clay layer would not be penetrated. The auger log revealed seven sediment layers, varying from dry sand to clayey sand, sandy clay and massive plastic clay (Figure 109). Major soil changes disclosed by the auger correlated well with the seismic and resistivity results. As shown in Figure 78, the top of the massive clay layer was established at 7.5 meters depth by the seismic method. This was within 1/3 meter of the depth established by the auger. The resistivity interpretation identified clay material beginning at about 3 meters, and a massive clay at 7.5 meters. The homogeneity and flat-lying



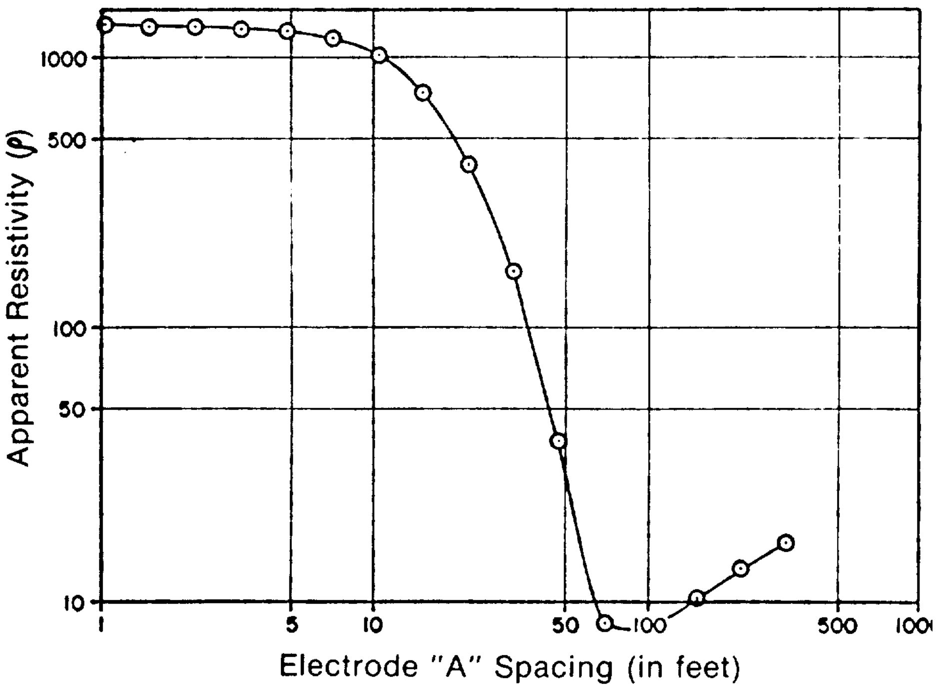


Figure 108. Data from a single seismic refraction line and resistivity sounding.

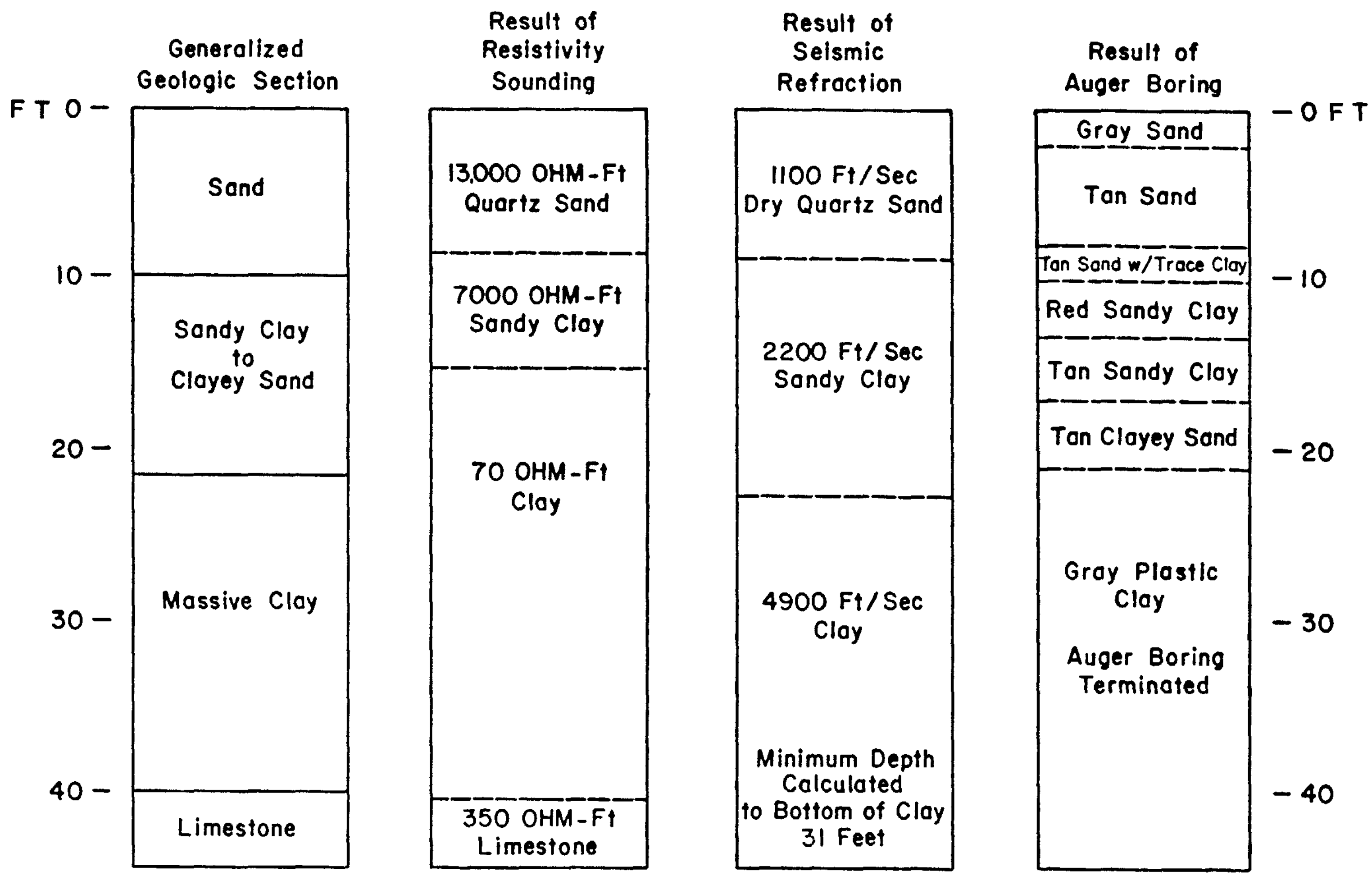


Figure 109. Comparison of data obtained by auger, seismic refraction and resistivity methods. Interpretation of this data yields a generalized geologic section.

strata of the subsurface structure permitted excellent correlation between the seismic, resistivity, and auger data.

The combination of two geophysical methods provided good correlation both vertically and laterally. With the overlapping positions of the seismic and resistivity stations, excellent spatial coverage of the site was achieved. The geophysical data, together with the data from the five auger borings, provided a very high level of confidence in the estimates of the depth, thickness and continuity of the clay layer.

<u>Mapping and Characterization of Bulk Buried Wastes</u>

A buried disposal site was thought to be located in an open grassy area, 300 meters wide by 400 meters long, which had been used as a playground. A small river bounded the park on one side. Stream sediment analysis had shown high concentrations of organic compounds, but the extent and depth of the toxic wastes believed present were unknown. A subsurface investigation using six monitor wells had revealed trace levels of contaminants at the site. However, the location of the burial site and the extent and type of contamination were still unknown.

The objectives of the geophysical work were to locate and map any buried disposal areas, to provide an estimate of the depth and volume of contaminants, and to assess the positions of the six monitor wells with respect to the buried wastes. Initial reconnaissance surveys using ground penetrating radar and electromagnetic indicated that anomalous soil conditions existed between several of the monitor well locations.

Parallel survey lines were established 15 meters apart for electromagnetic and radar measurements. Data from both measurements revealed the boundaries of the disposal area. Figures 110 and 111 show the boundaries based upon EM data. Radar was unable to penetrate to the base of the contaminants due to the conductive nature of the contaminant material. Radar did indicate that the top of the waste was within one meter of the surface. Electromagnetic soundings indicated that the maximum depth of the buried material was probably not more than 5 meters. The amplitude of the EM conductivity data in Figure 110 provided an estimate of the quantity of buried wastes.

