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Use of Airborne, Surface, and Borehole Geophysical Techniques at Contaminated Sites

A Reference Guide

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USE OF AIRBORNE, SURFACE, AND BOREHOLE GEOPHYSICAL TECHNIQUES AT CONTAMINATED SITES: A REFERENCE GUIDE

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Prepared by:

Eastern Research Group
110 Hartwell Avenue
Lexington, MA 02173

For:

Office of Science Planning and Regulatory Evaluation
Center for Environmental Research Information
U.S. Environmental Protection Agency
26 West Martin Luther King Drive
Cincinnati, OH 45268

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Author

J. Russell Boulding, Eastern Research Group, Inc. (ERG)

Project Management

Susan Schock, EPA CERI, Cincinnati, Ohio
Heidi Schultz, ERG, Lexington, Massachusetts

Reviewers:

Hugh F. Bennett, Department of Geological Sciences, Michigan State University, East Lansing, Michigan
Regina Bochicchio, Desert Research Institute, Las Vegas, Nevada
Peter Haeni, U.S. Geological Survey, Water Resources Division, Hartford, Connecticut
Paul C. Heigold Illinois State Geological Survey, Champaign, Illinois
Scott E. Hulse, Lockheed Corporation, Las Vegas, Nevada
J. Duncan McNeill, Geonics Limited, Mississaugua, Ontario, Canada
Gary Olhoeft, U.S. Geological Survey, Denver, Colorado
Benjamin H. Richard, Department of Geological Sciences, Wright State University, Dayton, Ohio

GLOSSARY OF ABBREVIATIONS

Method Abbreviations

AEM - airborne electromagnetic
AFMAG - audiofrequency magnetic
AMT - audiomagnetotelluric
ATV - acoustic televiewer
BH - borehole
CSAMT - controlled source audiomagnetotelluric
CSP - continuous seismic profling
Eh - Oxidation reduction
EM - electromagnetic (used when not enough information available to classify further)
EMI - electromagnetic induction
ER - electrical resistivity
GDT - geophysical diffraction tomography
GPR - ground penetrating radar
GR - gravity
IP/CP - induced polarization/complex resistivity
IR - infrared
MAG - magnetic
MD - metal detection
MT - Magnetotelluric
S - seismic (used when not enough information available to classify further)
SASW - spectral analysis of surface waves
SLAR - side-looking airborne radar
SP - Self-potential (surface and borehole)
SRR - seismic refraction
SRL - seismic reflection
TC - telluric current
TDEM - time domain electromagnetic
VSP - vertical seismic profiling

Other Abbreviations

AGWSE - Association of Ground Water Scientists and Engineers (of NWWA/NGWA)
AIMME - American Institute of Mining and Metallurgical Engineers
API - American Petroleum Institute
ASTM - American Society for Testing and Materials
CERI - Center for Environmental Research Information (U.S. EPA)
DNAPL - dense nonaqueous phase liquid
DOE - Department of Energy
EEGS - Environmental and Engineering Geophysical Society (SEMEG prior to 1992)
EPA - Environmental Protection Agency
GWM - Ground Water Management (NWWA/NGWA symposium series)
HMCRI - Hazardous Materials Control Research Institute
NAPL - nonaqueous phase liquid
NTIS - NationaI Technical Information Service
NWWA/NWGA - National Water Well Association (became National Ground Water Association in 1992)
NOAC - National Outdoor Action Conference (NWWA sponsored)
SAGEEP - Symposium on Application of Geophysics to Engineering and Environmental Problems
SEG - Society of Exploration Geophysicists
SEMEG - Society of Engineering and Mineral Exploration Geophysicists (became EEGS in 1992)
SPWLA - Society of Professional Well Log Analysts
UST - underground storage tank
VOC - volatile organic compounds

PREFACE

The Purpose of This Guide

The use of geophysical methods in the study of contaminated sites has gained wide acceptance in the last decade as a cost-effective means of performing preliminary site characterization and ongoing monitoring. At the same time, the multiplicity of available methods, the use of differing terms to describe the same method, and the high degree of technical proficiency required for the application and interpretation of data from specific methods often causes confusion and misunderstanding in the mind of the nongeophysicist.

There is a moderately large body of scientific literature on the use of geophysical techniques for ground-water investigations that dates back to the late 1930s. However, with the exception of perhaps a dozen or so papers published in the 1970s on the use of electrical resistivity methods for identifying contaminant plumes, the rapidly growing amount of literature on the use of geophysical methods for characterizing and monitoring contaminated sites has been published since 1980.

The purpose of this reference guide is four fold:

1. To describe both commonly used and less common geophysical methods in relatively nontechnical terms for nongeophysicists involved in investigating and monitoring contaminated sites. To this end, important terms are highlighted the first time they are introduced in the text.

2. To provide guidance on where to find more detailed information on specific methods, through the use of tables describing major texts and reports, and index tables that catalog references at the end of each chapter according to method and applications. Section 1.4 provides an introduction to the geophysical literature and suggestions on how it should be used.

3. To provide information on designing and evaluating a geophysical program at contaminated sites, including various tables summarizing the applicability of geophysical methods for different aspects of contaminated site characterization and monitoring (Chapter 8).

4. To provide summary information on case studies on the use of surface and borehole geophysical methods at contaminated sites (Appendix A). Summary tables include information on (1) site location, (2) contaminants involved, (3) site geology, (4) type of method used, and (5) the reference for the case study.

Relationship to Other EPA Documents

This guide is intended to complement rather than duplicate other EPA documents that deal with use of geophysical methods at contaminated sites, although some overlap is inevitable. The text is intended to provide some understanding of basic principles involved in the use of geophysical methods and a conceptual framework for understanding the relationship between both commonly used and less commonly used geophysical methods for **nongeophysicists.** This reference guide has been designed to serve as a companion to sections 1 and 3 of EPA's *Subsurface Field Characterization and Monitoring Techniques: A Desk Reference Guide* (U.S. EPA, 1993), * which cover remote sensing/surface geophysical and borehole geophysical methods, respectively. A number of the summary tables from that document also are used in this reference guide to reduce the need to go back and forth between the documents. However, users of this guide who are interested in further information about the less commonly used geophysical methods may want to refer to the summary sheets in the Desk Reference Guide before seeking out particular references. Table 1-1 (remote sensing and surface geophysical methods) and Table 7-1 (borehole geophysical methods) in this guide can be used to locate discussions of specific methods in the Desk Reference Guide.

This reference guide is *not* intended to provide guidance on how to use specific geophysical methods. EPA's *Geophysics Advisor Expert System* (Olhoeft, 1992)* is recommended for preliminary assistance in identifying the potential of commonly used surface geophysical methods for site-specific conditions. The following EPA documents are recommended for more detailed information on the use of the more commonly used geophysical methods at contaminated sites: *Geophysical Techniques for Sensing Buried Wastes and Waste Migration* (Benson et al., 1984),* and *A Compendium of Superfund Field Operations Methods, Part 2* (U.S. EPA, 1987).* The Society of Exploration Geophysicists' three-volume set, *Geotechnical and Environmental Geophysics* (Ward, 1990a-c)* is a good comprehensive source on theory and applications of geophysical methods in environmental investigations. Other major general references are described in Table 1-4 for surface geophysics and in Table 7-1 for borehole methods. Nongeophysicists who use this reference guide should consult several experts whenever in doubt about the capabilities or appropriateness of a specific method (see Appendix B).

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* See Chapter 1 for full citations,

CHAPTER 1
OVERVIEW

1.1 General Terminology

Geophysical techniques are used to assess the physical and chemical properties of soils, rock and ground water based on the response to either (1) various parts of the **electromagnetic** (EM) spectrum, including gamma rays, visible light, radar, microwave, and radio waves (Figure 1-la,b), (2) **acoustic** and/or **seismic** energy, or (3) other **potential** fields, such as gravity and the earth's magnetic field.

Most portions of the electromagnetic spectrum are used by one or more specific geophysical methods. In common usage, however, the term **electromagnetic is** restricted to techniques that measure subsurface conductivities by low-frequency electromagnetic induction (Benson et al., 1984a,b; Nabighian, 1988, 1991). Sections 3.1 discusses additional terminology used to describe electrical and electromagnetic methods, respectively. Terminology used for methods involving the radar and microwave portions of the EM spectrum varies considerably (see Section 6.1.1). The term **radioactive/nuclear** methods refers to sensing involving the shortest wavelengths (x-rays and gamma rays).

Acoustics refers broadly to the phenomena of the vibrations of elastic bodies (air, water or solids) in response to sound energy. Use of the term **seismic** usually is restricted to methods that observe the vibration response of acoustic energy in the earth (i.e., all seismic methods are acoustic, but the term acoustic does not necessarily imply a seismic method). Chapter 5 discusses additional terminology for seismic and acoustic methods.

In the broadest sense most geophysical techniques involve noninvasive, noncontact remote sensing; that is, the observation of an object or phenomenon without the sensor being in direct contact with the object being sensed. In common usage, however, the term **remote sensing** is often restricted to the use of airborne or satellite sensing methods in the visible and near-visible

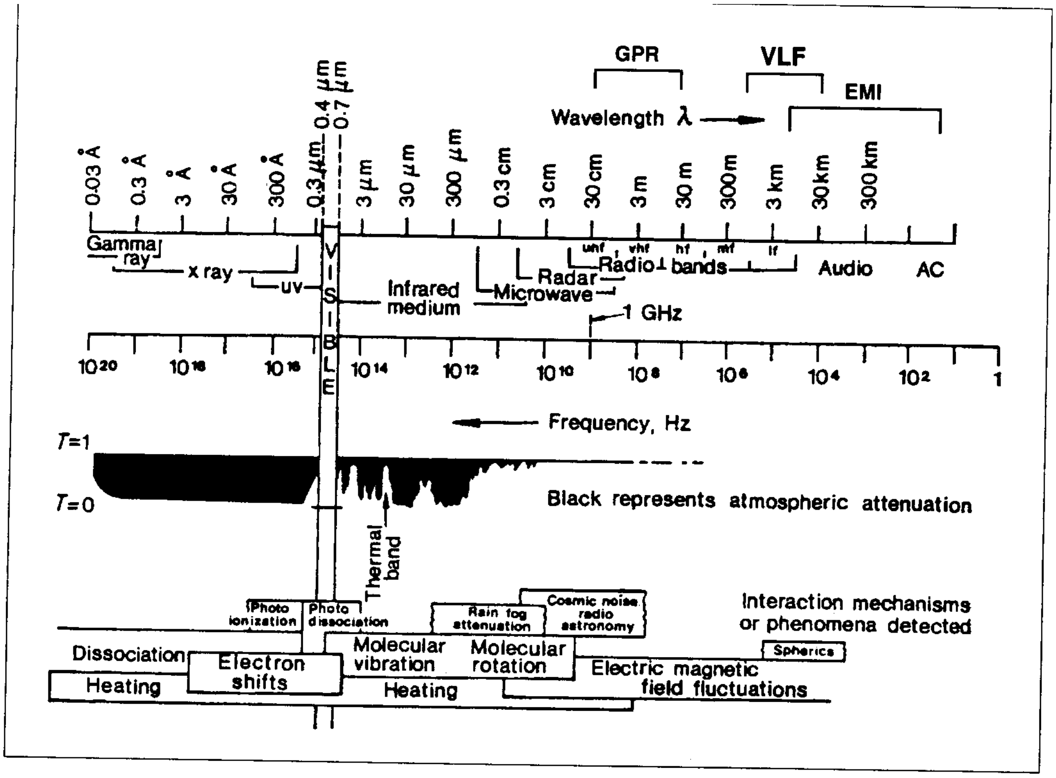

Figure l-la The electromagnetic spectrum: customary divisions and portions used for geophysical measurements (adapted from Erdé1yi and Gá1fi, 1988).

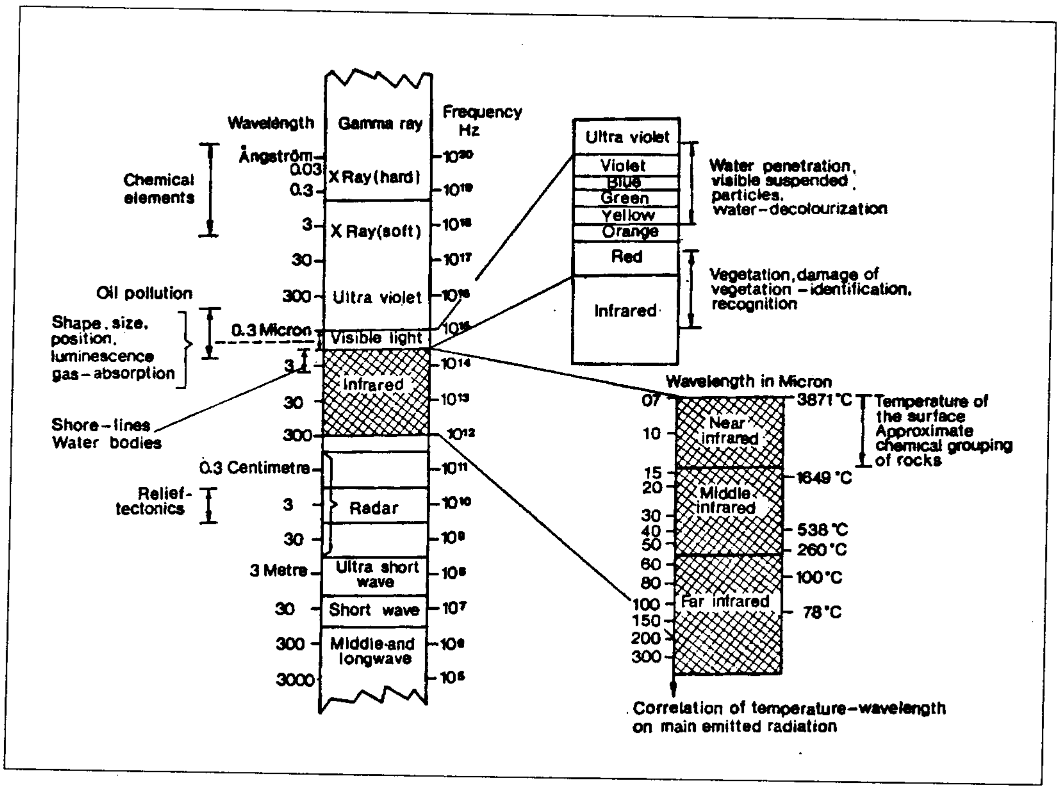

Figure l-lb The electromagnetic spectrum: factors and phenomena influencing the radiation of electromagnetic waves (adapted from Erdé1yi and Gálfi, 1988).

portions of the EM spectrum. While **nondestructive testing** (NDT) has been used to describe geophysical methods used in the context of detecting contained, subsurface hazardous waste (Lord and Koerner 1987), the term usually is restricted to methods for testing the integrity of manufactured materials.

Terminology in the published literature, particularly for electrical and electromagnetic methods, can vary considerably. This can be dealt with in two ways: (1) by becoming familiar with the variety of terms that are applied to a single method and (2) by understanding the basic principles of different methods so that a method can be identified by reading a description of the equipment and field techniques used (Nabighian, 1988, 1991).

1.2 Uses of Geophysical Methods

The greatest benefits of geophysical methods come from using them early in the site characterization process since they are typically nondestructive, less risky, cover more area spatially and volumetrically, and require less time and cost than using monitoring wells. On the other hand, great skill is required in interpreting the data generated by these methods, and their indirect nature creates uncertainties that can only be resolved by use of multiple methods and direct observation. Consequently, preliminary site characterization by geophysical methods will usually be followed by direct observation through the installation of monitoring wells.

Geophysical techniques can be used for a number of purposes in ground-water contamination studies:

- **Geologic characterization,** including assessing types and thicknesses of strata and the topography of the bedrock surface below unconsolidated material, and generating fracture mapping and paleochannels.
- **Aquifer characterization,** including depth to water table, water quality, hydraulic conductivity, and fractures.
- **Contaminant plume identification,** both vertical and horizontal distribution including monitoring changes over time.

- **Locating buried wastes and other anthropogenic features** through identification of buried metal drums, subsurface trenches, and other features (e.g., cables, pipelines).

The use of surface geophysical methods for prospecting for ground water using electrical resistivity methods dates from the late 1920s. A review of geophysical methods for water exploration by Breusse (1963) focuses almost exclusively on electrical resistivity methods. Electrical resistivity continued to be the most commonly used surface method for the study of ground water until the early 1980s when electromagnetic induction gained increasing popularity for near-surface investigations. The next most frequently used surface method for the study of ground water has been seismic refraction, dating primarily from the 1960s although there are scattered references in the literature back to 1949 (see Table 5-2).

Early successes in the 1970s using electrical methods (i.e., measurement of variations in conductivity or its reciprocal, resistivity) to locate contaminant plumes and measure the hydrogeologic properties of aquifers led to the adaptation of a large number of geophysical methods in ground-water contamination investigations. Then, in the late 1970s the availability of microcomputers revolutionized the use of field geophysics by allowing onsite processing of the vast amount of data generated by most of these techniques. Use of geophysical methods in hydrogeologic studies became so widespread in the 1980s that techniques such as electromagnetic induction, seismic refraction, ground-penetrating radar, and magnetometry are no longer considered innovative but state-of-the-practice. Innovations in these and numerous other geophysical methods continue at a rapid rate. Time domain electromagnetic methods (Section 4.2), shallow seismic reflection (Section 5.2), and seismic shear methods have been used with increasing frequency since the mid 1980s.

1.3 General Characteristics of Geophysical Methods

1.3.1 Airborne, Surface, and Downhole Methods

Geophysical investigation techniques can be broadly grouped into three categories: (1) airborne, (2) surface, and (3) borehole or downhole methods. **Airborne** remote sensing and geophysical methods are discussed in Chapter 2. **Surface** methods usually involve wave generators and sensors at or near the ground surface. In this reference guide surface methods are covered in four chapters: electrical (Chapter 3), electromagnetic (Chapter 4), seismic and acoustic (Chapter 5), and other surface methods, including ground penetrating radar, magnetic, gravimetric, and thermal methods (Chapter 6). (Table 1-1 provides an overview of the major uses and depth of penetration of airborne and surface geophysical methods; section numbers arc provided indicating where additional discussion can be found in **Subsurface Field Characterization and Monitoring Techniques** [U.S. EPA 1993]). **Downhole** methods, including single borehole, hole-to-hole, and surface-to-borehole methods, also are covered (Chapter 7), and a number of summary tables are provided on the characteristics and uses of borehole geophysical methods.

Each of these three major categories comprises numerous specific techniques, and a specific technique may have a number of variants. Table 1-2 describes seven major surface geophysical methods and their hydrogeologic applications. **Electromagnetic induction** (see Section 4.1) also is commonly used in both airborne and downhole studies. **Electrical resistivity** (see Section 3.2) also is commonly used as a downhole method, but cannot be used as an airborne method because it requires ground contact. **Ground penetrating radar** (see Section 6.1) can be used from the air, but is most commonly used on the ground surface and, less frequently, in boreholes. **Seismic refraction** (see Section 5.1) is primarily a surface method, although vertical seismic profiling is a relatively new downhole method that has been used in several studies of contaminated sites (see Section 7.3.3). **Magnetometry** and **gravimetrics** are used as airborne methods where large areas need to be evaluated, but site-specific investigations generally require use of surface measurements (see Sections 6.2 and 6.3). **Thermal** methods are most commonly used in downhole investigations (see Section 6.4), but shallow measurements have been used in the study of ground water (see Section 6.4.1). **Radioactive** methods in the study of ground water (not shown on Table 1-2) are used almost exclusively as a downhole method, but instruments that detect ionizing radiation are widely used as a surface technique at sites involving radioactive wastes. Various types of radiation monitoring instruments, such as proportional, Geiger-Mueller, and scintillation counters, can be used to detect radioactive contamination. Surface radiation detection methods are not covered further in this guide, but additional information can be found in U.S EPA (1993-Section 1.5.4).

Table 1-1 Summary Information on Remote Sensing and Surface Geophysical Methods (all ratings are approximate and for general guidance only)

Technique	Soils/ Geology	Leachate	Buried Wastes	NAPLs	Penetration Depth (m)[a]	Cost[b]	Section in U.S EPA (1993)
Airborne Remote Sensing and Geophysics							
Visible Photograpby+	yes	yes[c]	possiby[d]	yes[c]	Surf. only	L	1.1.1
Infrared Photography+	yes	yes[c]	possibly[d]	yes[c]	Surf. only	L-M	1.1.1
Multispectral Imaging	yes	yes[c]	no	yes[c]	Surf. only	L	1.1.1
Ultraviolet Photography	yes	yes[c]	no	yes[c]	Surf. only	L	1.1.2
Thermal Infrared Scanning	yes	yes (T)	possibly[d]	possibly	Surf. only	M	1.1.3
Active Microwave (Radar) +	yes	possibly	no	possibly	0.1-2	M	1.1.4
Airborne Electromagnetics	yes	yes (C)	yes	possibly	0-100	M	1.1.5
Aeromagnetics	yes	no	yes	no	10s-100s	M	1.1.6
Surface Electrical and Electromagnetic Methods							
Self-Potential	yes	yes (C)	yes	no	S ?	L	1.2.1
Electrical Resistivity+	yes	yes (C)	yes (M)	possibly	S 60 (km)	L-M	1.2.2, 9.1.1
Induced Polarization	yes	yes (C)	yes	possibly	S km	L-M	1.2.3
Complex Resistivity	yes	yes (C)	yes	yes	S km	M-H	1.2.3
Dielectric Sensors	yes	yes (C)	no	possibly	S 2[e]	L-M	6.2.3
Time Domain Reflectometry	yes	yes (C)	no	yes	S 2[e]	M-H	6.2.4
Capacitance Sensors	yes	yes (C)	no	possibly	S 2[e]	L-M	6.2.4
Electromagnetic Induction+	yes	yes (C)	yes	possibly	S 60(200)/ c 15(50)	L-M	1.3.1
Transient E1ectromagnetics	yes	yes (C)	yes	no	S 150 (2000+)	M-H	1.3.2
Metal Detectors	no		yes	no	C/S 0-3	L	1.3.3
VLF Resistivity	yes	yes (C)	yes	no	C/S 20-60	M-H	1.3.4
Magnetotellurics	yes	yes (C)	no	no	S 1000+	M-H	1.3.5
Surface Seismic and Acoustic Methods							
Seismic Refraction+	yes	yes	no	no	S l-30(200+)	L-M	1.4.1
Shallow seismic Reflection+	yes	no	no	no	S 10-30(2000+)	M-H	1.4.2
Continuous Seismic Profiling	yes	no	no	no	C 1-100	L-M	1.4.3
Seismic Shear/Surface Waves	yes	no	no	no	S 2 10s-100s	M-H	1.4.4
Acoustic Emission Monitoring	yes	no	no	no	S 2[e]	L	1.4.5
Sonar/Fathometer	yes	yes	no	no	C no limit	L-H	1.4.6
Other Surface Geophysical Methods							
Ground Penetrating Radar+	yes	yes (C)	yes	yes	C 1-25 (100s)	M	1.5.1
Magnetometry+	no	no	yes (F)	no	C/S 0-20[f]	L-M	1.5.2
Gravity	yes	yes	no	no	S l00s+	H	1.5.3
Radiation Detection	no	no	yes (nuclear)	no	C/S near surface	L	1.5.4
Near-Surface Geothermometry							
Soil Temperature	yes	yes (T)	no	no	S l-2[e]	L	1.6.1
Ground-Water Detection	yes	yes (T)	no	no	S 2[e]	L	1.6.2
Other Thermal Properties	yes	no	no	no	S 1-2[e]	L-M	1.6.3

Boldface = Most commonly used methods at contaminated sites; + = covered in Supcrfund Field Operations Manual (U.S. EPA 1987); (C) = plume detected when contaminant(s) change conductivity of ground wateer (F) = ferrous metals only (T) = plume detected by temperature rather than conductivity.

[a]S = station measurement C = continuous measurement. Depths are for typical shallow applications; ( ) = achievable depths.

[b]Ratings are very approximate L = low, M = moderate, H = high.

[c]If leachate or NAPLs are on the ground or water surface or indirectly affect surface properties; field confirmation required.

[d]Disturbed areas that may contain buried waste can often be detected on aerial photographs.

[e]Typical maximum depth, greater depths possible, but sensor placement is more difficult and cable lengths must be increased.

[f]For ferrous metal detection, greater depths require larger masses of metal for detection; l00s of meters depth can be sensed when using magnetometry for mapping geologic structure.

Table 1-2 Major Surface Geophysical Methods for Study of Subsurface Contamination

Method	Description	Hydrogeologic Applications
Electromagnetic induction (EMI) (Section 4.1)	Uses a transmitter coil to generate currents that induce a secondary magnetic field in the earth that is measured by a receiver coil. Well suited for areal searches.	Can be used to map a wide variety of subsurface features including natural hydrogeologic conditions, delineation of contaminant plumes, rate of plume movement, buried wastes, and other artificial features (e.g., buried drums, pipelines). Depth of penetration is typically up to 60 meters but depths to 200+ meters are possible.[a]
DC electrical Resistivity (Section 3.2)	Measures the resistivity of subsurface materials by injecting an electrical current into the ground by a pair of surface electrodes and measuring the resulting potential field (voltage) between a second pair of electrodes.	Similar to electrical conductivity (see above), except not widely used to detect metallic objects, for which magnetic and EMI methods are more effective. Better for depth sounding than frequency domain EMI.
Seismic refraction (Section 5.1) and reflection (Section 5.2)	Uses a seismic source (commonly a sledge hammer), an array of geophones to measure travel time of the refracted/reflected seismic waves, and a seismograph that integrates the data from the geophones.	Can be used to define the thickness and depth to bedrock or water table, thickness of soil and rock layers, and their composition and physical properties; may detect anomalous subsurface features such as pits and trenches.[b]
Magnetometry (Section 6.2)	Uses a magnetometer to measure the intensity of the earth's magnetic field. The presence of ferrous metals can be detected by the variations they create in the local magnetic field.	Used to locate buried metal drums that may be sources of soil and ground-water contamination.

Table 1-2 (cont.)

Method	Description	Hydrogeologic Applications
Ground penetrating radar (GPR) (Section 6.1)	Uses a transmitter coil to emit high-frequency radio waves that are reflected off subsurface changes in electrical properties (typically density and water-content variations) and detected by a receiving antenna.	Can map soil layers, depth of bedrock buried stream channels, rock fractures, cavities in natural settings, buried waste materials. Maximum depth of penetration under favorable conditions is around 25 meters. 100s of meters penetration may be possible in highly resistive materials (salt or ice).
Gravimetry (Section 6.3)	Uses one or more of several types of instruments that measure the intensity of the earth's gravitational field.	Can be used to estimate depth of unconsolidated material over bedrock and boundaries of landfills, which have a different density than natural soil material. Microgravity surveys may be able to detect subsurface cavities and subsidence voids.
Thermal (Section 6.4)	Uses temperature sensors anomalies in the soil or surface water.	Can be used to delineate shallow ground-water flow systems, buried valley aquifers, recharge and discharge zones, zones of high permeability, leakage beneath earthen dam embankments, and location of solution channels in karst.

[a]Depth of penetration more than 2,000 meters is possible with use of time domain methods (Section 4.2).

[b]High resolution shallow seismic reflection is increasingly being used as an alternative to seismic refraction. Minimum depth resolution is typically 10 meters but it can be as shallow as 3 meters (Section 5.2).

1.3.2 Natural versus Artificial Field Sources

Geophysical methods can be broadly classified according to whether the field source for which a subsurface response is measured is natural or artificial. Table 1-3 classifies 25 surface geophysical methods according to the type of field source. The majority of geophysical methods use artificial field sources, and all of the methods most commonly used at contaminated site, except magnetometry, measure artificial sources. Artificial sources have the advantage of being controlled more easily.

1.3.3 Measurement of Geophysical Properties

Most of the geophysical techniques discussed in this reference guide operate in a portion of the electromagnetic spectrum. Electromagnetic radiation can be described in terms of **wavelength,** the distance between two crests of a wave of electrical energy in a medium, and **frequency,** the number of waves measured passing a certain point in the medium in the course of one second (i.e., cycles per second, often abbreviated, as Hz after Heinrich Hertz, the discoverer of radio waves). The **geoelectrical** or **geoelectromagnetic** properties of earth materials vary as a result of physical properties such as porosity, density, fracturing, water content, and water chemistry. Most electrical and electromagnetic geophysical methods involve the inference of subsurface lithology, structure, and/or aquifer location as well as character from measurements of subsurface response to electrical or electromagnetic currents. These currents can be **natural** or **induced** as noted above, and the measurements can be in the **frequency domain** or in the **time domain** (see Section 3.1.1).

In contrast to electromagnetic methods, seismic methods record the **speed** with which reflected or refracted sound waves (acoustic energy) move from the source to sensors at various distances from the source (see Chapter 5). Gravitational methods involve the sensing of variations in the mass of subsurface materials through measurement of gravitational acceleration or potential.

Geophysical methods tend to measure a larger volume of the subsurface than monitor wells, thereby increasing the volume sampled for a given measurement. This is usually an

Table 1-3 Classification of Surface Geophysical Methods

Natural Field Source	Artificial Controlled Source
	Electrical
Self-Potential (SP)	**DC Electrical Resistivity** (ER) Induced Polarization (IP) Complex Resistivity
	Electromagnetic
Telluric Current (TC) Magnetotellurics (MT) Audio-Frequency MT (AMT) Audio-Frequency Magnetic (AFMAG) MT Array Profiling (EMAP)	**Electromagnetic Induction** (EMI) Time Domain EM (TDEM)[a] Very Low Frequency (VLF) Resistivity Controlled-Source Audiomagneto-Tellurics (CSAMT) **Metal Detectors** (MD)
	Seismic/Acoustic
Acoustic Emission Monitoring	**Seismic Refraction** (SRR) Shallow Seismic Reflection (SRL)[a] Continuous Seismic Profiling (CSP) Seismic Shear Spectral Analysis of Surface Waves (SASW) Side-Scan Sonar Fathometer
	Other Methods
Magnetometry Microgravimetry Natural Geothermal[c] Ionizing Radiation[c]	**Ground Penetrating Radar** (GPR)[b]

Boldface = Most commonly used methods at contaminated sites.

[a]Relatively recent improvements in instrumentation and methods for data analysis have resulted in increased use of TDEM and SRL.
[b]GPR is technically an electromagnetic method that uses microwave and high frequency radio waves, but is listed here to differentiate it from other electromagnetic methods that use low frequency and audio portions of the spectrum (see Figure l-l)
[c]Both temperature and radioisotopes can be used as artificial tracers in ground-water studies.

advantage, but can be a disadvantage if a feature or anomaly is so small that it escapes detection in a larger sampled volume. Data from these methods can be acquired in the form of (1) **profiles,** which record changes in measured properties in a linear transect along the ground surface, or (2) **soundings,** which measure vertical changes in the measured properties.

Multiple parallel profiles, using methods such as electromagnetic induction and magnetic and gravity surveys, create an areal view of the properties being measured that can be displayed two-dimensionally as contours of equal values **(isopleths)** or graphically to represent the data three dimensionally. Figure l-2a,b shows two- and three-dimensional portrayals of the same data. The three-dimensional perspective shown in Figure l-2b should **not** be mistaken for a physical representation of the subsurface, such as is provided by seismic methods (Chapter 5) and ground penetrating radar (see Section 6.1). A three-dimensional view can be obtained either by (1) taking multiple vertical soundings in a two-dimensional grid at the surface or (2) multiple profiles with different depths of measurement along the same transect. The term **resolution** is used to describe how well a method can measure changes in features horizontally (lateral resolution) and in sounding (vertical resolution).

Profile measurements can be either **stationary** or **continuous** (Benson et al., 1984a,b). Stationary or station measurements are taken at discrete intervals, whereas continuous methods measure subsurface parameters continuously along a survey line. Figure 1-3 shows the difference in output from the two types of measurements. The figure shows that continuous measurements, where feasible, provide better resolution; nonetheless, most traditional geophysical techniques involve station measurement. Continuous methods, such as short-coil spacing electromagnetic induction (EMI) and ground penetrating radar (GPR), commonly have shallower depths of penetration than methods involving station measurements, but are still preferred when applicable since they can approach 100-percent site coverage. In fact, all techniques that appear to be operating continuously (e.g., EMI, GPR) make point-by-point measurements, but at such small intervals that the resolution is the best that can be achieved by the particular instrument.

When station measurements are made, the measurement interval should be small enough to achieve adequate resolution. In Figure 1-3, for example, the sampling interval for the station

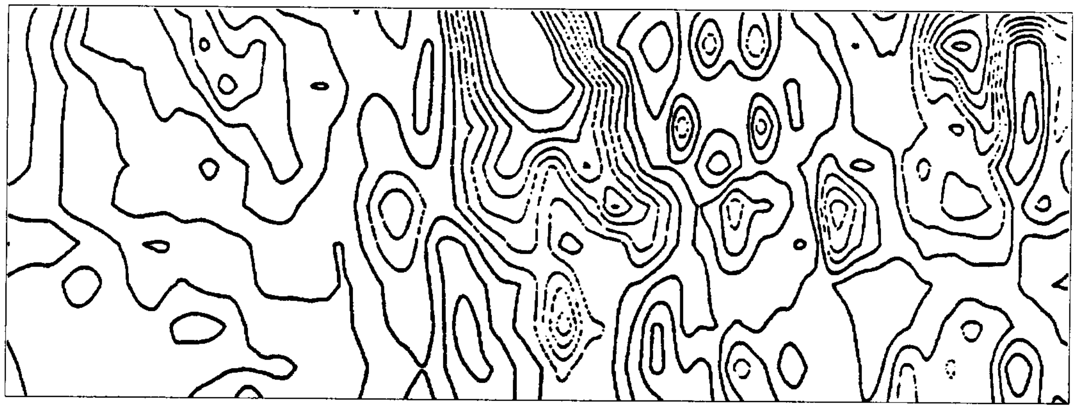

Figure 1-2a Ways of presenting areal geophysical measurements: an isopleth map of electrical conductivity measurement (from Benson et al., 1984a).