The burial area was then surveyed with a magnetometer to check for the presence of steel drums. A high sensitivity, 0.1 gamma total field magnetometer was found to be ineffective due to the extremely high variation in magnetic susceptibility of the soil and/or waste material. Since the objective of the magnetometer survey was to look for the presence of relatively shallow buried steel drums, a fluxgate gradiometer

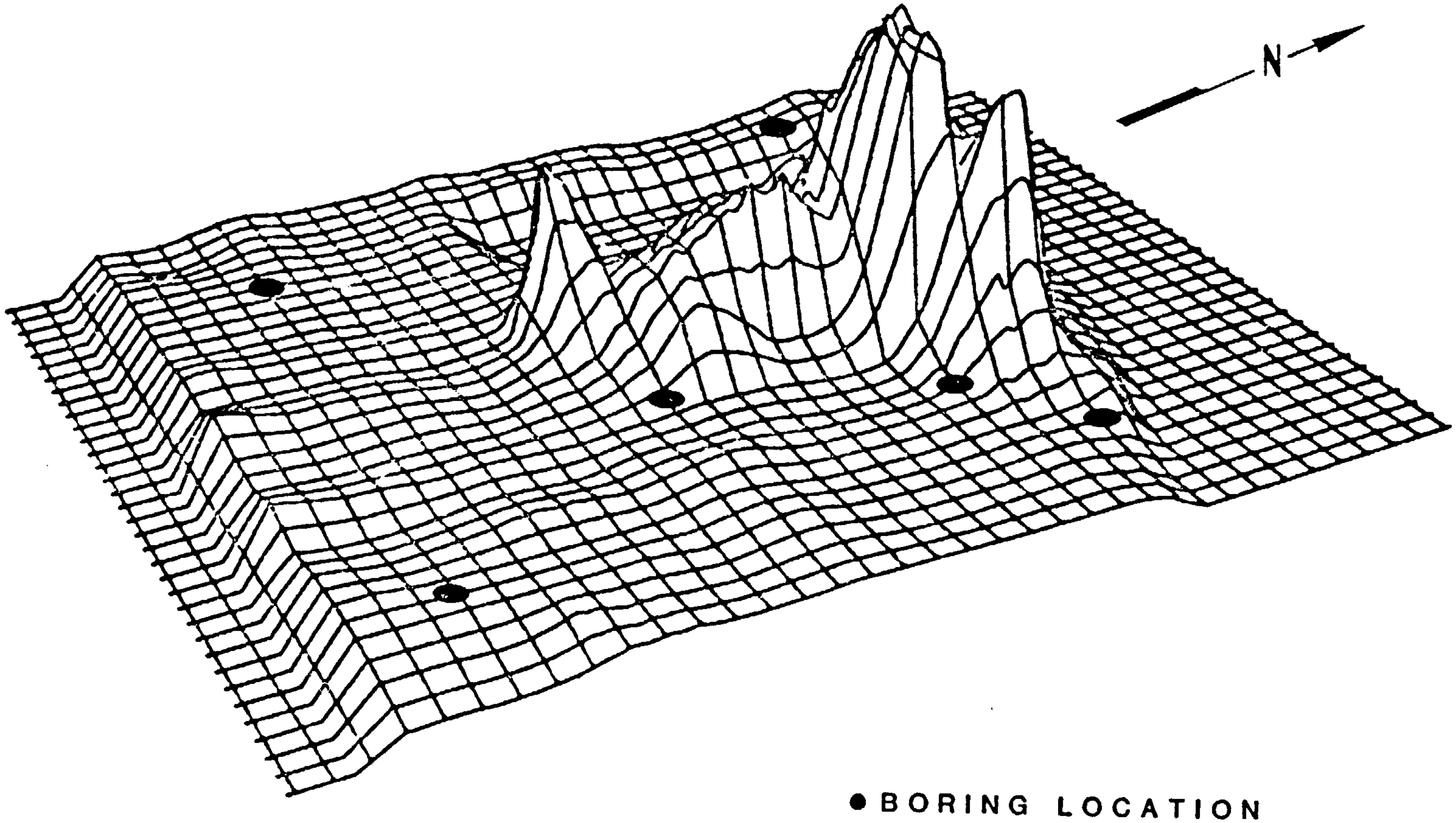


Figure 110. Three-dimensional perspective view of EM data showing spatial extent and magnitude of conductivity anomaly. Six borings have missed the burial site.

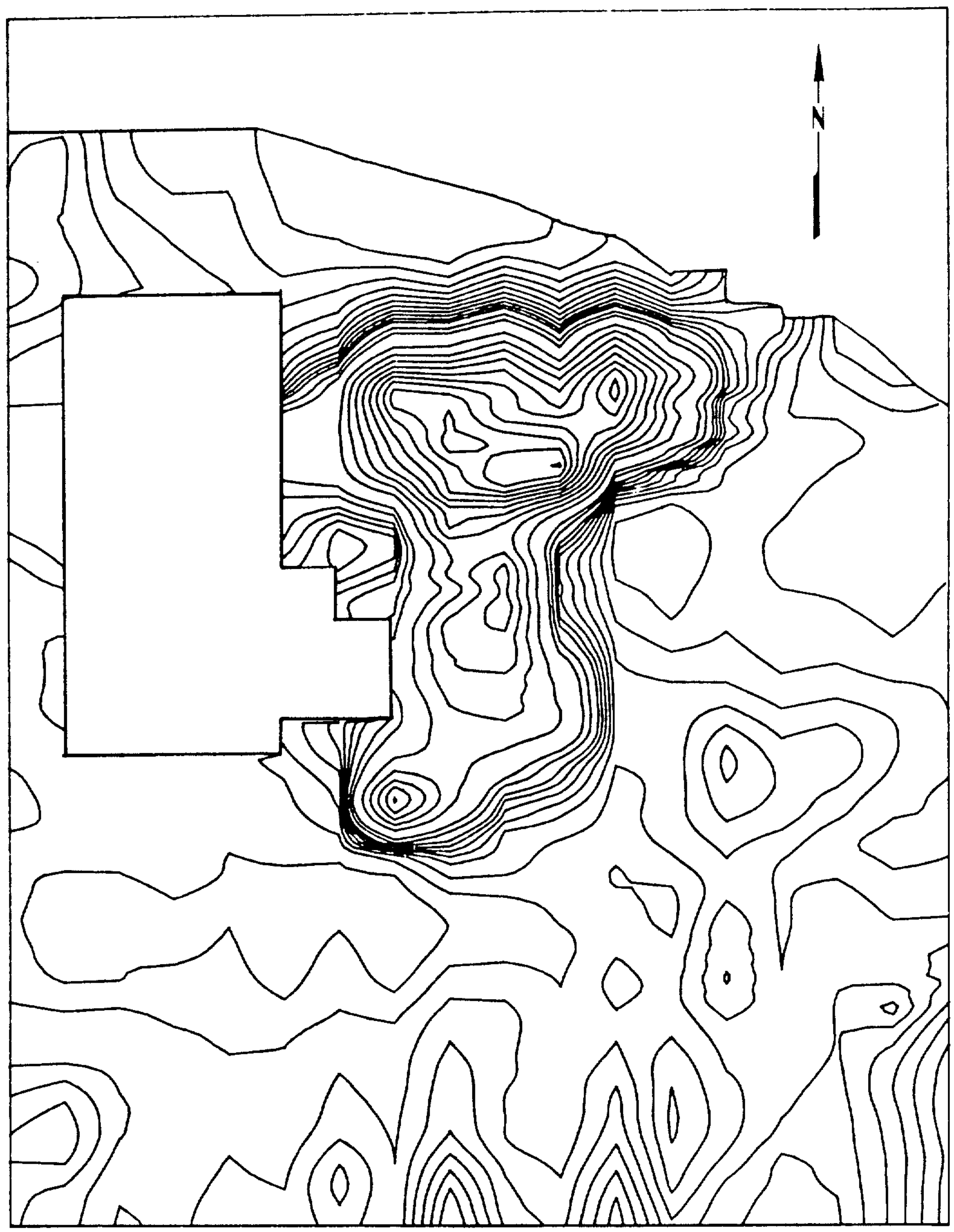


Figure 111. Contour plot of EM conductivity anomaly in figure 110 showing extent of buried contaminants.

magnetometer was used, at reduced sensitivity, to minimize the effects of the wide variations in magnetic response due to soil or waste material. Only two distinctive magnetometer anomalies were found which might have been single steel drums. The magnetometer survey indicated that the buried materials consisted primarily of bulk wastes with possibly a few scattered drums.

Radar, EM and magnetic surveys were completed within three additional days and revealed the detailed boundaries of the burial zone. (The boundaries were identified and marked in the field.) The field data was subsequently computer processed, and detailed maps (Figures 110 and 111) were produced in less than a week. These figures demonstrate two different forms of data presentation. The three-dimensional figure gives the viewer a quick grasp of the extent and magnitude of subsurface conductivity. The contour map provides an accurate means of locating contaminant boundaries.

Final. analysis indicated:

1) The material was not containerized but was dumped in bulk.
2) The existence of a few buried steel drums was possible.
3) The bulk material was highly conductive.
4) The top of the material was quite close to the surface (less than 1 meter deep) and the bottom of the material was variable, but less than 5 meters deep.
5) An estimate of the volume of the waste was possible, based upon the magnitude of EM data in Figure 110.
6) The material was a fly ash matrix containing other toxic contaminants (identification was based on samples from one drill hole).

Location and Delineation of Trench Boundaries

A number of burial sites containing an unknown quantity of steel drums were reported by an eye witness to the burial. The drums were suspected of containing highly toxic wastes. The exact number of individual sites was unknown, but four possible burial sites had been tentatively defined within an overall area of a few hundred acres. These areas were identified on aerial photographs which showed clearings in an otherwise densely forested area.

The first project objective was to conduct an initial survey to search the four possible target areas for the presence of buried drums. This initial survey was carried out using a commercial pipe/cable-locating metal detector (as in Figure 81). The detector was selected on the basis that it was to be handled by one person, and maneuvered through dense underbrush. This particular equipment is a reasonable choice for reconnaissance work when the drums are at shallow depth, or in sufficiently massive groups to enable detection at greater depths. In order for a metal detector to detect steel drums it must be passed directly over a single drum, or over the edge of a trench containing a number of drums; therefore each of the four prospective sites was given total site coverage due to the suspected critical nature of the buried waste.

This reconnaissance metal detector data was not recorded; instead, the operator simply made notes of his findings and marked any target locations with survey flags. (This practice is quite satisfactory for reconnaissance surveys where only an indication of the presence or absence of buried drums is required.) The results of this search effort identified only one burial site. Contaminants in the soil were characterized on the site by an organic vapor analyzer and subsequently by chemical analysis.

Once the burial site had been located, additional information was required to assess conditions and to provide a basis for remedial action. Project objectives were:

- To establish trench houndaries, so that sampling and monitor wells might be placed immediately outside the trench area. A high level of confidence was necessary in this phase of the geophysical work, as breaching the trench, or penetrating a drum, could he extremely dangerous.
- To determine the approximate dimensions and depth of the trench in order to estimate the number of drums.

Field work consisted of establishing the trench boundaries with three geophysical instruments: a specialized metal detector with a large diameter coil, a calibrated fluxgate gradiometer magnetometer and a ground penetrating radar system. Metal detector and magnetometer data are shown in Figure 112.

The special metal detector was capable of operation at full sensitivity within a few feet of a chain link security fence. This detector also provided better resolution of the trench edges than the pipe/cable locator used in the initial reconnaissance effort. The metal detector's output was recorded for later analysis. Figure 112(A) shows a single line of data from the trench, illustrating the accuracy with which the boundaries may be delineated. A composite data set of eleven traverses is shown in Figure 112(B). The lateral boundaries of the burial trench can be seen along each traverse, and the end of the trench can be seen in the last two lines of metal detector data in the foreground.

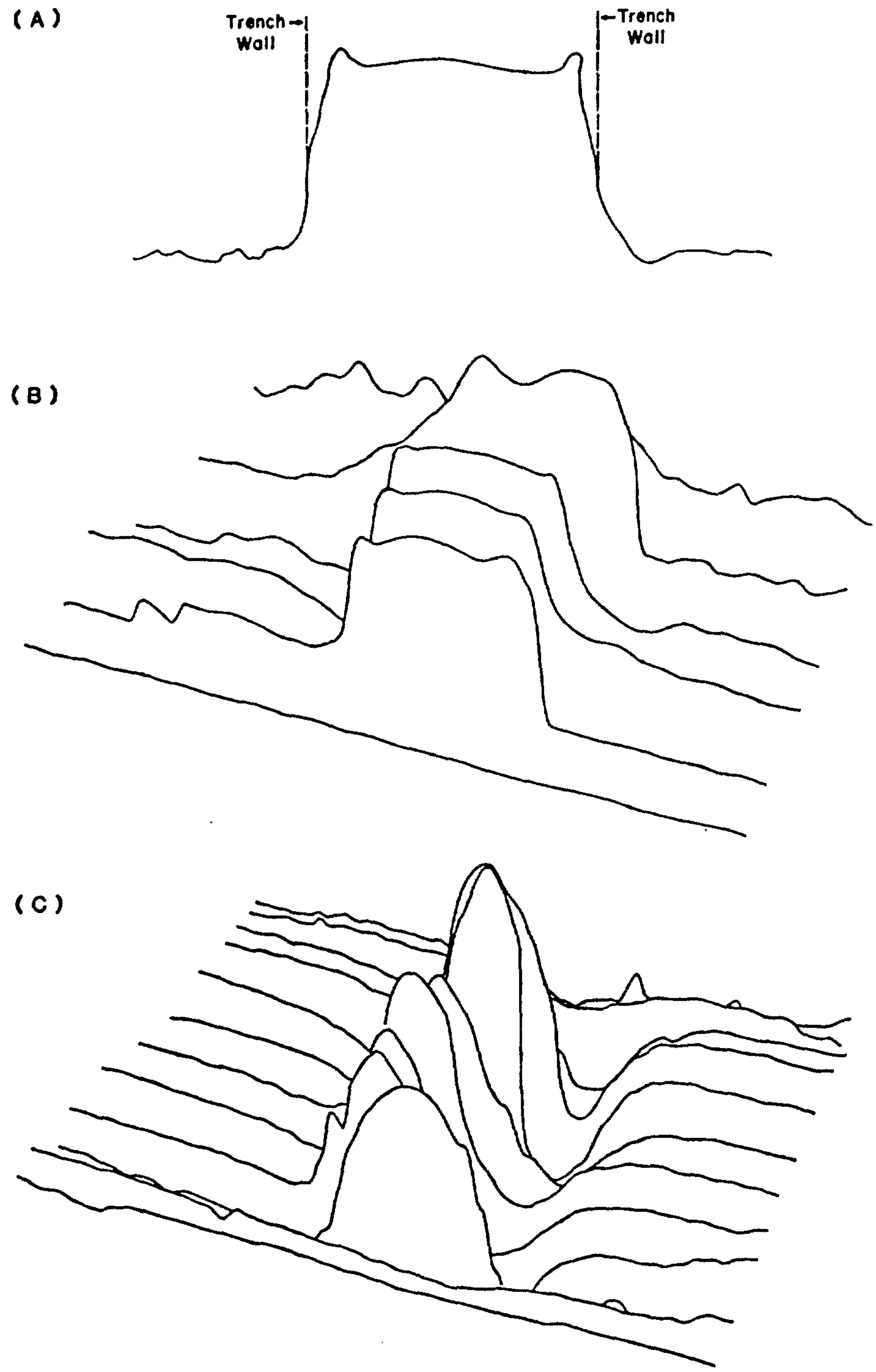


Figure 112. Metal detector and magnetometer data over a single trench containing buried drums. (A) Single metal detector traverse over trench. (B) Three-dimensional perspective view of metal detector data from parallel survey lines over trench. (C) Three-dimensional perspective view of magnetic profiles over trench.

Since the metal detector responds to both ferrous and non-ferrous metals, a complete magnetic survey was also carried out to confirm that the buried metals were primarily ferrous. The magnetometer selected was an adjustable sensitivity fluxgate gradiometer, and the data was run along the same transect lines as the metal detector and radar data, for correlation purposes. Special field procedures and processing were used to correct for the effects of the steel fence on the magnetometer. The composite magnetometer data shown in Figure 112(c) confirms that the trench contains ferrous metal (steel drums). The magnetometer data was not used to locate the trench boundaries because of the offset between the magnetic anomaly and the buried target location, due to dip of the earth's magnetic field (see Figure 101).

The radar results outlining the trench were based upon disturbed soil, Figure 113. The radar data provided a means for estimating the depth of the trench from 2 to 2.5 meters. From the metal detector, magnetometer and radar data:

- The boundaries of the trench were accurately established;
- The contents of the trench were tentatively identified as steel drums;
- The volume of the trench was calculated and the number of drums was estimated.

The geophysical work conducted in the vicinity of the burial site was carried out with protective suits and respirators. In addition, decontamination procedures were used to clean the equipment. These safety procedures increased the time required to conduct the survey by a factor of five. Overheating is a major problem for personnel using protective gear, and magnetic surveys are made more difficult by the presence of steel-toed boots and other ferrous parts of protective clothing and safety equipment.

Mapping and Assessment of Landfill Leachate Plume

Monitor well data and resistivity surveys located a plume at a 30-year-old landfill. (See example in Section VI and Figures 65 and 66.)