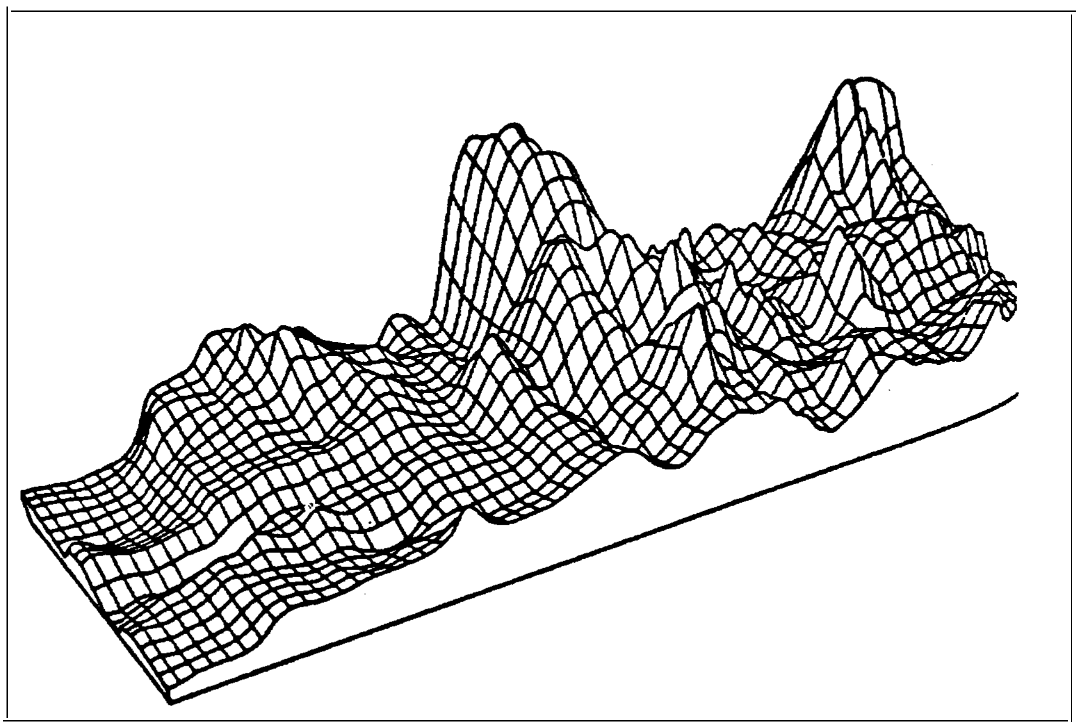

Figure l-2b Ways of presenting areal geophysical measurements: a 3-dimensional view of the data in Figure 1-2a (from Benson et al., 1984a).

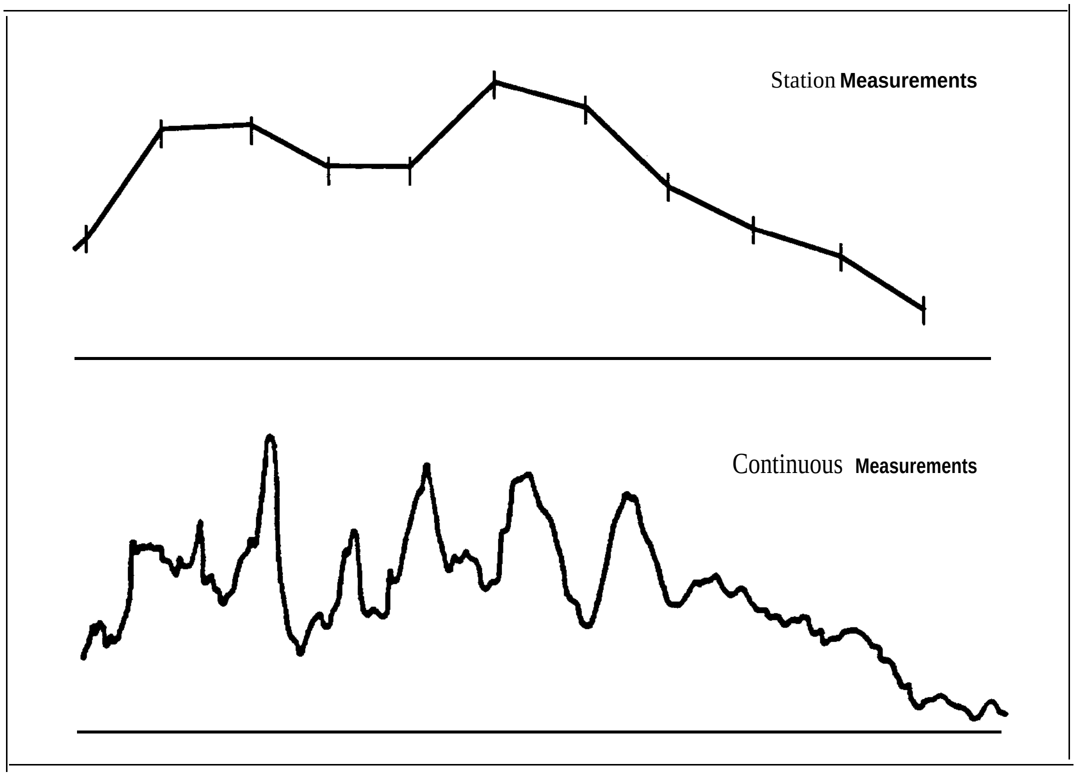

Figure 1-3 Discrete sampling versus continuous geophysical measurements (from Benson et al., 1984a).

measurements is sufficient to portray the slowly varying component, but failed to detect the highly localized anomalies that are apparent in the continuous measurement.

1.4 Introduction to the Geophysical Literature

1.4.1 General Geophysics

Historically, geophysical field methods have been primarily the domain of petroleum and mineral exploration geologists, and textbooks written from this perspective remain important source of information on basic theory and application of geophysical methods in the study of contaminated sites. Table 1-4 lists 21 basic geophysics texts along with the major methods covered in each. The reference section of this chapter provides detailed annotations of methods covered by individual texts (abbreviations in these annotations are defined in the Glossary to this guide). Older texts can provide useful information on basic principles, and even newer texts can become rapidly outdated with respect to specific methods. Information on the latest developments in geophysical methods is most likely to appear in the exploration-oriented geophysical journals: **Geophysics, Geophysical Prospecting,** and **Geoexploration** (renamed **Journal of Applied Geophysics** in 1992).[1] The expanded abstracts of the annual meeting of the Society of Exploration Geophysicists (SEG) is another important source of information on recent developments in geophysical methods (Table 1-5).

1.4.2 Ground Water and Contaminated Sites

Table 1-5 describes bibliographies, general reports, and proceedings of conferences and symposia that focus primarily on the application of surface geophysical methods in the study of ground water and contaminated sites. Zohdy et al. (1974), although a relatively old document, is still the best single report covering applications for ground-water investigations. Benson et al. (1984a,b) is the best single reference on applications of surface geophysical methods at contaminated sites.

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[1] See Appendix B for publishers' addresses.

Table 1-4 General Texts on Geophysics

Reference	Topics
Beck (1981)	Exploration: electrical, self potential, induced polarization, gravity, magnetic, electromagnetic, seismic, radioactive, well logging.
d'Amaud Gerkins (1989)	Exploration Geophysics: seismic refraction and reflection, gravity, magnetic, self potential, telluric current, magnetotelluric currents, electrical resistivity, induced polarization, electromagnetic induction (including airborne), time domain EM, radiometric.
Dobrin and Savit (1988)	Geophysical prospecting: seismic refraction and reflection, gravity, magnetic, electrical, electromagnetic.
Eve and Keys (1954)	Mineral exploration: magnetic, electrical, electromagnetic, gravity, seismic, radioactive, geothermal.
Grant and West (1965)	Interpretation theory in applied geophysics: seismic refraction and reflection, gravity, magnetic, electrical resistivity, electromagnetic induction.
Griffiths and King (1981)	Applied geophysics for engineers and geologists: electrical resistivity, electromagnetic, seismic refraction and reflection, gravity, magnetic.
Hansen et al. (1967)	SEG edited volume on mining geophysics: electrical electromagnetic, magnetic, gravity.
Heiland (1940, 1968)	Geophysical exploration: seismic, acoustic, electrical resistivity self potential, electromagnetic induction, metal detection, magnetic, gravity, radiometric, borehole, soil gas.
Howell (1959)	Introductory geophysics text focusing on seismology, gravity, geomagnetism.
Jakosky (1950)	Exploration geophysics: seismic, resistivity, magnetic, gravity.*
Kearey and Brooks (1991)	Geophysical exploration: seismic, gravity, magnetic, electrical, electromagnetic.
Milsom (1989)	Field geophysics.*

Table 1-4 (cont.)

Reference	Topics
Nettleton (1940)	Oil exploration: gravity, magnetic, seismic, electrical (including well logging).
Parasnis (1975)	Mining geophysics: magnetic, self potential, electromagnetic, electrical, induced polarization, gravity, seismic, radioactive, airborne magnetic, electromagnetic
Parasnis (1979)	Applied geophysics: magnetic, gravity, electrical, induced polarization, electromagnetic, seismic, radioactive, miscellaneous (borehole magnetometer, gamma and neutron logging, geothermal).
Robinson and Coruh (1988)	Basic exploration geophysics: seismic refraction and reflection, gravity, magnetic, electrical resistivity, induced polarization, self potential, telluric currents, electromagnetic induction, borehole.
Sharma (1986)	Geophysical methods in geologc seismic, gravity, magnetic, earth resistivity, radiometries, geothermal.
Sheriff (1989)	Geophysical methods: gravity, magnetic, radioactivity, heat flow, electrical and electromagnetic, seismic (16 chapters), borehole measurements, remote sensing.
Telford et al. (1990)	Applied geophysics with emphasis on deep exploration: gravity, magnetic, seismic reflection/refraction, electrical methods (ER, SP, IP), electromagnetic (EMI, TDEM), radiometric, borehole.
Van Blaricom (1980)	Practical geophysics.*
Ward (1990a-c)	Edited, three-volume series on geotechnical and environmental geophysics. Volume 1 covers basic concepts, Volume 2 covers environmental and ground-water applications (34 papers), and Volume 3 covers geotechnical applications (23 papers).

* All topics covered by text not listed here.

Note: See Table 7-1 for general references on downhole methods.

Table 1-5 Bibliographies, Reports, and Symposia Focusing on Application of Surface Geophysical Methods to Ground Water and Contaminated Sites

Reference	Description
Bibliographies	
Handman (1983)	Bibliography of more than 550 USGS publications on hydrologic and geologic aspects of waste management. Index identifies 15 on geophysical methods.
Johnson and Gnaedinger (1964)	Bibliography prepared for ASTM symposium on soil exploration containing over 300 references on air photo interpretation, surface electrical resistivity and seismic methods, and borehole geophysics.
Lewis and Haeni (1987)	Bibliography on use of surface geophysical methods for detection of fractures in bedrock with annotations to 31 English-language references and 12 foreign-language references.
Rehm et al. (1985)	Section 5 covers hydrogeologic applications of surface geophysics; Bibliography in Section 6 contains over 300 references on surface methods.
van der Leeden (1991)	Over 100 references on geophysical methods relevant to ground water.
Glossary	
Sheriff (1968, 1991)	1968 glossary of terms used in geophysical exploration and 1991 encyclopedic dictionary of exploration geophysics.
Texts/Reports on Ground Water Applications	
Redwine et al. (1985)	Ground-water manual for electric utility industry. Chapter 3 of Volume 3 covers surface geophysical methods (SRR, SRL, CSP, ER, SP, EMI, sonar, GPR, GR) and borehole methods with a focus on seismic techniques.
Rehm et al. (1985)	See description under *Bibliographies.*
USGS (1980)	Chapter 2 (Groundwater) of the Handbook of Recommended Methods for Water Data Acquisition covers geophysical methods: TC, MT, AMT, EM I, ER, IP, SRR, GR, BH.
Ward (1990b)	Volume 2 contains 34 papers on environmental and ground-water applications of geophysical methods.
Zohdy et al. (1974)	Manual on use of surface geophysical methods in ground-water investigations covers electrical, seismic refraction, gravirnetric, and magnetic techniques.

Table 1-5 (cont.)

Reference	Description
<u>Texts/RePorts on Contaminated Site Applications</u>	
Aller (1984)	EPA report on methods for determining the location of abandoned wells. Covers: air photos, color/thermal IR, ER, EMI, GPR, MD, MAG, combustible gas detectors.
Benson et al. (1984a,b)	EPA report focusing of GPR, EM I, resistivity, seismic refraction, and metal detection for sensing buried wastes and contamination migration.
Costello (1980)	U.S. Army Toxic and Hazardous Materials Agency report on surface and borehole geophysical techniques.
EC&T (1990)	U.S. Army Toxic and Hazardous Materials Agency manual on construction environmental site survey and clearance procedures covering GPR, EMI, magnetometry, metal detection, and soil gas surveys.
Frischknecht et al. (1983)	Evaluation of geophysical methods for locating abandoned wells prepared by U.S. Geological Survey.
HRB-Singer (1971)	Report on use of geophysical methods for detection of abandoned underground mines. Methods evaluated: included induced polarization, self potential, and VLF.
Lord and Koerner (1987)	EPA report evaluating metal detectors, electromagnetic induction, ground penetrating radar, and magnetometers for locating buried containers. Supporting reports on 17 distinct nondestructive testing (NDT) methods were prepared prior to selection of four methods that were field-tested.
O'Brien and Gere (1988)	Text on engineering aspects of hazardous waste site remediation that includes review of major surface geophysical methods: SRR, SRL, ER, EM, GPR, MAG.
Olhoeft (1992a)	Geophysics advisor expert system developed for U.S. EPA. Makes suitability ratings for specific methods based on site-specific inputs. Includes: ER, EMI, complex resistivity, SRR, SRL, GPR, GR, radiometric, soil gas.
Pitchford et al. (1988)	Report summarizing results of geophysical investigations at four Air Force bases. Includes review of major geophysical methods (EM I, ER, complex resistivity, GPR, SRR, SRL, MAG, MD) and guidelines for planning a geophysical investigation.
U.S. EPA (1987b)	EPA compendium on Superfund field operations methods. Section 8 covers DC resistivity, electromagnetic induction, ground-penetrating radar, magnetic and seismic methods.

Table 1-5 (cont.)

Reference	Description
<u>Texts on Geologic and Entineering Applications</u>	
Taylor (1984)	Report prepared for U.S. Bureau of Mine evaluating surface geophysical methods for characterizing hydrologic properties of fractured rock.
U.S. Army Corps of Engineers (1979)	Manual on geophysical techniques focusing on engineering applications. Surface methods include Seismic refraction and reflection, surface waves, sonar, ER, GR; borehole methods include seismic, electrical, nuclear.
Ward (1990c)	Volume 3 contains 23 papers on geotechnical applications of geophysical methods.
<u>Conferences/Symposia</u>	
Garland (1989)	Proceedings of symposium on exploration geophysics published by the Ontario Geological Survey with 77 papers covering electromagnetic, induced polarization, seismic, radiometric and remote sensing.
Morley (1970)	Proceedings of the Canadian Centennial Conference on Mining and Groundwater Geophysics (Niagara Falls, 1967). Contains state-of-the-art review papers on gravity, ground and airborne electromagnetic methods, induced polarization, and seismic methods, and 11 papers on ground-water applications.
NWWA (1984, 1985, 1986)*	Proceedings of conferences on surface and borehole geophysical methods in ground-water investigations. The 1984, 1985, and 1986 proceedings contain, respectively, 36, 19, and 24 papers on surface geophysical methods. These papers are indexed in the remaining chapters of this guide.
SEG (various dates)*	The Society of Exploration Geophysicists held its 61st annual meeting in 1991. Technical program presentations at the annual meetings are published as expanded abstracts of 1,000 to 2,000 words. The 1991 technical program was published as 2 volumes totaling 1,707 pages.
SEMEG/EEGS (1988-present)*	The Society of Engineering and Mineral Exploration Geophysicists (SEMEG) has held an annual symposium titled Symposium on Application of Geophysics to. Engineering and Environmental Problems (SAGEEP) since 1988. In 1992 SEMEG changed its name to the Environmental and Engineering Geophysical Society.
Thomas and Dixon (1989)	Proceedings of workshop with 25 papers on geophysical studies used to characterize the area in the vicinity of the Chalk River Nuclear Laboratory, Ontario.
Van Eeckhout and Calef (1992)	Summary of workshop on site characterization using geophysical methods.

* See Appendix B.2 for addresses.

Information on the latest developments in application of geophysical methods in the investigation of ground water and contaminated sites is most likely to appear in the hydrogeologic journals **Ground Water** and **Ground Water Monitoring Review** (renamed **Ground Water Monitoring and Remediation** in 1993). Other important journals include **Water Resources Research** and **Journal of Hydrology.**[2]

The Symposium on the Application of Geophysics to Engineering and Environmental Problems (SAGEEP), sponsored by the Society of Engineering and Mineral Exploration Geophysicists (SEMEG), has been held annually since 1988 and is an exceptional source of information on hydrogeologic and contaminated site applications. Each volume of proceeding includes several applications-oriented review papers and numerous case studies. In 1992, SEMEG became the **Environmental and Engineering Geophysical Society (EEGS),** which continues to sponsor the SAGEEP.

Another important source of information on recent developments are a number of symposium series sponsored by the National Water Well Association (NWWA) or the affiliated Association of Ground Water Scientists and Engineers (AGWSE), and the Hazardous Materials Control Research Institute (HMCRI). NWWA changed its name to the National Ground Water Association (NGWA) in 1992. Table 1-6 lists the year and title of a number of these conference/symposium series. Proceedings of the NWWA'S annual **National Outdoor Action Conference (NOAC) on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods** (titled **National Symposium on Aquifer Restoration and Ground Water Monitoring** prior to 1987) generally provide the largest number of papers related to geophysical methods. The NWWA regional ground-water issues conferences typically have at least six papers related to use of geophysical methods.

The annual **Conference on Petroleum Hydrocarbons and Organic Chemicals in Ground Water—Prevention, Detection and Restoration,** sponsored jointly by NWWA and the American Petroleum Institute, is an important source for papers on developments in the use of geophysical methods for detection of hydrocarbons. Proceedings from the HMCRI's annual **Hazardous**

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[2] See Appendix B for publishers' addresses.

Table 1-6 Conferences and Symposia Prceedirrgs with Papers Relevant to Subsurface Characterization and Monitoring

Sponsor	Year	Title
SEMEG	1988	[lst] Symposium on the Application of Geophysics to Engineering and Environmental Problems (SAGEEP)
	1989	[2nd] (SAGEEP '89)
	1990	[3rd] (SAGEEP '90)
	1991	[4th] (SAGEEP '91)
	1992	[5th] (SAGEEP '92)
NWWA	1981	1st National Ground Water Quality Monitoring Symposium and Exposition
	1982	2nd National Symposium on Aquifer Restoration and Ground Water Monitoring
	1983	3rd
	1984	4th
	1985	5th
	1986	6th
	1987	1st National Outdoor Action Conference on Aquifer Restoration, Ground Water Monitoring, and Geophysical, Methods
	1988	2nd
	1989	3rd
	1990	4th GWM 2
	1991	5th GWM 5
	1992	6th GWM 11
NWWA/API	1984	[lst] Conference on Petroleum Hydrocarbons and Organic Chemicals in Ground Water—Prevention, Detection and Restoration
	1985	[2nd]
	1986	[3rd]
	1987	[4th]
	1988	[5th]
	1989	[6th]
	1990	[7th] GWM 4
	1991	[8th] GWM 8
	1992	[9th] GWM 14
Geophysics		
NWWA/EPA	1984	[lst] Conference on Surface and Borehole Geophysical Methods in Ground Water Investigations
	1985	[2nd]
	1986	Surface and Borehole Geophysical Methods and Ground Water Instrumentation Conference and Exposition
Vadose Zone		
NWWA/EPA	1983	[lst] Conference on Characterization and Monitoring in the Vadose (Unsaturated) Zone
	1985	[2nd]
	1986	3rd
Karst		
NWWA	1986	[lst] Conference on Environmental Problems in Karst Terranes and Their Solutions
	1988	2nd
	1991	3rd Conference on Hydrogeology, Ecology, Monitoring and Management of Ground Water in Karst Terranes GWM 10
Miscellaneous NWWA Conferences		
NWWA/AGWSE	1989	Conference on New Field Techniques for Quantifying Physical and Chemical Properties of Heterogeneous Aquifers
	1990	Cluster of Conferences (Agricultural Impacts on Ground Water Quality Ground Water Geochemist, Ground Water Management and Wellhead Protection; Environmental Site Assessments: Case Studies and Strategies) GWM 1
	1991	Environmental Site Assessments Case Studies and Strategies: Tire Conference GWM 6

Table 1-6 (cont.)

Sponsor	Year	Title
NWWA Eastern Regional Conferences		
NWWA/AGWSE	1984	[lst] Eastern Regional Ground Water Conference
	1985	[2nd]
	1986	3rd Annual Eastern Regional Ground Water Conference
	1987	4th
	1988	[5th] Focus Conference on Eastern Regional Ground Water Issues
	1989	[6th]
	1990	[7th] GWM 3
	1991	[8th] GWM 7
	1992	[9th] GWM 13
Other NWWA Regional Conferences		
NWWA	1983	Eastern Regional Conference on Ground Water Management
		Western Regional Conference on Ground Water Management
	1984	Conference on Ground Water Management
	1985	Southern Regional Ground Water Conference
		Western Regional Ground Water Conference
	1986	Conference on southwestern Ground Water Issues
		Focus Conference on Southeastern Ground Water Issues
	1987	Focus Conference on Midwestern Ground Water Issues
		Focus Conference on Northwestern Ground Water Issues
	1988	[2nd] Focus Conference on Southwestern Ground Water Issues
Hazardous Materials Control Research Institute Conferences		
HMCRI	1980	1st National Conference on Management of Uncontrolled Hazardous Wastes Sites
	1981	2nd
	1982	3rd
	1983	4th
	1984	5th
	1985	6th
	1986	7th
	1987	8th Superfund '87
	1988	9th Superfund '88
	1989	10th Superfund '89
	1990	1lth Superfund '90
	1991	12th Hazardous Materials Control (HMC-Superfund '91)
	1992	13th HMC-Superfund '92
HMCRI	1984	1st National Conference on Hazardous Wastes and Environmental Emergencies
	1985	2nd
	1986	3rd National Conference on Hazardous Wastes and Hazardous Materials
	1987	4th
	1988	5th (HWHM '88)
	1989	6th (HWHM '89)
	1990	7th (HWHM '90)

[ ] indicate that number is not included in the title of the published proceedings.
GWM indicates that proeeedings have been published in NWWA's Ground Water Management Series.

Abbreviations

AGWSE	Association of Ground Water Scientists and Engineers (NWWA)
API	American Petroleum Institute
EPA	U.S. Environmental Protection Agency
HMCRI	Hazardous Materials Control Research Institute
NWWA	National Water Well Association (name changed to National Ground Water Association in 1992)
SEMEG	Society of Engineering and Mineral Exploration Geophysicists

Materials Control Conference (titled **Superfund** from 1987 to 1990 and the **National Conference on Management of Uncontrolled Hazardous Waste Sites** prior to 1987) and **National Conference on Hazardous Waste and Hazardous Materials** usually include a few papers related to geophysical methods. Most of the papers in the conferences identified in Table 1-6 are indexed in this reference guide.

The American Society for Testing and Materials (ASTM) has sponsored conferences that present several papers on use of geophysical methods at contaminated sites (Collins and Johnson, 1988) and for geotechnical investigations (Paillet and Saunders, 1990). Subcommittee D-18.21 (Ground Water and Vadose Zone Investigations) of ASTM is preparing a number of standard guides on the more commonly used geophysical methods (these are identified in the appropriate subsections in U.S. EPA, 1993). Papers from Collins and Johnson (1988) and a number of relevant papers from other ASTM publications are indexed in this guide.

Table 1-5 provides additional information on three conferences sponsored by NWWA from 1984 to 1986 on surface and borehole geophysical methods in ground-water investigations. The proceedings document of the 1967 Canadian Centennial Conference on Mining and Groundwater Geophysics (Morley, 1970) remains an excellent general reference source on ground-water applications.

1.4.3 Evaluation of Literature References

The field of geophysics in general and specific applications in ground-water and contaminated site investigations is changing so rapidly that great care is required when evaluating the literature, especially when dealing with a method that is outside one's area of expertise. Several factors affect the weight that should be given conclusions or recommendations concerning a particular method: (1) whether the it is from a peer-reviewed or non-peer reviewed source; (2) where the authors come from; and (3) how recently it has been published.

Greatest weight should be given to the content of papers published in peer-reviewed scientific journals such as **Geophysics, Ground Water,** and **Ground Water Monitoring Review.** Most conference proceedings (ASTM conferences being an exception) are not peer-reviewed, consequently there is more likely to be diversity of opinion concerning conclusions or recommendations in individual papers. When non-peer-reviewed papers are considered, greater weight can be given to those authored by individuals from academic institutions or research-oriented government agencies (e.g., U.S. Geological Survey, personnel from EPA research laboratories) than to papers authored by consultants who may have an interest in promoting a particular method. Finally, more recently published papers can generally be given greater weight that earlier publications because they are more likely to address recent developments and advances in geophysical techniques. As a general rule, review of multiple references from a variety of sources that deal with a specific method should help determine the method's appropriateness for a specific application or for site-specific conditions. When in doubt, one or more experts should be consulted (see Section 1.5).

1.4.4 Use of Reference Index Tables in This Guide

This guide contains many more references than are mentioned in the text. They were initially compiled using: (1) the ground-water oriented bibliographies listed in Table 1-5; (2) conference proceedings listed in Table 1-6; (3) reference sections in papers gathered in the first-round review of references related specifically to geophysical applications to ground water and contaminated sites; (4) recent issues (up to late 1992) of **Geophysics, Geoexploration, Ground Water,** and **Ground Water Monitoring Review.**

All identified references that directly relate applications of geophysical methods to the study of ground water and contaminated sites are included. References from the general geophysical exploration literature are limited to (1) texts related to basic theory, principles of operation of geophysical methods, and interpretation of data, and (2) papers reviewing the literature and state-of-the-art of specific geophysical methods that are used in the study of ground water and contaminated sites.

To facilitate locating references on specific topics of interest, two types of reference tables are included in this guide. **Descriptive reference tables** (see, e.g., Tables 1-4 and 1-5) provide information on the contents of major references; not all chapters have tables of this type. One or more **reference index tables** catalog references in each chapter by type of report and topics covered; these precede the reference section in each chapter (see, e.g., Table 1-7). Although the organization of information varies somewhat from chapter to chapter, general references on the method always appear first, followed by references describing applications of the method.

Specific applications are indexed separately so that the same reference may appear more than once in the index. For example, in Table 1-7 the NWWA geophysics proceedings are listed under the subheadings for both “contaminated sites” and “ground water” under the general heading of texts/reports. This same table lists 25 papers on general use of geophysical methods in five subcategories (only a couple of these references were actually cited in the text).

1.4.5 Obtaining References

When out-of-print EPA documents and other government-sponsored publications are available from the National Technical Information Service (NTIS, U.S. Department of Commerce, Springfield, VA 22161; 800-336-4700), the NTIS order number is provided with the citation. When an NTIS number could not be found (usually for more recent publications), the sponsoring EPA office or EPA laboratory is identified and availability can be determined by contacting the appropriate office/laboratory. U.S. Geological Survey libraries have computer searchable library catalogs.

EPA maintains a microfiche catalog of publications in EPA libraries in Washington, DC, and at Regional Offices and EPA laboratories. Many of the publications cited in this reference guide, including conference proceedings, are available in one or more of these libraries. Also, these libraries maintain extensive microfiche collections of out-of-print EPA and other documents that are available from NTIS. If an EPA library is nearby, this may be fastest way to review documents for which an NTIS number is known (see Appendix B.3 for addresses and holdings).

Tracking down references of interest in the conference series identified in the previous section can be complicated. Proceedings for recent years, however, can usually be purchased

Table 1-7 Index to Texts and Papers on General Applications of Geophysics to the Study of Ground Water and Contaminated Sites

Topic	References
Texts/Reports	
General Geophysics	Beck (1981), d'Arnaud Gerkins (1989), Dobrin and Savit (1988), Eve and Keys (1954), Garland (1989), Grant and West (1965), Griffith and King (1981), Hansen et al. (1967), Heiland (1940, 1968), Howell (1959), Jakosky (1950), Kearey and Brooks (1991), Milsom (1989), Nettleton (1940), Parasnis (1975, 1979), Robinson and Coruh (1988), Sharma (1986), Sheriff (1968, 1989, 1991), Telford et al. (1990), Valley (1965), Van Blaricom (1980), Ward (1990a)
Ground Water	Erdélyi and Gálfi (1988), Karous and Mareš (1988), Merely (1970), NWWA (1984, 1985, 1986), Redwine et al. (1985), Rehm et al. (1985), Taylor (1984), U.S. EPA (1987a), USGS (1980), Ward (1990b), Zohdy et al. (1974); Bibliographies: Handman (1983), Johnson and Gnaedinger (1964), Lewis and Haeni (1987), Rehm et al. (1985), van der Leeden (1991)
Contaminated Sites	Aller (1984), Benson et al. (1984a,b), Cleff (1991—hydrocarbon detection), Costello (1980), EC&T et al. (1990), Frischknecht et al. (1983), HRB Singer (1971), Lord and Koerner (1987), NWWA (1984, 1985, 1986), O'Brien and Gere (1988), Olhoeft (1992a), Pitchford et al. (1988), SEGEM (1988-present), Technos (1992), Thomas and Dixon (1989), U.S. DOE (1990), U.S. EPA (1987b, 1992), Van Eeckhout and Calef (1992), Wailer and Davis (1984), Ward (1990b)
Engineering	Paillet and Saunders (1990), U.S. Army Corps of Engineers (1979), SEG (various dates), SEGEM (1988-present), Ward (1990c)
Signal Detection	Hancock and Wintz (1966), Helstrom (1968)
Papers on General Use of Geophysical Methods	
Ground Water (General)	Dobecki and Romig (1985), Heiland (1937), Hoekstra and Blohm (1988-fracture zones and karst), Meinzer (1937), National Water Well Association (1971), Ogilvy (1970), Peterson et al. (1989), Schwarz (1988), Tucci (1989)
Buried Wastes Detection	Benson (1991), Benson and Yuhr (1986), Benson et al. (1984), Johnson and Johnson (1986), Lord et al. (1980), Neev (1988)
Contaminant Plumes	Applegate and Rodriguez (1988), Benson (1991), Benson and Yuhr (1986), Benson et al. (1984a,b), Evans and Schweitzer (1984)

Table 1-7 (cont.)

Topic	References
<u>Papers on General Use of Geophysical Methods (cont.)</u>	
Monitoring	Regan et al. (1987), Tuttle and Chapman (1989), Wruble et al. (1986)
Site Assessment	Benson (1991), Benson and Yuhr (1992), Cichowicz et al. (1981), Evans et al. (1982), Evans and Schweitzer (1984), Emilsson and Simonson (1989), Flatman et al. (1986), French et al. (1988), Hatheway (1982), Hoekstra and Hoekstra (1990), Johnson and Johnson (1986), MacLeod and Dobush (1990), McGinnis et al. (1988), McKown and Sandness (1981), Nelson (1988), Nichol and Cain (1992), Olhoeft (1992b), Olsson et al. (1984), Tuttle and Chapman (1989), Wruble et al. (1987)

from the originating organization (see Appendix B.2 for addresses): ASTM, NGWA/NWWA, EEGS/SEMEG, SEG, SPWLA.

The NGWA's National Ground-Water Information Center (6375 Riverside Drive, Dublin, OH; 614-761-1711) is probably the only library in the country with a complete set of the NWWA/NGWA conference series. Similarly, the Hazardous Materials Research Institute (9300 Columbia Boulevard, Silver Spring, MD 20910-1702; 301-587-9390) maintains a complete collection of its conference series. Copies of specific conference proceedings can often be found in the libraries maintained by EPA regional office and EPA laboratories or in university libraries (see Appendix B.3).

Beginning in 1990, NWWA (now NGWA) began publishing the proceedings of its various conferences under the title **Ground Water Management: A Journal for Rapid Dissemination of Ground Water Research.** A subscription ($140 for members and $192.50 for nonmembers) consists of 6 coupons that can be redeemed for published proceedings (larger proceedings may require 2 coupons).

1.5 Where to Obtain Technical Assistance

Technical assistance from EPA personnel is available at EPA's Environmental Monitoring Systems Laboratory, Las Vegas, NV, and at EPA's Region V office. Appendix B.1 provides the names and phone numbers of individuals in EPA and at the U.S. Geological Survey who may be able to provide advice on geophysical applications at contaminated sites.

1.6 References

See Glossary for meaning of method abbreviations.

Aller, L. 1984. Methods for Determining the Location of Abandoned Wells. EPA/600/2-83/123 (NTIS PB84-141530), 130 pp. Also published in NWWA/EPA series by National Water Well Association, Dublin, OH. [air photos, color/thermal IR, ER, EMI, GPR, MD, MAG, combustible gas detectors]

Applegate, J.K. and B.D. Rodriguez. 1988. Integrated Geophysical Mapping of Hazardous Plumes in Glacial Terrain. In: Proc. (1st) Symp. on the Application of Geophysics to Engineering and Environmental Problems, Soc. Eng. and Mineral Exploration Geophysicists, Golden, CO, pp. 722-734.

Beck, A.E. 1981. Physical Principles of Exploration Methods. Macmillan, New York, 234 pp. [Reprinted in 1982 with corrections]. [ER, SP, IP, GR, MAG, EMI, VLF, SRR, SRL, radiometric, BH].