A few years after the resistivity survey was completed, a new auxiliary well field was installed nearer the landfill, at a distance of approximately 1-1/2 miles downgradient and in the direction of ground water flow. After this welL field had been pumping intermittently for about two years, analysis of the water from the well field showed increasing levels of ammonia. A newly installed early-warning monitor well had failed to indicate the presence of contaminants. The landfill had also been identified by EPA as one of the major hazardous waste sites in the country

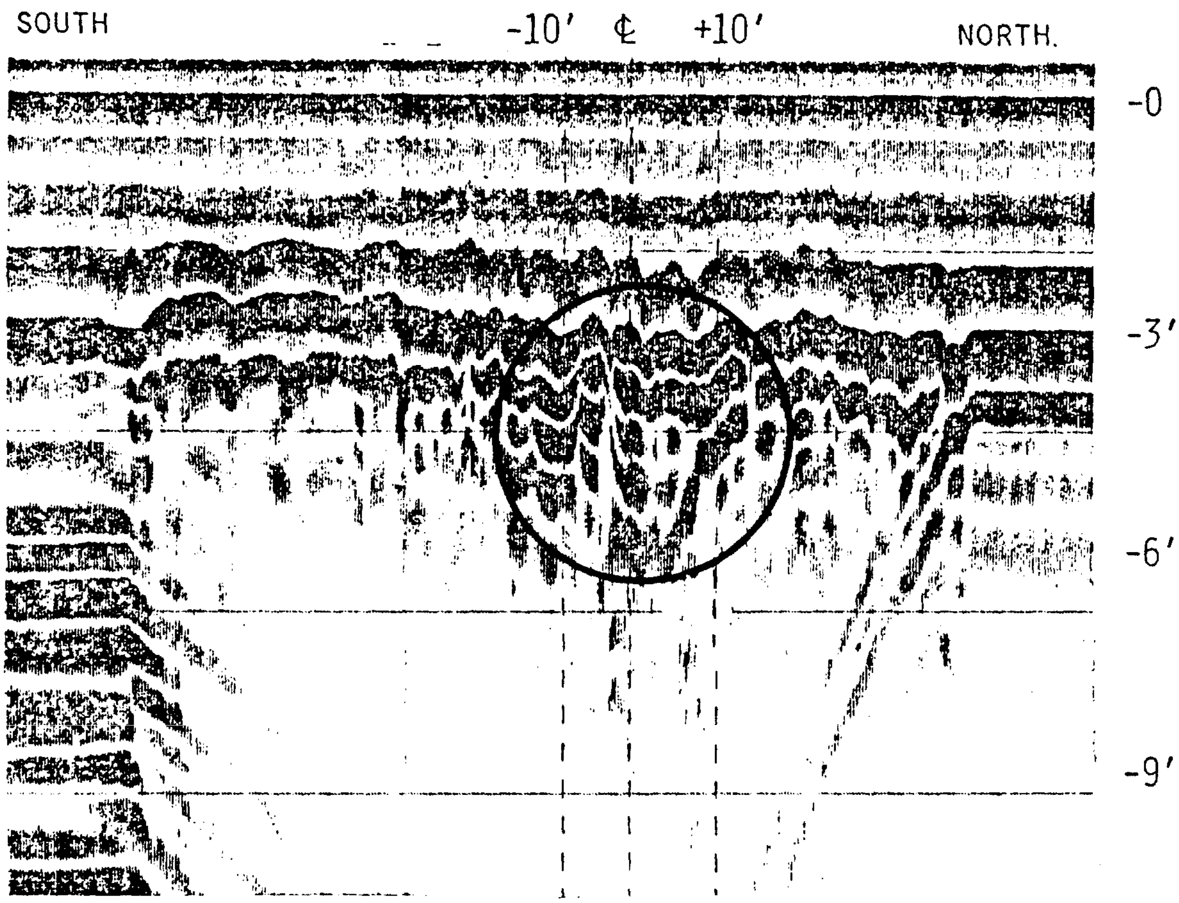


Figure 113. Radar traverse across same burial trench as in Figure 112. Although trench is full of drums, individual drums cannot be identified in the radar data.

because of its proximity to the local municipal well field which supplied drinking water to a large city.

Before selecting the locations for additional wells, a second geophysical survey was conducted to define the current extent of the leachate plume and to aid in the interpretation of existing monitor well data. This second resistivity survey (four years after the first) was performed using the same equipment and station locations. The time of year was the same as in the previous study. The new survey area was extended beyond the earlier survey area in order to cover more area downgradient. Results of this second survey are also shown in

Figure 114. The following conclusions were drawn:

1) The plume had shifted direction and had migrated to the northeast in response to a change in the local ground-water gradient created by the newly-active auxiliary well field. The plume had extended into the well field cone of influence, creating the increases in ammonia observed in the water analysis.

2) As may be seen in Figure 114, the "early-warning" well had not detected any leachate, because the well was located in an anomalous area relatively clear of leachate. A review of the monitor well's geologic log indicated the presence of fine sand and clay, instead of the highly permeable limestone which was typical of the area. The well had inadvertently been located in a small zone of lower permeability.

3) Comparison of the two sets of geophysical data revealed that the lateral extent of the plume had increased by approximately one kilometer (0.6 miles) in four years, which is a migration rate of about 0.5 meters (1.5 feet) per day, roughly half the rate of the calculated regional ground water flow. This migration rate, measured in this manner, takes into account the combined effects of all the variables influencing the rate of leachate migration.

4) The areal and vertical extent of the plume, determined by resistivity, made possible a calculation of the total volume of aquifer contamination.

5) The survey identified a number of other point sources which were contributing to the contamination of the aquifer (not shown in the data).

With a map of the leachate plume, a measure of how fast it was migrating, an understanding of the factors influencing its path, and an evaluation of previous water quality data, it was possible to obtain a more accurate understanding of site conditions. In addition, new monitor wells could be installed with a high degrees of confidence, with their locations being representative of ground water conditons.

Measured by resistivity or EM techniques, the plumes shown in Figure 114 are representative of conservative chemical parameters (e.g., chlorides, sodium, etc.). The outer contours are near background values and represent a reasonable estimate of the maximum extent of contamination by sanitary landfill leachates. Many contaminants of a hazardous nature will remain within these boundaries, not migrating as far as the conservative parameters. Although there are some contaminants which do migrate

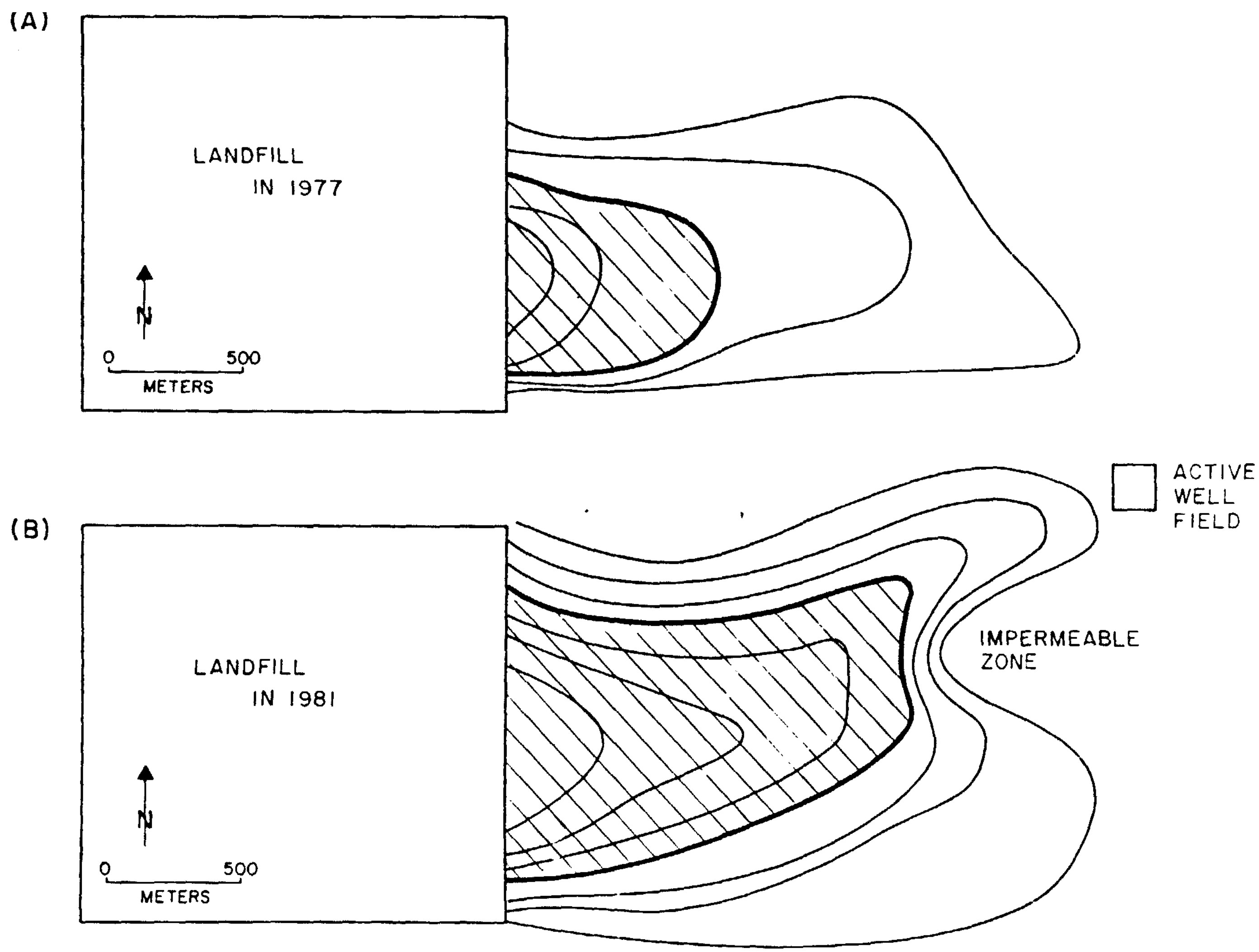


Figure 114. Mapping of leachate plume using resistivity methods shows changes in plume over four-year period. (Shaded area represents 200 Ohm-ft contour.)

faster than ground water, they are not commonly associated with sanitary landfills in large enough quantities to make them a dominant factor in plume behavior.

Locating Monitor Wells at an Uncontrolled Hazardous Waste Site

A ground water investigation was initiated at an uncontrolled hazardous waste site to determine the direction and extent of any contaminant migration. Existing information noted a regional ground water gradient to the northeast. In addition, geologic logs revealed a highly variable geohydrologic setting composed of sand and gravel lenses within a clay matrix. The occurrence of these more permeable sand and gravel deposits could significantly influence the path of contaminant migration and the placement of monitor wells.

Before locating any monitor wells, a detailed electromagnetic (EM) conductivity survey was conducted to map contaminant migration and to evaluate the natural setting. This data was then used to direct the placement of monitor wells and provide a guide for soil sampling.

The field data consisted of about 30 parallel profile lines, 1000 meters long, spaced 30 meters apart. Data was acquired only around the perimeter of the site and not directly over it.

Using continuously-recorded data, the high density EM survey was accomplished in less than a week. Continuous EM data was obtained to 6-meter and 15-meter depths using two EM systems. Subsequently, the recorded data was digitized, computer-processed and then plotted in both contour (Figure 115) and three-dimennsional perspective (Figure 116) formats. The contoured data was used to locate the monitor wells accurately. The three-dimensional view aided in the interpretation of overall site conditions. The EM data showed a high degree of natural variability at the site. The data helped to identify clearly the existence and extent of two plumes.

The size and extent of the main plume emanating from the storage area is clearly seen in the center of the figure as a conductivity high. The major plume appeared to migrate toward the east-northeast, with minor lobes extending north, east and south (see Figure 115). The highest conductivities occurred around the northeast corner of the site where a disposal impoundment was located. A minor plume which extended toward the west (regionally upgradient) was probably caused by the mounding of ground water within the elevated hazardous waste site. Extensive background data, obtained outside the immediate site, allowed a good statistical assessment of the range of natural variations in conductivity. Once the maximum range of natural variations was determined, any higher values measured were attributed to contaminated ground water. The

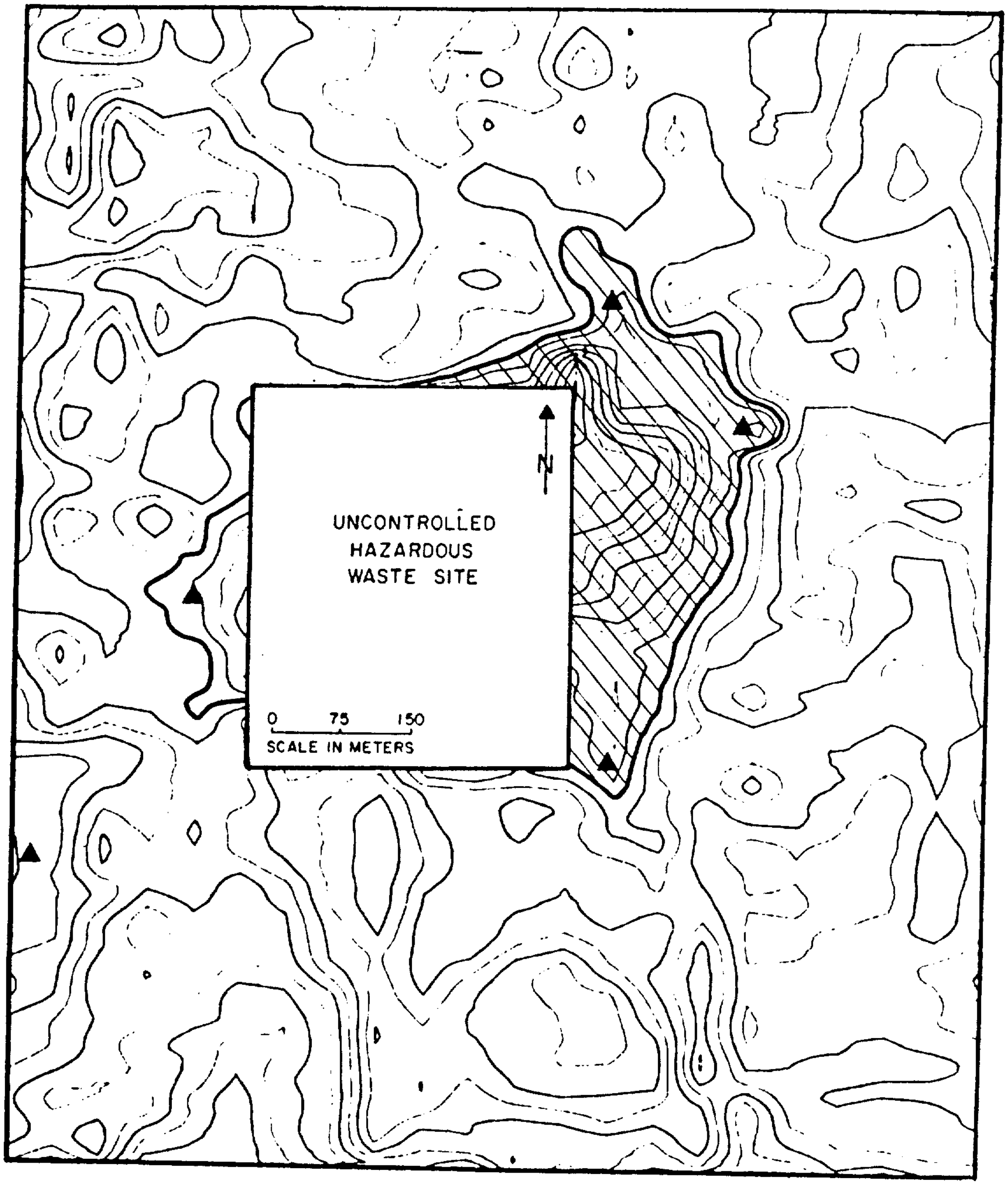


Figure 115. Isopleth map of EM conductivity data at a hazardous waste site shows a plume (Shaded area) leaving the site and considerable variation in surrounding site conditions.

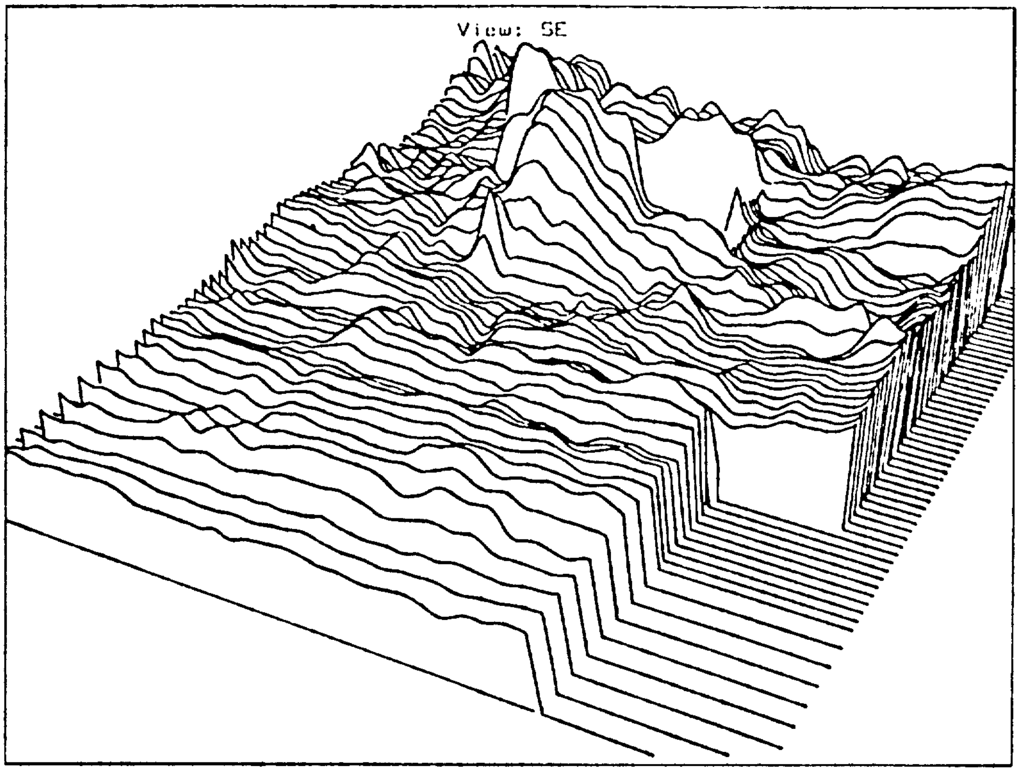


Figure 116. Three-dimensional perspective view of EM data shown in Figure 115. Note plume in center of plot and variability in conductivity due to natural geohydrologic conditions.

outer boundaries of this contaminated water are delineated by the shaded area in Figure 115.

The use of continuous recording EM technique and high data density, together with the computer presentation, permitted identification of the conductive plume boundaries well into the "noise level" caused by variations in the natural site conditions.