Benson, R.C. 1991. Remote Sensing and Geophysical Methods for Evaluation of Subsurface Conditions. In: Practical Handbook of Ground-Water Monitoring, D.M. Nielsen (ed.), Lewis Publishers, Chelsea, MI, pp. 143-194. [GPR, EMI, TDEM, ER, SRR, SRL, GR, MAG, MD, BH]

Benson, R.C. and L.P. Yuhr. 1986. Geophysical Techniques for Sensing Buried Wastes and Waste Migration: An Update. In: Proc. Seventh Nat. Conf. on Management of Uncontrolled Hazardous Waste Sites, Hazardous Materials Control Research Institute, Silver Spring, MD, pp. 465-466. [EMI, ER, GPR, GR, MAG, MD, SRL, SRR, BH]

Benson, R.C. and L.P. Yuhr. 1992. A Summary of Methods for Locating and Mapping Fractures and Cavities with Emphasis on Geophysical Methods. In: SAGEEP '92, Society of Engineering and Mineral Exploration Geophysicists, Golden, CO, pp. 471-486.

Benson, R. C., R.A. Glaccum, and M.R. Noel. 1984a. Geophysical Techniques for Sensing Buried Wastes and Waste Migration. EPA 600/7-84/064 (NTIS PB84-198449), 236 pp. Also published in 1982 in NWWA/EPA series by National Water Well Association, Dublin, OH. [EMI, ER, GPR, MAG, MD, SRR]

Benson, R. C., R.A. Glaccum, and M.R. Noel. 1984b. Geophysical Techniques for Sensing Buried Wastes and Waste Migration: An Applications Review. In: NWWA/EPA Conf. on Surface and Borehole Geophysical Methods in Ground Water Investigations (lst, San Antonio TX), National Water Well Association, Dublin, OH, pp. 533-566. [EMI, ER, GPR, MAG, MD, SRR, SRL]

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* Addresses in Appendix B.2.

CHAPTER 2
AIRBORNE REMOTE SENSING AND GEOPHYSICS

Hydrogeologists have used the term **remote sensing** loosely to apply to all airborne sensing methods (Ellyett and Pratt, 1975). Exploration geophysicists usually use the term airborne **geophysics to** refer to magnetic, gravimetric, and electromagnetic measurements taken from ecmventional aircraft and they restrict the term remote sensing to observations of electromagnetic radiation from satellites and high-altitude aircraft (Regan, 1980).[1] Figure 2-1 shows the portion of the electromagnetic spectrum that is most commonly used for remote sensing.

Airborne sensing and methods are more commonly used in regional investigations where large areas must be evaluated, rather than for site-specific studies. Table 2-1 summarizes information on hydrogeologic applications for five airborne sensing techniques that were evaluated by Ellyett and Pratt (1975) for their potential value in hydrogeological investigations. A sixth method photographic ultraviolet, which can be used to map oil spills on surface water is also included in this table. Table 1-1 provides additional summary information of airborne remote sensing and geophysical methods with a focus on applications at contaminated sites.

Photographic methods have the widest applicability to site-specific investigations of contaminated sites as discussed in Section 2.1. Airborne geophysical methods other than the thermal infrared method have received relatively limited use in hydrogeologic studies, as discussed in Section 2.2.

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[1]Various types of satellite remote sensing imagery equipment are available for most areas of the United States. Typically, however, the scale of the images yielded with this technology is too large to provide much useful information for site-specific investigations. Still, such information may be of value for investigation of particularly large sites. Chapter 11 of U.S. EPA (1986) provides information on how to obtain such images.

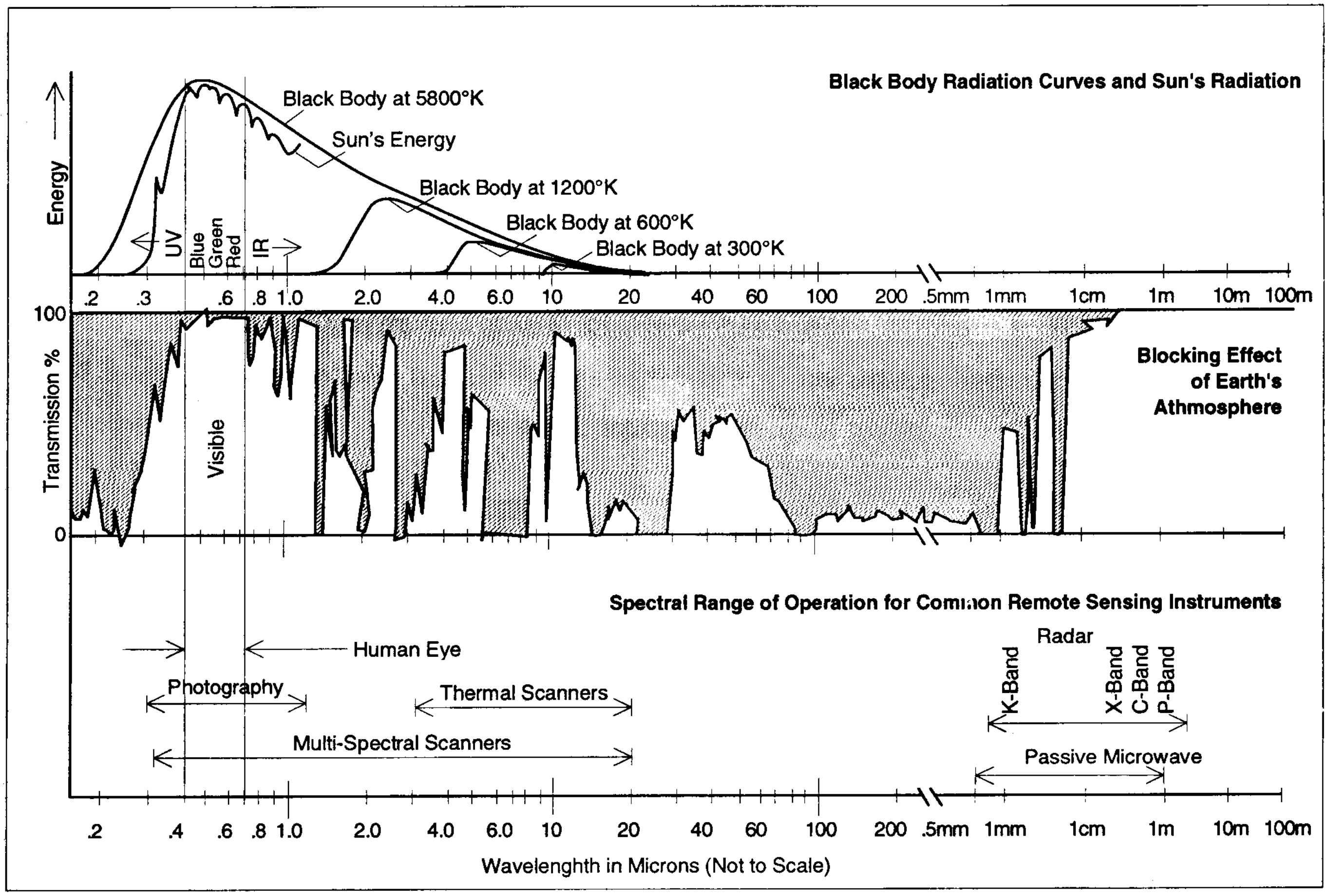

Figure 2-1 Portions of the electromagnetic spectrum used for remote sensing (Scherz and Stevens, 1970).

Table 2-1 Use of Airborne Sensing Techniques in Hydrogeologic and Contaminated Site Studies

Method	Description	Applications
Visible and near infrared	Aerial photographs (black and white, color, false color, infrared multi-spectral). Imaging limited to surface features.	Air photo interpretation of geologic and surface hydrologic features, fracture trace analysis, soil moisture patterns, and vegetation (infrared).
Photographic ultraviolet”	Aerial photographs using special film and filters for sensing reflected ultraviolet radiation.	Mapping of oil spills on surface water bodies sometimes used for geologic mapping of carbonate formations.
Thermal infrared	Scanners used to detect infrared radiation beyond the range of infrared photography.	Routinely used to detect ground-water discharge into rivers, lakes, and the sea; detects variations in soil moisture content (seepage from leach fields and underground storage tanks), evaporation, and thermal properties.
Side-looking airborne radar (SLAR)	Creates a continuous radar image (reflected radio frequency pulses) of the ground surface.	Similar applications to air photos; can distinguish grain size in alluvium if there is no interference from vegetation. Can also be used for fixture trace analysis.
Low frequency airborne electromagnetic methods (AEM)	Uses a low frequency electromagnetic wave transmitter and receiver that responds to changes in the ground electrical conductivity.	Detects variations in soil and reek types; variations in ground-water salinity; location of shallow subsurface aquifers and deeper brine contaminated aquifers.
Aeromagnetic	Measures the earth’s total magnetic field.	Primarily used in petroleum and mineral exploration to assist with geological mapping and structural interpretations. Also used to locate abandoned wells with metallic easings.

* Not mentioned in Ellyett and Pratt (1975).

Source Adapted from Ellyett and Pratt (1975).

2.1 Visible and Near-Infrared Aerial Photography

Aerial photographs, which record the visible portion of the electromagnetic spectrum, are by far the most common form of remote sensing and are basic to any geologic or hydrogeologic investigation. Much information can be obtained from stereopairs of black-and-white (also called panchromatic) air photos, which provide a three-dimensional image of the surface when viewed with a stereoscope. Patterns of vegetation, variations in grey tones in soil and rock drainage patterns, and linear features allow preliminary interpretations of geology, soils, and hydrogeology. Various standard texts are available for guidance in air photo interpretation methods (Avery, 1968; Denny et al., 1968; Lueder, 1959 Ray, 1960). All air photo interpretations should be field checked and revised where “ground truthing” indicates features that were missed or incorrectly delineated.

Using photogrammetric techniques to develop topographic contours from stereoscopic (overlapping) aerial photographs is often the cheapest way to produce reasonably accurate topographic maps (1 or 2 foot contour intervals) for site-specific investigations. However, such maps may not be sufficiently accurate for locating the elevations of boreholes and monitoring wells for water level measurement and subsurface mapping.

Black-and-white air photos are available from various federal agencies for almost any location in the United States and are the cheapest type of air photo to obtain. Black-and-white photographs most frequently are reported as being useful in ground-water contamination studies. Other types of images that can be obtained, usually at greater expense, include:

- **True color** records all colors in the visible spectrum as they appear to the naked eye.
- **Color infrared film** records yellows and reds as green and the near infrared (not visible to the eye) as red. Since vegetation reflects near-infrared radiation, this image is especially useful for observing vegetation patterns. Other types of images that record or display colors differently than they are perceived by the eye (called **false color)** can be created in a similar fashion.
- **Photographic ultraviolet** uses special film and filters to record UV energy. Oil and carbonate minerals are fluorescent in UV bands when photostimulated by sunlight. A disadvantage of UV photography is that UV wavelengths are

scattered in the atmosphere and result in a low contrast image, especially when dust or haze is present.

Multiband (also called **multispectral)** images, use multiple lenses and filters to record simultaneous exposures of different portions of the visible and near-infrared spectrum of the same area on the ground. Images can also be recorded electronically using a multispectral scanning system.

Air photos often reveal linear features called fracture traces that indicate zones of relatively higher permeability in the subsurface. Fracture-trace analysis using air photos can provide preliminary information on possible preferential movement of contaminants. Fetter (1980, pp. 406-411) provides a useful introduction to fracture-trace analysis. Sonderegger (1970) describes use of panchromatic, color, and infrared photography to locate fracture traces as an aid to the interpretation of the occurrence and movement of ground water in limestone terraine. Parizek (1976) provides a thorough review of the North American literature on fracture-trace and lineament analysis. DiNitto (1983) recommends that air photo fracture-trace analysis be supplemented, if possible, by surface analysis of bedrock fracture orientations.

Aerial photography can also be a vaIuable tool in documenting pre-existing physical conditions and monitoring the progress of cleanup operations at hazardous waste sites (Finkbeiner and O'Toole, 1985). Color infrared photography is particularly useful where contamination results in vegetation changes, such as in cases involving a failed septic tank absorption system (Farrell, 1985), fertilizers, or oil pollution and natural gas leaks (Svoma and Pyšek, 1985). A bibliography compiled by Rehm et al. (1985) lists 30 references on thermal and color infrared remote sensing. Table 2-2 lists 18 references on use of aerial photography at contaminated sites.

2.2 Other Airborne Remote Sensing and Geophysical Methods

Table 2-1 describes four other aerial remote sensing techniques that may have applications in hydrogeologic studies. Thermal infrared scanning can detect ground-water discharge into surface waters by sensing temperature differences in the ground water and surface water. Ellyett and Pratt (1975) considered this technique to be potentially the most useful remote sensing tool in the study of direct hydrogeological indicators. Huntley (1978) evaluated thermal infrared imagery as a means of detecting shallow aquifers and concluded that it is not practical to estimate ground-water depth directly. The use of thermal infrared imagery to estimate soil moisture (Jackson and Schmugge 1986; Jackson et al. 1982 Price, 1980; U.S. Geological Survey 1982) and evaporation (Price, 1980; Ottle et al., 1989 U.S. Geological Survey 1982) is reasonably well established. Meierhoff and Weil (1991) reported use of thermal infrared as one of several methods to locate underground storage tanks at a 50-acre site. The thermal IR imagery successfully located the only confirmed leaking UST at the site and also identified several areas of buried pipe and metallic debris. Table 2-2 lists approximately 30 references on hydrogeologic and contaminated site applications of thermal IR.

Airborne geophysical methods such as **side-looking airborne radar (SLAR), airborne electromagnetic** (AEM) methods, and **aeromagnetics** have not been used widely in ground-water contamination studies, although the potential exists for their use in regional water quality studies. A special feature of SLAR is its ability to distinguish grain size in alluvium. This technique requires unvegetated surfaces, a condition that is most likely to occur in arid areas (Ellyett and Pratt, 1975).

Surface, rather than airborne, electromagnetic methods are generally better adapted to site-specific ground-water contamination studies, since the spatial resolution of airborne EM methods (on the order of several tens of meters) is usually too coarse for contamination investigations. EPA has been supporting research on the use of airborne electromagnetic to locate areas of near-surface brine contamination in the Brookhaven oil field in Mississippi (Smith et al., 1989). Aeromagnetic surveys have been used as a complement to other methods to locate abandoned wells (Frischknecht, 1990).

Palacky and West (1991) provide a general review of airborne EM methods. Hoekstra et al. (1975) and Arcone (1979) compared airborne and ground resistivity using very low frequency (VLF) electromagnetic methods (see Section 4.4) and found that airborne measurements lost much of the detail of ground measurements.

Table 2-2 Index for References on Airborne Remote Sensing and Geophysical Methods

Topic	References
Remote Sensing Texts	Colwell (1983), Dury (1990), Holz (1973), Kondratyev (1969), Rees (1990), Reeves (1968, 1975), Regan (1980), Sabins (1978), Ulaby et al. (1982-microwave), Verstappen (1977), Watson and Regan (1983); Hydrologic/Contamination Applications: Burgy and Algaz (1974), Deutsch et al. (1979), Ellyett and Pratt (1975), Goodison (1985), Lund (1978), Reeves (1968), Scherz (1971), Scherz and Stevens (1970), Sers (1971), Thomson et al. (1973)
Aerial Photography	
Photo-Interpretation	Avery (1968), Ciciarelli (1991), Denny et al. (1968), Dury (1957), Johnson and Gnaedigner (1964-bibliography), Lattman and Ray (1965), Lillesand and Kiefer (1979), Lueder (1959), Miller and Miller (1961), Ray (1960), SCS (1973), Strandberg (1967), Wolfe (1974- photogrammetry)
Fracture-Trace Analysis	DiNitto (1983), Fetter (1980), Henry (1992), Jansen and Taylor (1988), Lattman (1958), Lattman and Matzke (1961), Lattman and Nicholsen (1958), Lattman and Parizek (1964), Mabee et al. (1990), Parizck (1976), Setzer (1966), Sonderegger (1970), Trainer (1967), Trainer and Ellison (1967), Wise and McCrory, (1982), Wobber (1967), Zeil et al. (1991)
Ultraviolet	Phillipson and Sangrey (1977), Redwine et al. (1985)
Color Infrared	Aller (1984-abandoned wells), Estes et al. (1978), Farrell (1985), Lee (1992-wetlands), Rehm et al. (1985), Svoma and Pysek (1985), Warren and Wielchowsky (1973), Williams and Ory (1967), Wilson et al. (1990), Wolfe (1971)
Multispectral	Cornillon (1987), Davis and Fosbury (1973), Phillipson and Sangrey (1977), Lee (1991–wetlands, 1992), Wruble et al. (1986)
Hydrogeology	Estes et al. (1978), Fisher et al. (1966), Howe (1958), Sauer (1981), Wiltala and Newport (1963), Wood (1972)
Contaminated Sites	Texts: Aller (1984-abandoned wells), U.S. EPA (1987); Papers: Baer and Stokely (1984), Davis and Fosbury (1973-surface water), Erb et al. (1981), Evans and Mata (1984), Farrell (1985), Finkbeiner and O'Toole (1985), Hill and Dantin (1984), Howard (1984), Landers and Johnson (1978), Merin (1990), Pease and James (1981), Phillipson and Sangrey (1977), Sangrey and Phillipson (1979), Shelton (1984), Scherz (1971), Sitton and Baer (1984), Svoma and Pysek (1985), Vizy (1974-oil slicks), Wilson et al. (1990-septic systems), Wruble et al. (1986)

Table 2-2 (cont.)

Topic	References
Other Airborne Methods	
Aeromagnetic	Adams et al. (1971), Fitterman (1990), Frischknecht (1990), Frischknecht and Raab (1984), Frischknecht et al. (1985), Hanna (1990), Mattick et al. (1973), Plume (1988), Smith et al. (1989), Vacquier et al. (1951), Zeil et al. (1991)
Electromagnetic (AEM)	Arcone (1979), Becker (1990), Hoeckstra et al. (1975), Palacky (1986), Palacky and West (1991), Pemberton (1962), Smith et al. (1989)
Radar (SLAR)	Lee (1992-wetlands), Mabee et al. (1990), U.S. EPA (1987), Warren and Wielchowsky (1973)
Other Active Microwave	Cameron and Goodman (1989-airbome GPR), Schmugge et al. (1980-soil moisture measurement)
Thermal Infrared	Texts: Aller (1984-abandoned wells), Lord and Koerner (1987), Poe et al. (1971), Rehm et al. (1985), Sharp (1970), Ulaby et al. (1980), U.S. EPA (1987), USGS (1982); Papers Adams et al. (1971), Davis and Fosbury (1973), Englund and Johnson (1977), Estes et al. (1978), Fisher et al. (1966), Huntley (1978), Idso et al. (1975), Jackson and Schmugge (1986), Jackson et al. (1982, 1985), Kennedy and Wogec (1991–USTS), Lord and Koerner (1980), Meierhoff and Weil (1990-USTS), Ottle et al. (1989), Price (1980), Sabins (1973), Schmugge and Gurney (1986), Seer (1980), Souto-Maior (1973), Sucksdorff and Ottle (1990), Wruble et al. (1986), Yates et al. (1988)
Other Airborne Applications	
Abandoned Wells	Aller (1984), Frischknecht (1990), Frischknecht and Raab (1984), Frischknecht et al. (1985)
Contaminated Sites	Cameron and Goodman (1989), Kennedy and Wogec (1991), Meierhoff and Weil (1991), Smith et al. (1989-brine), Rossiter (1990-oil slicks on water), Wruble et al. (1986)
Ground Water	Adams et al. (1971), Estes (1978)

2.3 References

See Glossary for meaning of method abbreviations.

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CHAPTER 3

SURFACE GEOPHYSICS: ELECTRICAL METHODS

No other surface geophysical methods have been used more widely than electrical and electromagnetic methods in the study of ground water and contaminated sites. Only downhole logging methods are more confusing in their classification and terminology to the uninitiated (see Chapter 7). Terms such as **geoelectrical, geoelectromagnetie,** and **resistivity** survey may be used in the literature to apply to one or more of a variety of geophysical methods. The same method may be called by different names.

3.1 Electrical versus Electromagnetic Methods

Usually the term **electrical** applies to methods in which electrical currents are injected into the ground by the use of direct contact electrodes. Electrical methods operate using direct current (DC) or frequencies that are so low (perhaps 10 Hz) that there are no electromagnetically induced currents in the ground, only those generated by the electrodes.

Electromagnetic methods (as the term is commonly used), which involve the use of lower frequency radio waves and audio portions of the EM spectrum (see Figure l-l), are covered in Chapter 4. Direct contact of EM instruments with the ground may be required depending on the measurement technique used, but in all cases electric currents are electromagnetically induced in the ground, rather than generated with electrodes. EM methods such as ground penetrating radar that use the higher frequency portion of the EM spectrum (radar and microwaves) are discussed in the Chapter 6 (Section 6.1). DC electrical resistivity methods cause different current patterns in the ground and may not measure the same subsurface properties as EM methods.

3.1.1 Types of Electrical Methods

As noted in Chapter 1, electrical and EM methods can be broadly classified according to whether the field source for which a subsurface response is measured is natural or artificial (see Table 1-3). The three major types of electrical methods are **DC electrical resistivity** and **induced polarization** (including complex resistivity), which involve artificial field sources, and **self-potential,** which involves the measurement of natural electrical currents in the subsurface.

The principal method used in the study of ground water and contaminated sites until about 10 years ago was DC electrical resistivity. Since the 1980s, electromagnetic induction methods have gained increasing popularity and now are generally the preferred method for ground-water contamination studies.

3.1.2 Subsurface Properties Measured

Electrical and electromagnetic methods also can be classified by the subsurface properties they measure. These involve three major phenomena and properties associated with rocks and ground water:

- **Resistivity,** or the reciprocal **conductivity,** which governs the amount of current that moves through rock material when a specified potential difference is applied. ER and electromagnetic methods measure the same subsurface properties and can be reported in either of two types of units (see below for conventions).

- **Electrochemical** activity, which is caused by chemical activity in ground water and charged mineral surfaces. This provides the basis for self-potential and induced polarization methods.

- The **dielectric constant,** which is a measure of the polarizability of a material in an electric field, and gives information on the capacity of rock material to store an electric charge. This property is important in the use of induced polarization (Section 3.5) and ground penetrating radar (Section 6.1).

As noted above, since conductance and resistance are reciprocals, the output of both EM and ER methods can be expressed in either of two measurement scales (i.e., 1 ohm-meter =

1000 milliSiemens/meter). By convention ER and VLF (Section 4.4) measurements are typically reported in units of resistivity. Electromagnetic induction (Section 4. 1) and time domain electromagnetic measurements (Section 4.2) are typically reported in units of conductivity. The published literature on ER and EM methods, however, does not always follow these conventions; thus EM measurements may be reported in terms of resistivity or ER measurements in terms of conductivity. The method used to measure subsurface properties (induction for EM, and current injection by electrodes for ER) will indicate the technique, but not necessarily the units in which the measurements are reported. EM and ER methods are by far the most widely used surface geophysical techniques in ground-water contamination studies (see Tables 3-1 and 3-2 for ER, and Tables 4-1 and 4-2 for EMI).

3.2 Direct Current Electrical Resistivity

The direct current (DC), also called “galvanic”, electric resistivity method measures the resistance to flow of electricity in subsurface material. DC methods involve the placement of electrodes, called **current electrodes,** on the surface for injection of current into the ground. The current stimulates a potential response between two other electrodes, called **potential electrodes,** that is measured by a voltmeter (Figure 3-l). Resistivity (measured in ohm-meters) can be calculated from the geometry and spacing of the electrodes, the current injected, and the voltage response.

DC methods date from the early part of this century (Ward, 1980), with applications in ground-water investigations dating from the late 1930s (Lee, 1936; Sayre and Stephenson, 1937; Swartz 1937, 1939). DC methods are identified according to the arrangement of the current and potential electrodes. Until the 1960s, the most common electrode arrays used in resistivity investigations were the **Wenner, Lee-Partitioning,** and **Schlumberger** arrays (Figure 3-2). In more recent years the Schlumberger array generally has been the preferred method in ground-water investigations, although the Wenner array also is commonly used.

Advantages of the Schlumberger array over the Wenner array include the following (Zohdy et al., 1974):

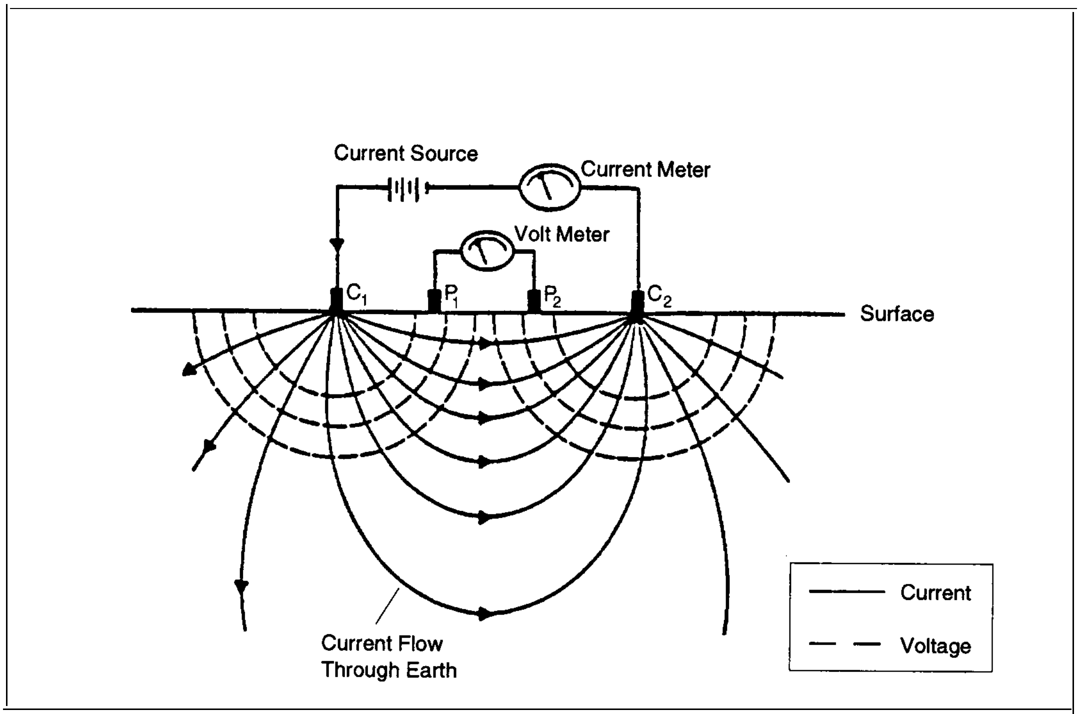

Figure 3-1 Diagram showing basic concept of resistivity measurement (from Benson et al., 1984).

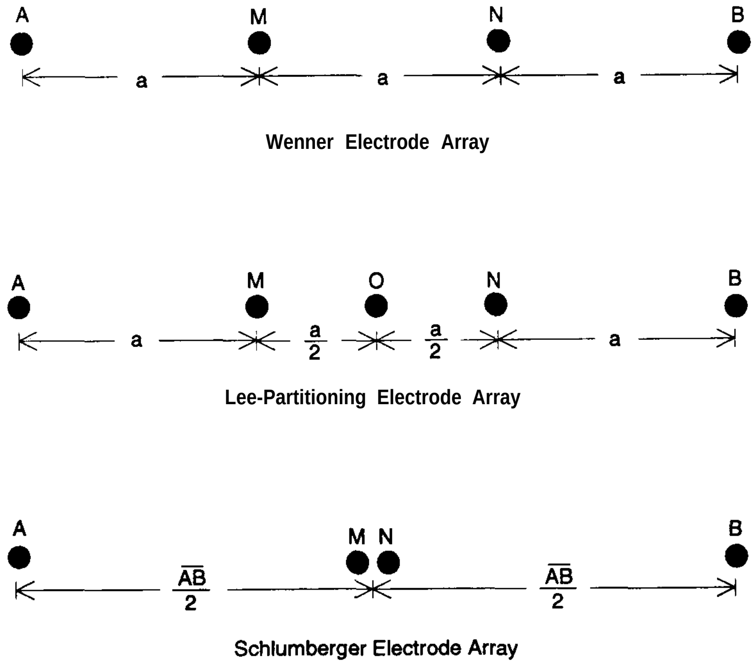

Figure 3-2 Wenner, Lee-Partitioning, and Schlumberger electrode arrays. A and B are current electrodes, M, N, and O are potential electrodes; a, $\frac{a}{2}$, and $\frac{\overline{AB}}{2}$ are electrode spacings (from Zohdy et al., 1974).

- Sounding curves provide slightly greater probing depth and resolving power than Wenner soundings for equal AB electrode spacing.

- Less manpower and time is required for making soundings than for a Wenner array.

- When wide electrode spacings are used, stray currents in industrial areas and telluric currents are more likely to affect measurements with the Werner array.

- The Schlumberger array is more sensitive in measuring lateral variations in resistivity.

- The Wenner array is more susceptible to drifting or unstable potential differences created by driving electrodes into the ground.

- Schlumberger sounding curves can be more readily smoothed.

The Wenner array, however, holds several advantages over the Schlumberger array, including simplicity of the apparent resistivity formula, relatively small current values required to produce measurable potential differences, and availability of a large album of theoretical master curves for two-, three-, and four-layer earth models (Mooney and Wetzel, 1956).

Dipole-dipole arrays, originally developed in the Soviet Union in the 1950s, have certain advantages over the Schlumberger array for deep soundings because relatively short AB and MN lines reduce field measurement times. Also, fewer problems are associated with current leakage and inductive coupling than for Schlumberger soundings. The **equatorial** variant of this type of array (Figure 3-3) has been used in this country for ground-water investigations (Zohdy, 1969). Paired electrodes that are close together are called **dipoles;** if widely spaced, they are called **bipoles,** as with the current electrodes in the equatorial array (see Figure 3-3). The main disadvantages of dipole-dipole arrays are that a large generator is required to provide current, especially for deep soundings, and interpretation of data is less straightforward than for Schlumberger and Wenner array measurements (Zohdy et al., 1974).

Figure 3-4a shows use of resistivity measurements in delineating a leachate plume from a landfill by isopleths of equal resistance measured in ohm-feet. Since landfill leachate contains ions that decrease the resistivity of ground water, the lower-value isopleths in Figure 3-4a

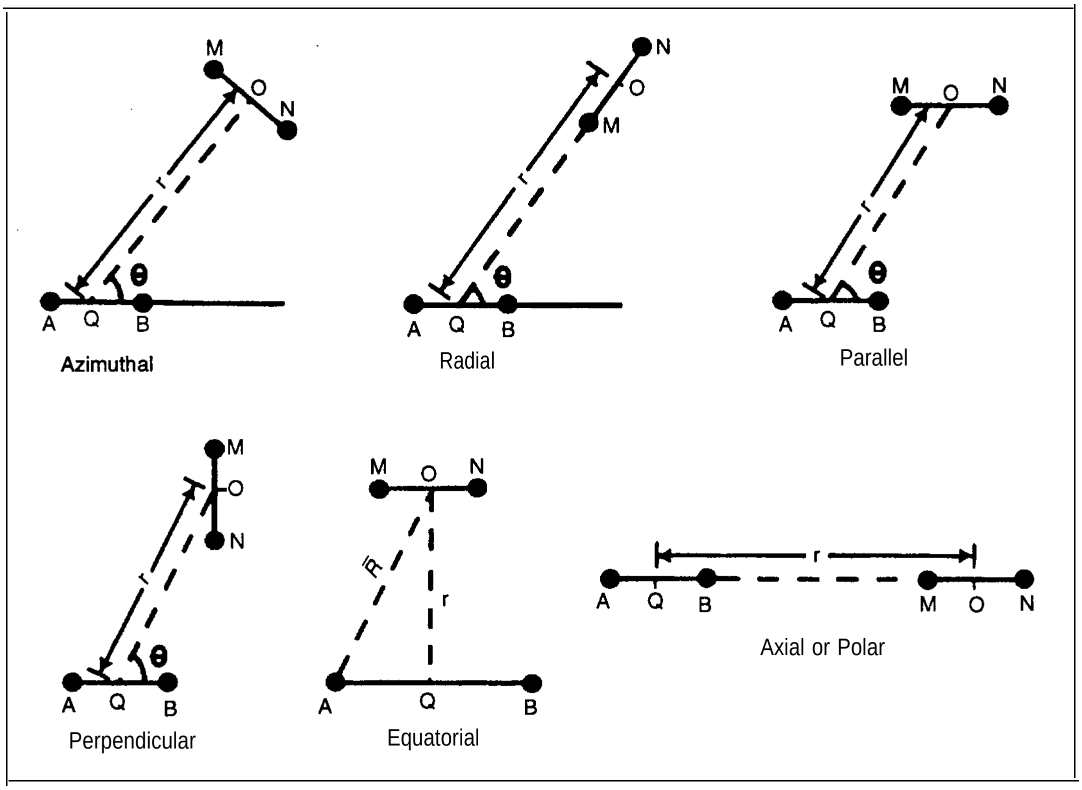

Figure 3-3 Dipole-dipole arrays. The equatorial array is bipole-dipole because AB is large (from Zohdy et al., 1974).