Besides identifying the contaminant plume, the EM data had indicated that natural background conductivities were extremely variable. State geologic references, plus well-placed borings, revealed that these natural conductivity fluctuations were associated with river-deposited lenses of sand, gravel and clay. This variability is related to the complex distribution of permeable sand and gravel deposits (low conductivity) within the clay matrix (high conductivity). These variations in sand and gravel content were due to differential deposition of these materials in old buried stream beds. The existence of such buried stream beds had been established from local geologic literature. The two sets of EM data (6 meter and 15 meter depths) revealed that most of the variations in the sand and clay deposits lay within 6 meters of the surface. Below this depth, conditions were much more homogeneous.

Water flow and contaminant migration may be expected to follow the most permeable routes (low conductivities) in this shallow unconfined system. Therefore, higher trace levels of contaminants might be expected in these more permeable zones, and the EM lows could be used to place monitor wells beyond the extent of the obvious conductive plume.

Four wells were located within the identified plume. A fifth well was located upgradient in a low conductivity sand lens for background determination. Augering confirmed the existence of the sand and gravel deposits, as suggested in the EM maps and geologic literature.

The plume boundary delineated by the EM method (Figure 115) represented the extent of transport of the conservative ionic parameters. Quantitative data subsequently obtained from the wells indicated that the boundary of the conductivity plume approximated the 1 ppm level of the priority pollutants. (This correlation is applicable only at this site and should not be used as a rule of thumb.)

It has been recommended that the EM survey be repeated in two years, to observe any changes in the plume, and to correlate these changes with the longer-term quantitative well data. Comparison of the two EM surveys made at different times will show the absolute migration rate, and indicate whether the minor lobes are developing into primary pathways.

SECTION XI

CLOSING COMMENTS

Most geophysical methods have been in existence for many years. With the exception of radar, the principles and early applications of the methods discussed in this document can be traced back to the 1930's. In recent years, however, remarkable advances in electronics have allowed geophysical measurements to be carried out more effectively and, in some cases, have helped bring about new technologies.

Most of the geophysical methods have evolved in the mining and oil exploration industries, where the methods are used to evaluate much deeper and larger targets than those at HWS. The use of geophysical methods for evaluations of ground water contamination and geotechnical investigations has become widespread only in the past 5 to 10 years.

Although airborne remote-sensing and downhole geophysical methods are viable investigative approaches at hazardous waste sites, this document addresses only surface geophysics: specifically, the six methods that have been successfully applied to numerous hazardous waste site investigations. These six surface methods are only part of the total geophysical technology which may be applicable to hazardous waste site investigations (Figure 117). Further, geophysics itself is only a small piece of the total subsurface investigation systems approach. Drilling, analytical laboratory methods, trained earth science personnel, sound project management, and many other factors must be used in combination with geophysical technologies in order to solve site investigation problems.

Of the three remote-sensing geophysical approaches, only surface geophysics is considered in this document, and in that connection, only six methods are discussed. The criteria used for the selection of the six methods were presented in Section III and are repeated here:

- the methods are regularly used in HWS assessments;
- they have proven capability in HWS assessments;
- they are suitable for broad application to the problems typically found at HWS.

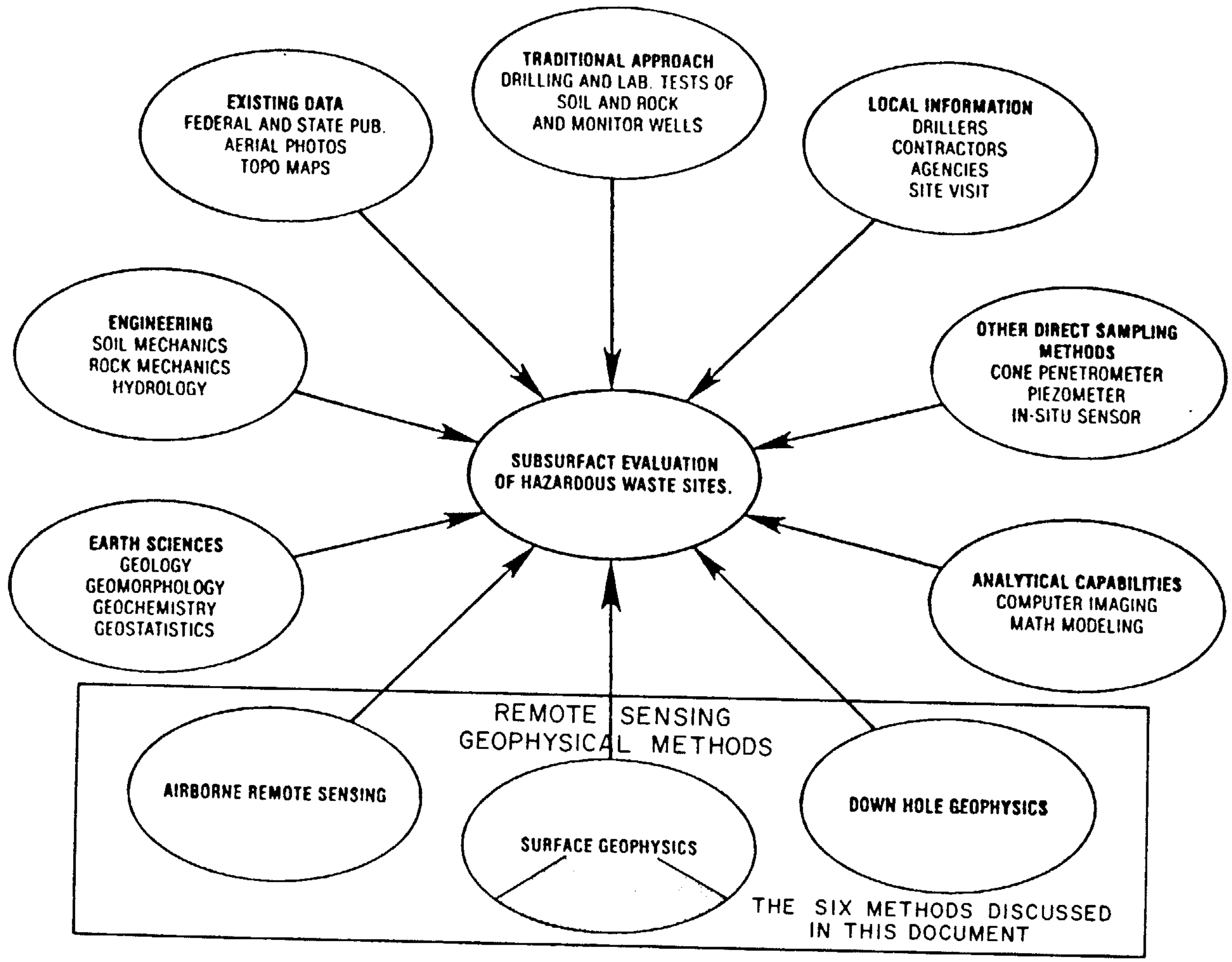


Figure 117. Technical resources and tools which may be applied to subsurface investigations at hazardous waste sites. The six methods discussed in this document represent a small but important portion of the total technology which may be brought to bear.

There are many other geophysical methods and approaches which might be used at HWS, but at this time the authors believe that only those included in this document have met the above cireria.

Pitfalls in Using Geophysical Methods

In the past, use of the geophysical methods in hydrology and engineering geology has been cyclical. One reason for this is that in gathering, processing, and interpreting the data, many pitfalls await the unwary investigator. This section will attempt to outline some of the areas in which pitfalls commonly occur.

Many technical limitations of the methods have been pointed out in this document, although the listing is by no means all-inclusive. However, further discussion of technical limitations, field problems and their pitfalls in data processing and interpretation is well beyond the scope of this document. Unfortunately, this information is not well documented and is much more likely to be discovered by actual experience than by exploring existing literature or texts. This is one reason that trained professionals, with experience in the field, must be used to carry out this work. Pitfalls related to the non-technical aspects of geophysical work are just as important as those in technical areas. Some of them are outlined below.

Non-technical Pitfalls in Using Geophysical Methods

With any technology (drilling, installing monitor wells, analyzing water samples, or computer modeling ground water flow) the user must realize that some problems may arise. They can generally be minimized by well-trained, experienced professional personnel.

- Geophysical instruments are as sophisticated, but unfortunately not as well known or accepted, as the chemist's gas chromatography or mass spectrometer. They are all based upon solid scientific principles, yet many professionals consider geophysical tools to be mysterious "black boxes". Often these black boxes are expected to provide the solution to a problem in some mysterious way. Obviously, they cannot do this.