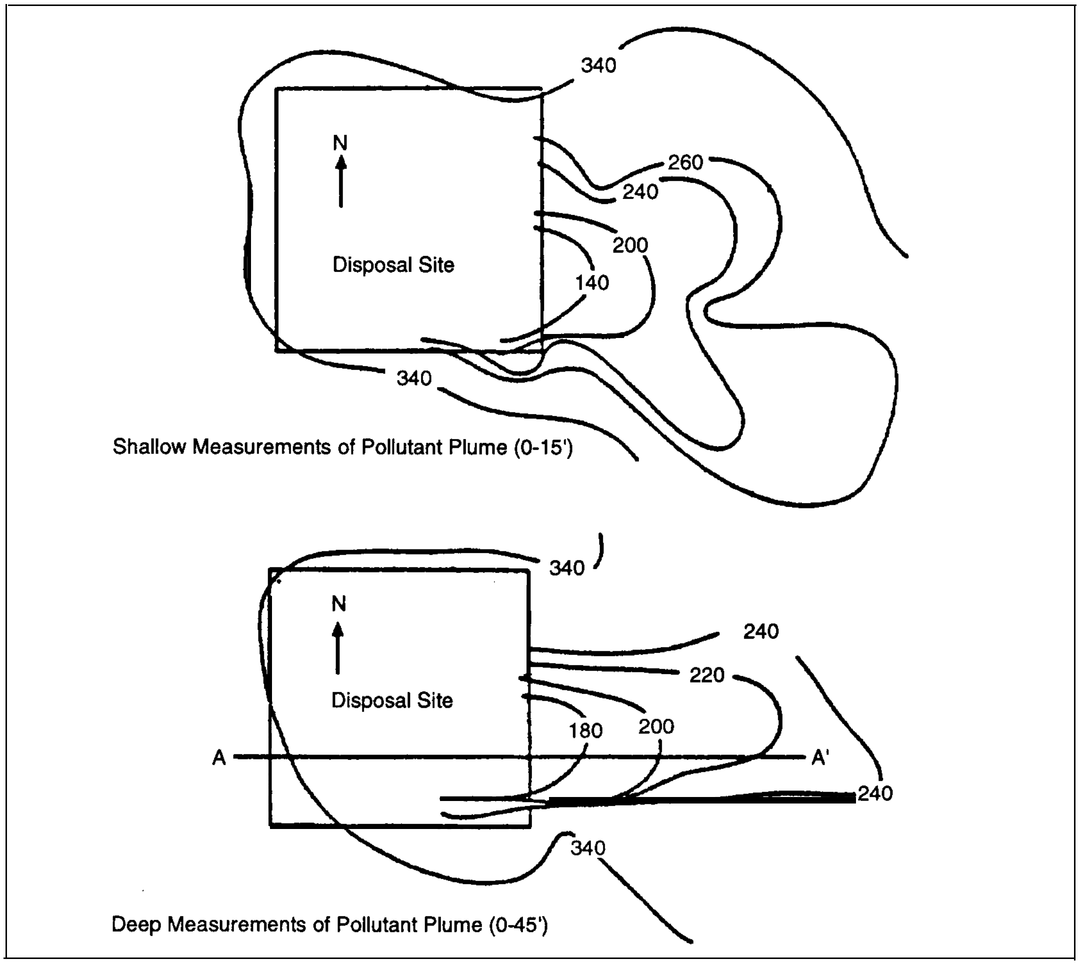

Figure 3-4a Resistivity soundings and profiles: isopleths of resistivity sounding data showing extent of a landfill plume (from Benson et al., 1984).

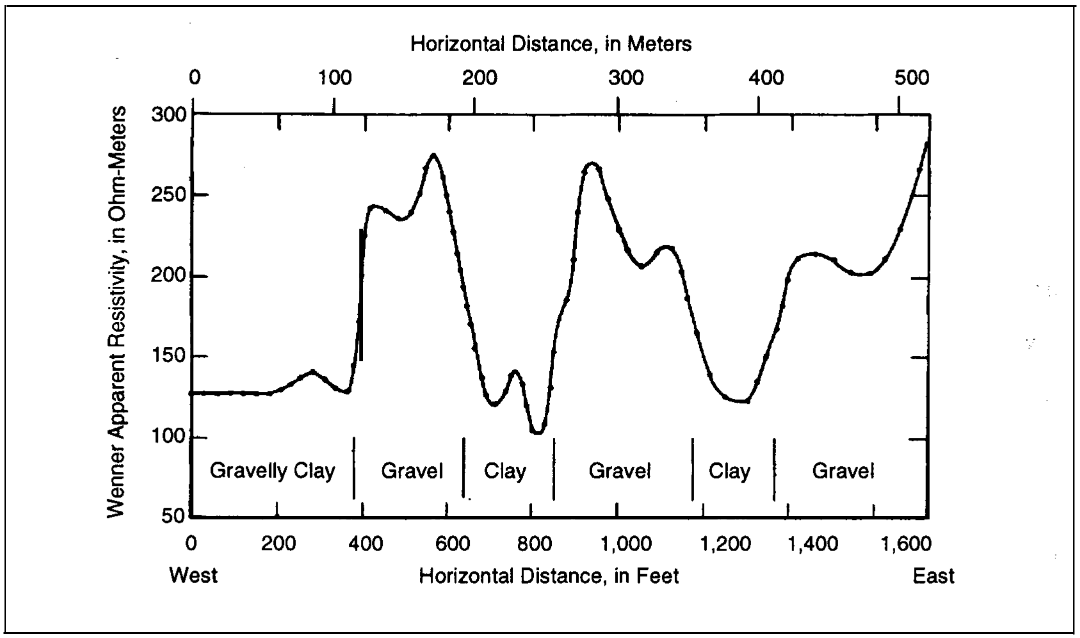

Figure 3-4b Resistivity soundings and profiles: resistivity profile across glacial clays and gravels (from Zohdy et al., 1974).

delineate the most contaminated areas (140 ohm-feet in the upper map and 180 ohm-feet in the lower map). In the figure, the deep measurements (O to 45 feet) include an averaging of the resistivity of the shallow measurements and the resistivity of the 15- to 45-foot depth interval. Figure 3-4b shows a horizontal resistivity profile that indicates lateral changes from clay and gravel material in the subsurface. Table 3-1 provides a general index to major texts and review papers on DC resistivity, and Table 3-2 lists over 250 references on applications for ground-water, geologic- and contaminated site characterization.

3.3 Specialized **Applications of DC Resistivity**

Azimuthal resistivity uses conventional Wenner or Schlumberger arrays, but the configuration is rotated 10 degrees clockwise and successive resistivities are measured (Figure 3-5a). The variations in electrical response to changes in the orientation of electrode arrays can be used to identify the location of subsurface fractures and joint orientations. Figure 3-5b shows variations in resistivity readings over fractured (Array A) and unfractured (Array B) areas of landfill cover. The fractured area is evidenced by overall higher readings during wet conditions and asymmetrical resistivities during dry conditions. In recent years, this method has gained some popularity for characterization of fractured rock and contaminated sites (Table 3-3). Although this method was first described by Zohdy (1970a) as the **variable azimuth** method to differentiate it from the azimuthal method developed by the Russians (a variant of the equatorial array-see Figure 3-3), the term azimuthal resistivity seems to have taken hold in the recent literature.

Tri-potential resistivity, which involves taking readings from three arrays (Wenner, dipole-dipole, and bipole-bipole-Figure 3-5c) at each station was first proposed by Carpenter (1955). A simple switching circuit built into the resistivity meter permits the rapid switching from one array to the next without physically moving the electrodes. The additional information obtained from multiple readings at the same site is especially useful for locating fracture zones, filled sinks, and subsurface cavities. As the reference list in Table 3-3 indicates, this is not a very commonly used method; however, its limited use seems to stem more from a lack of familiarity

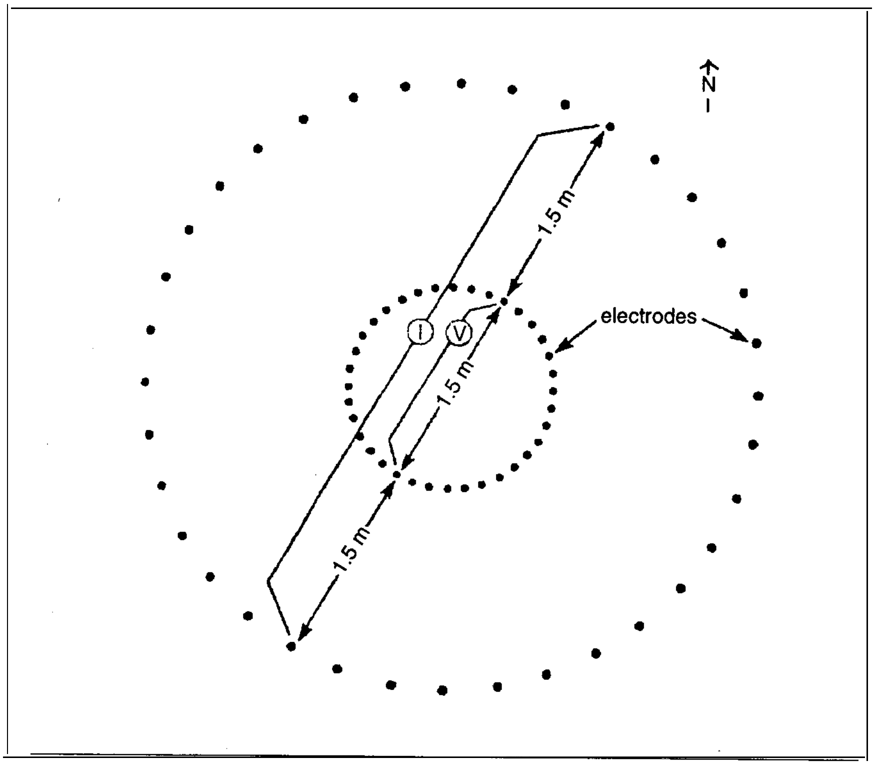

Figure 3-5a Specialized DC resistivity electrode configurations: layout of azimuthal resistivity array (Carpenter et al., 1991).

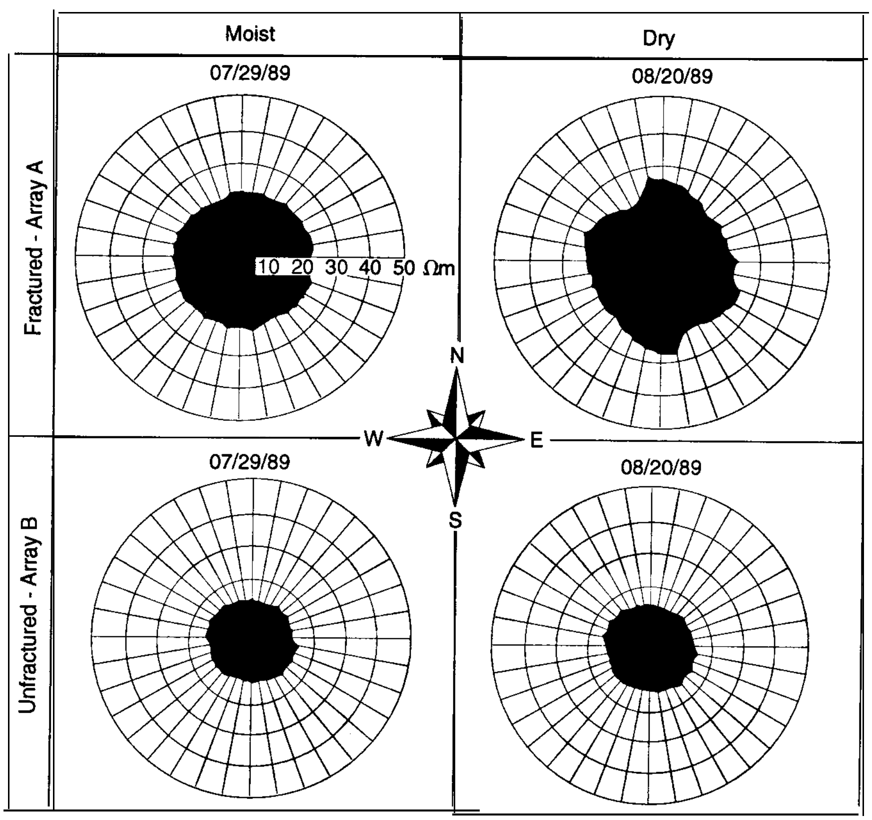

Figure 3-5b Specialized DC resistivity electrode configurations: azimuthal resistivity variations of fractured and unfractured landfill cover (Carpenter et al., l99l).

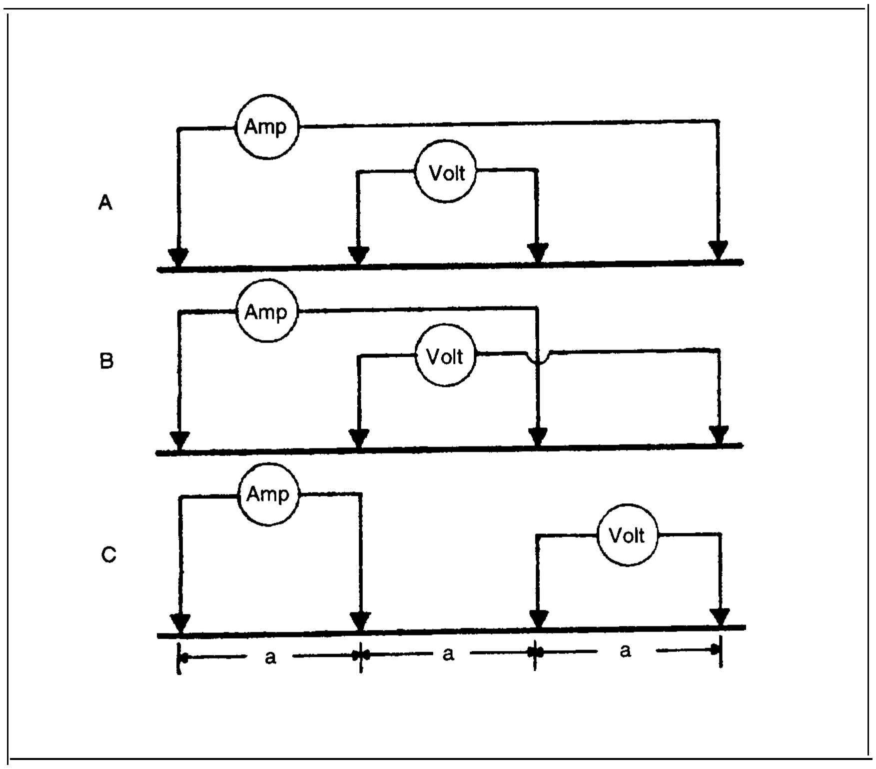

Figure 3-5c Specialized DC resistivity electrode configurations: tri-potential electrode array (Kirk and Rauch, 1977b).

with the method than from any inherent problems, and more widespread use for the applications mentioned above is probably merited.

Tomographic imaging is a relatively new DC resistivity method in which a grid of electrodes is established on the ground surface. Controlled currents are introduced into a subset of electrodes in a prescribed sequence and the electrical response of the other electrodes is measured. These signals are processed using tomographic theory to create a three-dimensional image of the subsurface (see Section 7.2.3). High vertical and horizontal resolution of contaminant plumes have been obtained in the laboratory, but grid edge effects have created difficulties in field applications (Tamburi et al., 1988).

3.4 Self-Potential

Self-potential involves the measurement of natural electrical potentials developed locally in the subsurface by electrochemical or electrofiltration processes. Several types of natural potentials may be measured by this method. **Spontaneous polarization** is a natural voltage difference that occurs as a result of electrical currents induced by chemical disequilibria within the earth. **Streaming potential** is an electrokinetic effect related to the movement of fluid containing ions through the subsurface.

The method is very simple, requiring only the measurements of the potential between two electrodes along transects in the area of interest (Figure 3-6a). Care is required to make sure that there is good ground-electrode contact for each measurement. This method can be used to (1) locate areas of ground-water flow in fractured rock and sinkholes, (2) locate leaks in reservoirs and canals, and (3) detect and monitor movement of contaminant plumes (Table 3-3). Gilkeson and Cartwright (1982) note that ER and EM methods can be expected to provide superior results in the detection of contaminant plumes. Section 1.2.2 in U.S. EPA (1993) summarizes advantages and disadvantages of self-potential measurements. Perhaps the most common use of this method has been in mineral exploration where ore bodies are in contact with solutions of different compositions.

A variant of self-potential in which current is injected into the ground to enhance the streaming potential effect has been developed to detect leaks in lined ponds (Figure 3-6b). Geomembrane liners have high resistivity and will provide relatively uniform potential readings between two electrodes. If the liner is punctured, fluid flow through the leak creates a conductive path for the flow of injected current and produces anomalous potential readings in the vicinity of the leak.

3.5 Induced Polarization and Complex Resistivity

Induced polarization (IP) is an electrical method that measures electrochemical responses of subsurface material (primarily clays) to an injected current. In time domain IP surveys, the rate at which voltage decays after current injection stops is measured, while infrequency domain IP surveys, the effect of frequency on electrical resistivity is measured. Frequency domain measurements are more precise when induced polarization effects increase with depth; time domain are better when induced polarization effects decrease with depth (Patella and Schiavone, 1977)$

IP surveys are conducted in a similar manner to DC surveys, and all IP instrumentation can be used for conventional DC surveys. IP surveys are more expensive than DC surveys and have some of the same disadvantages relative to EM methods, such as the requirement for good electrode contact with the ground. In some situations, particularly where clayey and nonclayey unconsolidated materials must be differentiated IP surveys can provide more useful information than DC surveys alone. A few investigators have reported use of IP surveys in ground-water exploration (Table 3-4). Use at contaminated sites has been rare (Hughes et al., 1986; Krumenacher and Taylor, 1988), however, and should be considered experimental. Lord and Koerner (1980, 1987) gave this method a low rating compared to alternative methods for detection of buried containers.