- Geophysical techniques alone do not generally provide unique solutions to problems. By integrating other knowledge with the geophysical results in a systematic approach, unique solutions can be obtained. If the tools are properly integrated, they can provide outstanding results in terms of site assessment capability. If, however, they are improperly used, the methods can lead to disappointment. The information obtained by integrating geophysics into a program will simply help the investigator arrive at a better answer faster. This requires:

- trained personnel
- experienced personnel
- the right equipment
- a total understanding of the problem
- the ability to integrate a variety of information into the interpretation.

o Like the chemist using a mass spectrometer, the geophysicist must be properly trained in order to obtain accurate results. Not only should this training include equipment operation, it also must encompass a background in the earth sciences. Few universities offer courses in geophysics; those that do are inclined to slant them toward mineral and oil exploration. These applications are sufficiently different from those discussed in this text that direct transfer of technology and personnel is not readily made. Civil engineering programs may also mention some of the geophysical technologies in courses on soil and rock mechanics, but little if any solid training has been provided in these areas.

o Experience has shown that whoever plans to interpret the data should be involved in the data acquisition. No matter how well trained a person may be, an interpretation can be grossly misleading without first-hand familiarity with field conditions.

o There is often a tendency to use short-cut interpretation procedures. Approximation methods are sometimes acceptable if their limitations are clearly understood. All too often, however, approximations are treated as absolutes.

o Investigators often develop a dependence upon a single technology. Individuals or firms may be familiar with only a single geophysical method, which they tend to promote and use extensively. Under such circumstances, the technology may often be applied where its use is not appropriate.

o Often when a specific technique is oversold, it is expected (and often fails) to provide information under conditions for which it was not designed. The potential user must appreciate the limitations as well as the benefits of a geophysical method and must apply that method in the proper manner.

- The use of equipment may be extended beyond its designed capability. This practice may lead to poor results.

Selection of Professional Consultants to Perform Site Investigations

After the project manager has defined his project objectives, they may be achieved in the following ways:

(1) He can contract for data acquisition only, in which case data interpretation must be done by someone else.
(2) He can contract for both data acquisition and interpretation in a single package.
(3) If he is certain of what needs to be done from a geophysical point of view, he may write a contract specifying the use of only a single method.
(4) Many HWS investigations will demand flexibility and may require multiple methods to be used as determined in the field. Such effort requires a very flexible contract and a consultant capable of providing the appropriate geophysical services. The geophysical data must be incorporated with the existing geological, hydrological, biological and chemical data into a composite understanding of site conditions.

There are firms which offer data acquisition only, at reduced prices. The authors of this document do not believe that this is an effective approach to the problem, because the data acquisition is often accomplished by non-professionals who may not be able to evaluate site conditions and to respond accordingly.

There are many qualified persons and firms who are capable of providing both data acquisition and interpretation with any single seismic refraction or resistivity method discussed in this text. On the other hand, in some of the newer or specialized areas (radar, continuous EM, specialized metal detectors and magnetometry) there are only a few experienced persons to be found in the entire U.S. In many cases, their expertise covers only one method. However, if project requirements can be defined with sufficient accuracy for one method to yield the necessary information, then this can be a viable approach.

Only a limited number of professional firms have the broad-based capability and experience in applying the six methods discussed herein. Even fewer have experience on hazardous waste sites. The authors estimate that at the time of this writing there are fewer than ten firms in the U.S. which might offer this inclusive capability. Clearly, this integrated systems approach to carry out the HWS investigation with the flexibility and synergism of multiple geophysical methods provides the most cost-effective approach to the project. It is in this area that the most effective HWS investigations have been carried out to date. By use of this approach, the project manager can construct a complete package including:

- flexibility;
- multiple geophysical methods;
- data acquisition;
- data interpretation;
- total integration of the project;
- a professionally trained and experienced staff.

Clearly, the project manager should determine if the firm and individual(s) performing the services are experienced in such investigations. Further, he should ascertain the qualifications and training of personnel, and the types of equipment recommended to perform the surveys. In most instances, the consultant should own the equipment used for the survey. If not, chances are that the firm and its field party do not have adequate experience. A hazardous waste site is not a training ground.

Finally, the project manager must develop confidence in the professional abilities of his qualified consultants. He should utilize his consultant's experience to optimize the outcome of the field investigation. In addition, he should see that the contract is flexible and that it allows for options in adjusting the work to achieve optimal project objectives.

Cost Comparison: Systems vs. Traditional Approach

When making a cost comparison, one cannot evaluate geophysical field project costs versus the costs of drilling and installing a monitor well only. The only reasonable way to make a cost comparison is to look at the total project bottom-line costs. If it will speed the basic understanding of site conditions and improve the accuracy of an assessment, the integrated systems approach which uses geophysics is the low-cost approach to take. The systems approach requires less drilling and fewer monitor wells, thereby minimizing the number of chemical analyses necessary. The results are lower program costs with a better understanding of site conditions achieved in a shorter time.

Figure 118 shows a cost comparison of a combined geophysical systems approach versus monitor wells only. The curve shows cost versus number of wells. Monitor well costs are based upon a total program cost of $3,000 to $10,000 per well which includes drilling, installation of a quality monitor well, well development, initial sampling, analysis of priority pollutants, and a subsequent quarterly sample program over one year, including supporting reports and project management. All wells are assumed to be 10 meters deep. The costs are conservative in that the direct costs and intangible risks of drilling into highly hazardous areas are included.

Costs for the geophysical systems approach are based upon a site survey coverage approaching 100%, plus three monitor wells and all supporting efforts, reports and project management as described above. One well is typically used for background measurement, and two are placed in representative locations to quantify specific contaminants within a plume.

The geophysical systems approach becomes increasingly cost-effective as the number of required monitor wells increases. The more complex the site, and the greater the number of unknowns and risks, the greater are the benefits to be derived from using such a systems approach. The level of confidence in the results of the site investigation will increase, and the risk that the investigation will create a serious health, fire or explosion hazard will be reduced.

Future Possibilities

A methodology for investigation of HWS exists today--there is no need to wait for future developments to occur, although some improvements in the six methods are expected. Each method has potential for refinements in hardware, processing and interpretation. For example, some improvement in the depth and operation of radar in more difficult soil conditions can be expected. Advances in real-time processing and plotting of radar data are also under way. Seismic methods will be using processing systems which provide higher resolution, thus permitting more detailed investigations. Metal detectors will attain slightly greater depth capabilities, and interpretive techniques for both metal detector and magnetometer data are expected to improve.

The greatest advancement will likely be the integration of various hardware systems into a single sensing network. Highspeed recording and processing will be applied to combined data sets, as well as to individual sensor data.

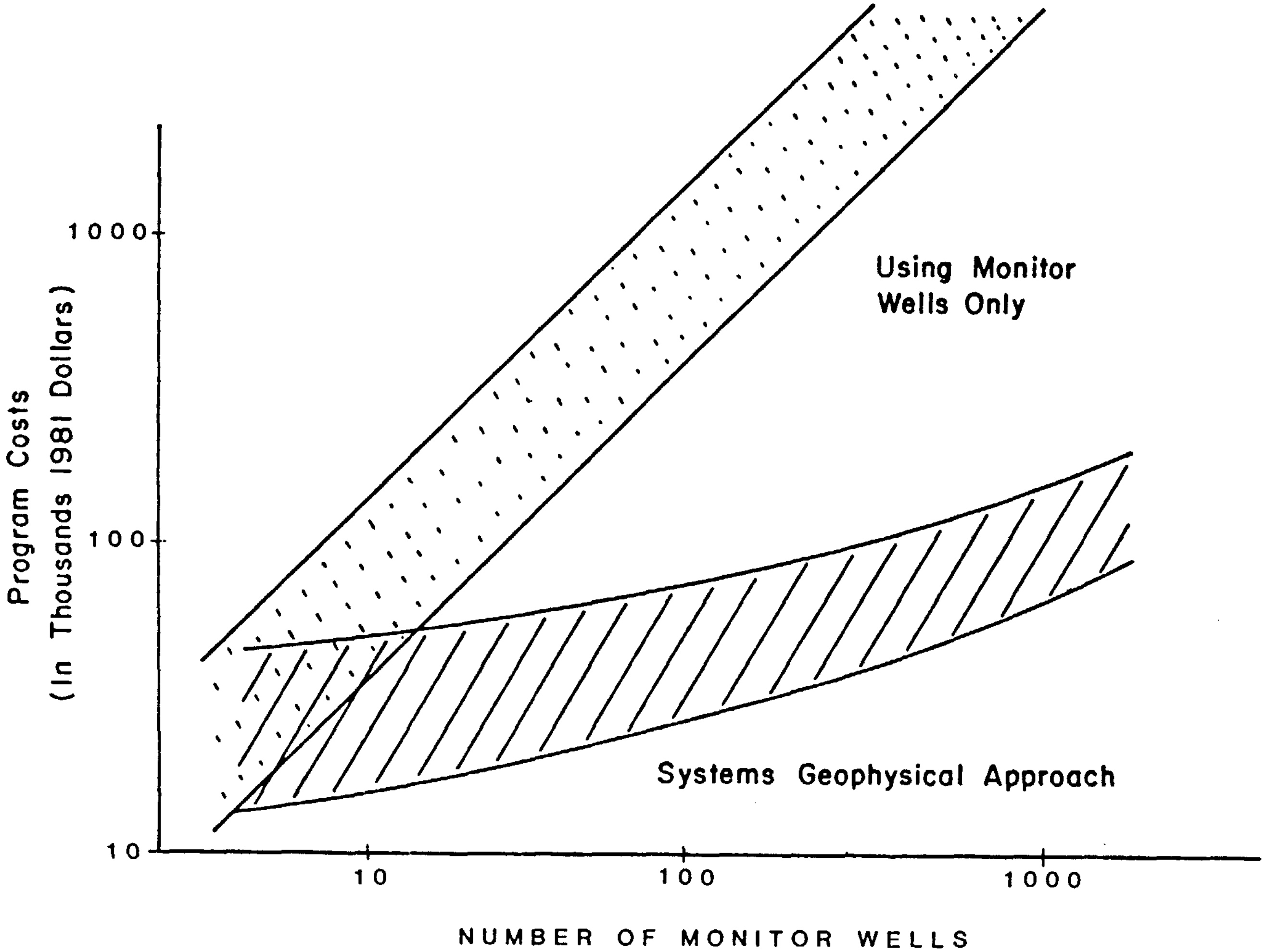


Figure 118. Cost comparison curve for hazardous waste site investigation using monitor wells alone versus an integrated systems approach. (Overall project accuracy and effectiveness are not considered in this data.)

Other techniques will come into use. For example, transient EM can provide increased sounding capability to depths of 300 meters or more, and complex resistivity may provide more diagnostic information than traditional resistivity measurements. While neither of these methods has yet been applied to hazardous waste sites, they and others may eventually come to be used and may one day supplement the six existing technologies described in this document.

Meanwhile, those six methods will continue to make a contribution to hazardous waste site assessment.

BIBLIOGRAPHY

Benson, R. C., and R. A. Glaccum. 1979a. Radar Surveys for Geotechncal Site Assessment. In: Geophysical Methods in Geotechnical Engineering, Specialty Session, American Society of Civil Engineers, Atlanta, Georgia. pp. 161-178.

Benson, R. C., and R. A Glaccum. 1979b. Remote Assessment of Pollutants in Soil and Groundwater. In: Proceedings of the Hazardous Material Risk Assessment, Disposal and Management Conference, Miami Beach, Florida. pp. 188-194.

Benson, R. C., and R. A. Glaccum. 1980. Site Assessment: Improving Confidence Levels with Surface Remote Sensing. In: Proceedings of National Conference on Management of Uncontrolled Hazardous Waste Sites, Washington, D.C. pp. 59-65.

Benson, R. C., R. A. Glaccum, and P. Beam. 1981. Minimizing Cost and Risk in Hazardous Waste Site Investigations Using Geophysics. In: Proceedings of National Conference on Management of Uncontrolled Hazardous Waste Sites, Washington, D.C. pp. 84-88.

Breiner, S. 1973. Applications Manual for Portable Magnetometers. Geometric, Sunnyvale, California. 58 pp.

Evans, R. B. 1982. Currently Available Geophysical Methods for Use in Hazardous Waste Site Investigations. American Chemical Society Symposium Series, No. 204. pp. 93-115.

Evans, R. B., R. C. Benson, and J. Rizzo. 1982. Systematic Hazardous Waste Site Assessments. In: Proceedings of National Conference on Management of Uncontrolled Hazardous Waste Sites, Washington, D.C. pp. 17-22.

Freeze, R. A, and J. A. Cherry. 1979. Groundwater. Prentice-Hall, Inc., Englewood Cliffs, New Jersey. 604 pp.

Geraghty and Miller. 1978. Electrical Resistivity Evaluations at Solid Waste Disposal Facilities. U.S. Environmental Protection Agency, Washington, D.C. 94 pp.

Geraghty, J. J. 1980. Evaluation of Hydrogeologic Conditions. In: Proceedings of National Conference on Management of Uncontrolled Hazardous Waste Sites, Washington, D.C. pp. 49-52.

Glaccum, R. A., R. C. Benson, and M. R. Noel. 1982. Improving Accuracy and Cost-Effectiveness of Hazardous Waste Site Investigations. Ground Water Monitoring Review, Summer, 1982. pp. 36-40.

Gilkeson, R. H., and K. Cartwright. 1982. The Application of Surface Geophysical Methods in Monitoring Network Design. In: Proceedings of Second National Symposium on Aquifer Restoration and Ground Water Monitoring, Columbus, Ohio. pp. 169-183.

Greenhouse, J. P., and D. D. Slaine. 1982. Case Studies of Geophysical Contaminant Mapping at Several Waste Disposal Sites. In: Proceedings of Second National Symposium on Aquifer Restoration and Ground Water Monitoring, Columbus, Ohio. pp. 299-315.

Griffiths, D. H., and R. F. King. 1969. Applied Geophysics for Engineers and Geologists. Pergamon Press, Elmsford, New York. 223 pp.

Horton, K. A., R. M. Morey, L. Isaacson, and R. H. Beers. 1981. The Complementary Nature of Geophysical Techniques for Mapping Chemical Waste Disposal Sites: Impulse Radar and Resistivity. In: Proceedings of National Conference on Management of Uncontrolled Hazardous Waste Sites, Washington, D.C. pp. 158-164.

Johnson, R. W., R. A. Glaccum, and R. Wojtasinski. 1980. Application of Ground Penetrating Radar to Soil Survey. In: Proceedings of Soil and Crop Science Society of Florida, vol. 39. pp. 68-72.

Leis, P. G., and K. A. Sheedy. 1980. Detailed Location of Inactive Disposal Sites. In: Proceedings of National Conference on Management of Uncontrolled Hazardous Waste Sites, Washington, D.C. pp. 116-118.

Lord, A. E. Jr., R. M. Koerner, and J. E. Brugger. 1980. Use of Electromagnetic Wave Methods to Locate Subsurface Anomalies. In: Proceedings of National Conference on Management of Uncontrolled Hazardous Waste Sites, Washington, D.C. pp. 119-124.

McKown, G. L., and G. A. Sandness. 1981. Computer-Enhanced Geophysical Survey Techniques for Exploration of Hazardous Waste Sites. In: Proceedings of National Conference on Management of Uncontrolled Hazardous Waste Sites, Washington, D.C. pp. 300-305.

McNeill, J. D. 1980a. Electrical Conductivity of Soils and Rocks. Technical Note TN-5. Geonics Limited, Ontario, Canada. 22 pp.

McNeill, J. D. 1980b. Electromagnetic Terrain Conductivity Measurement at Low Induction Numbers. Technical Note TN-6. Geonics Limited, Ontario, Canada. 15 pp.

McNeill, J. D. 1982. Electromagnetic Resistivity Mapping of Contaminant Plumes. In: Proceedings of National Conference on Management of Uncontrolled Hazardous Waste Sites, Washington, D.C. pp. 1-6.

Mooney, H. M. 1973. Handbook of Engineering Geophysics, Volume 1: Seismic. Bison Instruments, Minneapolis, Minnesota. 216 pp.

Mooney, H M. 1980. Handbook of Engineering Geophysics, Volume 2: Electrical Resistivity. Bison Instruments, Minneapolis, Minnesota. 90 pp.

Noel, M. R., R. C. Benson, and R. A. Glaccum. 1982. The Use of Contemporary Geophysical Techniques to Aid Design of Cost-Effective Monitoring Well Networks and Data Analysis. In: Proceedings of Second National Symposium on Aquifer Restoration and Ground Water Monitoring, Columbus, Ohio. pp. 163-168.

Pease, R. W. Jr., and S. C. James. 1981. Integration of Remote Sensing Techniques with Direct Environmental Sampling for Investigating Abandoned Hazardous Waste Sites. In: Proceedings of National Conference on Management of Uncontrolled Hazardous Waste Sites, Washington, D.C. pp. 171-176.

Sgambat, J. P., and J. R. Stedinger. 1981. Confidence in Ground-Water Monitoring. Ground Water Monitoring Review, Spring, 1981. pp. 62-69.

Telford, W. M., L. P. Geldart, R. E. Sheriff, and D. A. Keys. 1976. Applied Geophysics. Cambridge University Press, New York. 860 pp.

White, R.M., and S. S. Brandwein. 1982. Application of Geophysics to Hazardous Waste Investigations. In: Proceedings of National Conference on Management of Uncontrolled Hazardous Waste Sites, Washington, D.C. pp. 91-93'

Yaffe, H. J., N. L. Cichowicz, and P. J. Stoner. 1980. Remote Sensing for Investigating Buried Drums and Subsurface Contamination at Coventry, Rhode Island. In: Proceedings of National Conference on Management of Uncontrolled Hazardous Waste Sites, Washington, D.C. pp. 239-249.

Zohdy, A. A., G. P. Eaton, and D. R. Mabey. 1974. Application of Surface Geophysics to Ground-Water Investigations. Techniques of Water-Resources Investigations of the United State Geological Survey, Chapter D1. 116 pp.

Procedures Manual for Ground Water Monitoring at Solid Waste Disposal Facilities. U.S. Environmental Protection Agency, Cincinnati, Ohio, 1977. 269 pp.