Complex resistivity, a more refined version of induced polarization, measures the frequency characteristics of different materials over a larger frequency spectrum than frequency domain IP. The method potentially allows greater differentiation of subsurface materials than

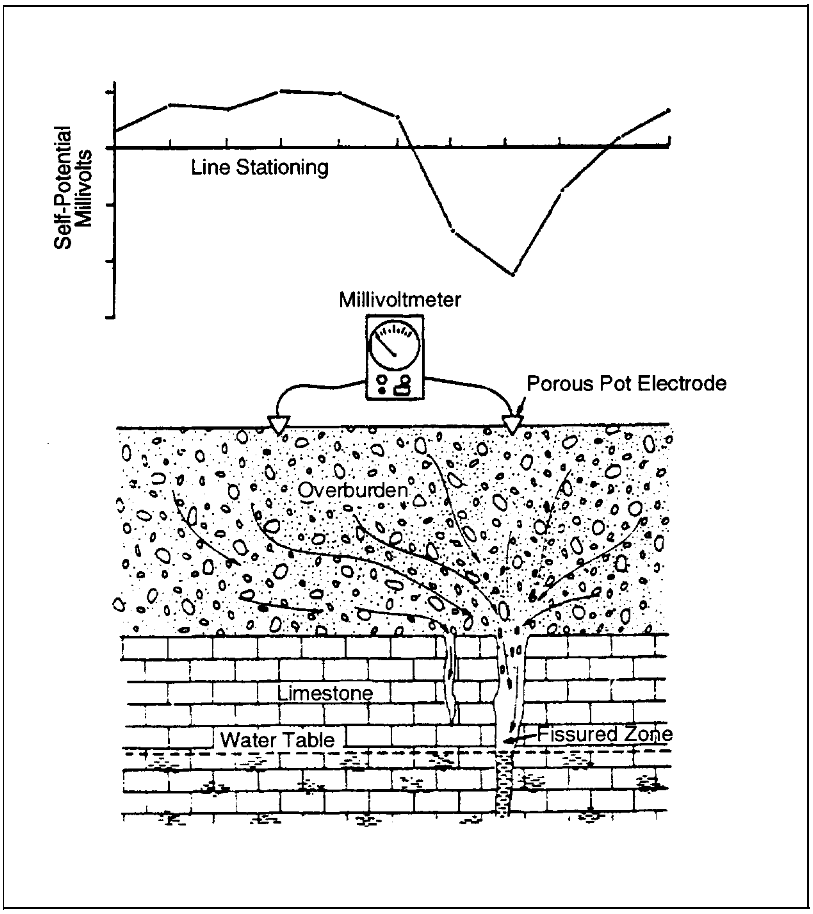

Figure 3-6a Self-potential measurements: apparatus and graph of measurement over a fissured zone of limestone illustrating negative streaming potential caused by ground-water seepage (Ogilvy and Bogoslovsky, 1979).

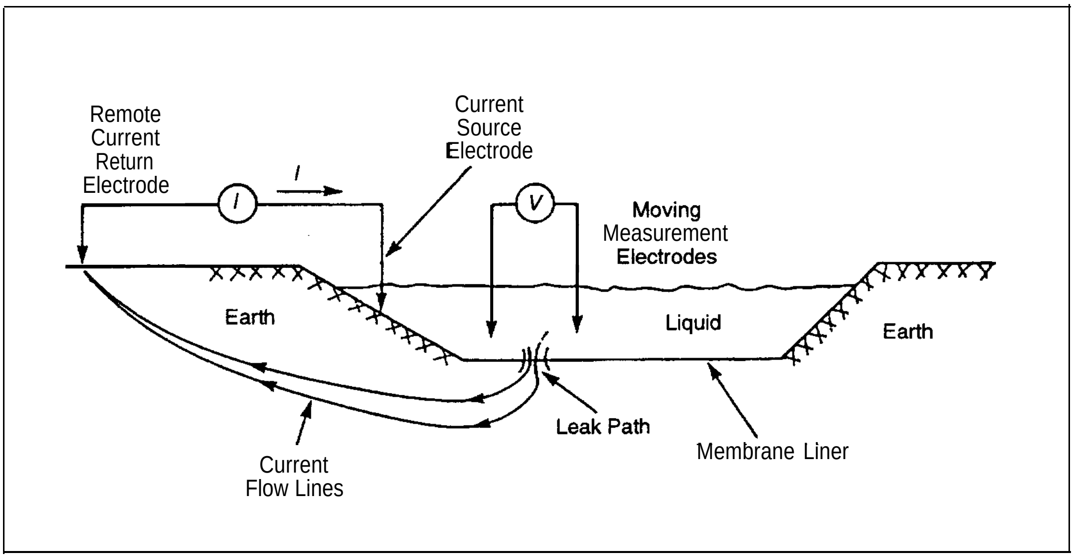

Figure 3-6b Self-potential measurements: electrical leak detection using modified self-potential method (Darilek and Parra, 1988 b).

conventional IP, but the instrumentation for signal detection and analysis is more complex and consequently costs are even higher. Complex resistivity has the potential advantage of being able to detect organic contaminant plumes where DC methods are relatively unsuccessful in this application (Pitchford et al., 1988; Olhoeft, 1990, 1992). Nonetheless complex resistivity methods are still more or less at the research stage of development and instrumentation is not widely available. Because of the larger frequency spectrum, complex resistivity is the method most susceptible to interference from cultural materials (e.g., buried metallic containers, cables, pipelines) of the electrical methods.

Table 3-1 Index to General References on DC Electrical Resistivity Methods

Topic	References
Textbooks/Reports	
Electrical Resistivity	Bhattacharya and Patra (1968), Goldman (1990-nonconventional methods), Keller and Frishcknecht (1970), Kofoed (1979), Kunetz (1966), Mooney (1980), Patra and Mallick (1980), Soiltest, Inc. (1968); see also Table 1-4 for identification of general geophysics texts covering electrical methods
Interpretation	Texts: Kalenov (1957), Mooney and Wetzel (1956), Orellana and Mooney (1966, 1972), Van Nostrand and Cook (1966), Verma (1980); Computer Programs: Basokur (1900), Davis (1979), Sheriff (1992), Zohdy (1974a,b), Zohdy and Bisdorf (1975); Papers: Cook and Van Nostrand (1954), Frangos (1990), Keck et al. (1981), Radstake et al. (1991), Zohdy (1964, 1974c, 1975, 1989)
Geoelectric Properties	Parkhomenko (1967), Wait (1982), Wheatcraft et al. (1984)
Other Texts	Benson et al. (1984), Kirk and Warner (1981- cavity detection), Redwine et al. (1985), Rehm et al. (1985), U.S. EPA (1987), Lord and Koerner (1987), Pitchford et al. (1988), USGS (1980), Zohdy et al. (1974)
General Papers	
Review Papers	Maillet (1947), Roman (1952), Roy and Apparao (1971), Ward (1980, 1988)
EM/ER Comparisons	See references indexed in Table 4-1
Data Analysis	Jones (1937), LaBrecque et al. (1984), LeBrecque and Weber (1984)
Subsurface Electrical Properties	Barton (1984), Collett and Katsube (1973), Hackett (1956), Jackson et al. (1978), Jagammadha and Rao (1962), Kean et al. (1984), Kelly and Frohlich (1985), Ward and Fraser (1967), Wong et al. (1984), Worthington (1977a)
Instrumentation	Electrode Arrays: Carrington and Watson (1981), Zohdy (1970a,b,c); Automated Data Acquisition: Jackson et al. (1990), Taylor (1985)

Table 3-2 Index to References on Applications of DC Resistivity Methods

Topic	References
<u>Ground-Water Applications</u>	
General	Bays (1946, 1950), Bays and Folks (1944), Benson (1991), Bernard and Valla (1991), Breusse (1963), Buhle (1953), Butler and Llopis (1985), Cook et al. (1992-recharge), Harmon and Hajicek (1992-stream-aquifer connections), Henriet (1976), Kelly (1961), Kelly et al. (1989), Mark et al. (1986), Meidav (1964)), Paver (1945), Ringstad and Bugenig (1984), Shields and Sopper (1969—watershed hydrology), Stewart et al. (1983), Stickel et al. (1952), Urish and Frohlich (1990), Van Dam (1976), Workman and Leighton (1937), Worthington (1975a), Worthington and Griffiths (1975)
U.S. Case Studies	Ackermann (1976-permafrost areas), Adams et al. (1971), Bisdorf (1990), Bisdorf and Zohdy (1979), Buhle and Brueckmann (1964), Carpenter and Bassarab (1964), Cherkauer and Taylor (1988), Dudley and McGinnis (1962), Foster and Buhle (1951), Frohlich (1973, 1974), Gabanksi et al. (1984), Hoekstra et al. (1975—permafrost), Joiner and Scarborough (1969), Joiner et al. (1967, 1968), Kent and Sendlein (1972), Lee (1937), Mattick et al. (1973), Merkel and Kaminski (1972), Page (1968), Pool and Heigold (1981), Priddy (1955), Rijo et al. (1977), Samuelson (1987), Stewart and Wood (1986), Stewart et al. (1985), Stierman et al. (1986), Taylor (1992), Tucci (1984), Underwood et al. (1984), Wantland (1953), Watson et al. (1990), Wilson et al. (1970), Windschauer (1986), Woessner et al. (1989), Zohdy (1965, 1969, 1988), Zohdy and Jackson (1969)
Non-U.S. Case Studies	<u>Canada</u>: Hobson et al. (1962), Lennox and Carlson (1970); <u>Germany</u>: Flathe (1955, 1964, 1970, 1976), Hallenbeck (1953); <u>Other</u>: Fournier (1989—France), Maderios and de Lima (1992-Brazil), Martinelli (1978-South Africa), Mbonu et al. (1991—Nigeria), Sayed (1984-Egypt), Topper and Legg (1974-Zambia), Van Dam and Meulenkamp (1967), Van Overmeeren (1981-Sudan; 1989—Yemen), Verma et al. (1980-India), Wachs et al. (1979—Israel), Worthington (1977a–Kalahari)
Aquifer Properties	Ahmed et al. (1988), Bardossy et al. (1986), Barker and Worthington (1973), Biella et al. (1983), Coetsee et al. (1992), Frohlich (1972), Frohlich and Kelly (1983, 1988), Frohlich and Smith (1974), Gilmer et al. (1986-alluvial aquifer), Heigold et al. (1979), Huntley (1986), Huntley and Mishler (1984), Jackson et al. (1978), Jagammadha and Rao (1962), Kean et al.(1984), Kelly (1976a, 1977), Kelly and Frohlich (1985), Kelly and Reiter (1984), Kosinski and Kelly (1981), Kwader (1985), Mazac et al. (1985), Niwas and Singhal (1985), Park and Dickey (1989), Ritzi and and Andolesk (1992), Sauk and Zabik (1992), Sehimsal (1981), Sjostrom and Sill (1991), Taylor and Cherkauer (1984), Urish (1981), White (1988-chloride tracer), Worthington (1975b, 1976, 1977b)

Table 3-2 (cont.)

Topic	References
<u>Geologic Characterization Applications</u>	
General	Benson (1991), Cook and Nostrand (1954-filled sinks), Emilsson and Morin (1989—buried channel), Ghatge and Pasicznyk (1986-bedrock topography), Hawley (1943—fault location), Hubbert (1944-faults), Page (1968), Smith (1974-buried valley), Spicer (1952), Tucci (1986), Wantland (1952—depth weathered rock), Wilcox (1944--sand and gravel)
Glacial Deposits	Denne et al. (1984-glacial buried valleys), Hackett (1956), McGinnis and Kempton (1961), Reed (1985), Reed et al. (1983), Samuelson (1987), Shoepke and Thomsen (1991), Stierman et al. (1986), Urish (1981)
Karst	Filler and Kuo (1989), Fretwell and Stewart (1981), Frohlich and Smith (1974), Joiner and Scarborough (1969), Kirk and Werner (1981), Riitzi and Andolesk (1992), Rodriguez and Wellner (1988), Smith and Randazzo (1986, 1989), Stewart and Wood (1986), Watson et al. (1990)
Fractured Rock	Adams et al. (1988), Bernard and Valla (1991), Burdick (1982), Johnson and Saylor (1987), Pfeiffer et al. (1990), Smith and Randazzo (1989), Ritzi and Andolesk (1992), Williams et al. (1990)
Permafrost	Hoeckstra et al. (1975)
<u>Contaminated Site Abdications</u>	
General/Unspecified	Benson (1991), Borns and Pickering (1990), Bruehl (1983, 1984a,b), Corwin (1986), Evans and Scwheitzer (1984), Fowler and Ayubcha (1986), Fox and Gould (1984), Gilkeson et al. (1984), Mazac et al. (1987, 1989, 1992), Pennington (1985), Pitchford et al. (1988), Rodriguez (1984), Urish (1983), White and Brandwein (1982), White et al. (1984), Williams et al. (1984)
Ground-Water Monitoring	Beeson and Jones (1988), Benson et al. (1985, 1988), Bogoslovsky and Olgilvy 1970a--dam seepage), Ehrlich and Rosen (1987), Gilkeson and Cartwright (1982), Kean and Rogers (1981), Lange et al. (1986), Noel et al. (1982), Rumbaugh et al. (1987), Stearns and Dialmann (1986), Yazicigil and Sendlein (1982)
Vadose Zone Monitoring	Frohlich and Parke (1989), Kean et al. (1987)

Table 3-2 (cont.)

Topic	References
Contaminated Site Applications (cont.)	
Contaminant Plumes	Brickell (1984), Greenhouse et al. (1985), Kean and Rogers (1981), LeBrecque et al. (1984a,b), Schneider and Greenhouse (1992-perchloroethylene), Tamburi et al. (1985, 1988-tomographic imaging), Urish (1984-radioactive plume)
Industrial/Hazardous Waste Sites	Allen and Rogers (1989), Bradley (1986), Cichowicz et al. (1981), Evans and Schweitzer (1984), Gilmer and Helbling (1984), Harman (1986), Hitchcock and Harman (1983), Horton et al. (1981), Kolmer (1981), Pease et al. (1981), Peterson et al. (1986), Rudy and Caolie (1984), Saunders and Stanford (1984), Shoepke and Thomsen (1991), Stellar and Roux (1975), Slaine and Greenhouse (1982), Stearns and Dialmann (1986), Stierman (1981), Stierman and Ruedisili (1988), Walther et al. (1983), White and Brandwein (1982), Williams et al. (1984)
Landfill Leachate	Allen (1984-paper mill), Carpenter (1990), Carpenter et al. (1990a-landfill structure), Cartwright and McComas (1968), Evans and Schweitzer (1984), Greenhouse and Harris (1983), Keck et al. (1981), Kelly (1976a), Kelly et al. (1988), Klefstad et al. (1975), Laine et al. (1985), Roberts et al. (1989), Roux (1978), Rudy and Caolie (1984), Rumbaugh et al. (1987), Russell (1990), Russell and Higer (1988), Seitz et al. (1972), Stellar and Roux (1975), Sweeney (1984), Walsh (1988)
Salt Water Interface/ Brine Contamination	Berk and Yare (1977—sodium salts), Chapman and Bair (1992), Ginsberg and Lavanon (1976), Gorban (1976), Gondwe (1991), Knuth (1988), Plivas and Wong (1975), Reed et al. (1981), Roy and Elliot (1980), Sayre and Stephenson (1937), Schroeder (1970), Stewart (1982), Swartz (1937, 1939), Warner (1969—brine ponds)
Soil Salinity	Table 9-3 in Boulding (1992) contains an index of over 70 references related to use of four-electrode resistivity, electrical conductivity probes and electrical resistance salinity sensors for measurement and monitoring of soil salinity
Miscellaneous	Adams et al. (1988-UST), Allen et al. (1985—spray irrigation leachate), Aller (1984-abandoned wells), Andres and Canace (1984-hydrocarbons), Burdick (1982-abandoned mines and mine leachate), Fink and Aulenbach (1974-sewage effluent), Fountain (1976-cavity detection), Hackbarth (1971—sulfite liquor), Merkel (1972—acid mine drainage), Rogers and Kean (1980-flyash leachate), Van et al. (1991—pond leaks), Warner (1969—sewage effluent)

Table 3-3 Index to References on Specialized DC Electrical Resistivity and Self-Potential Methods

Topic	References
Specialized DC Resistivity Methods	
Azimuthal Resistivity	Contaminated Sites: Jansen and Taylor (1989); Carpenter et al. (1990b, 1991—fractured landfill cover); Fractured Rock Jansen (1990), Ritzi and Andolesk (1992), Taylor (1984), Taylor and Jansen (1988), Taylor and Fleming (1988), Jansen and Taylor (1989), Leonard-Mayer (1984a,b), Zohdy (1970a); Other: Sauck and Zabik (1992)
Tri-potential	Carpenter (1955), Habberjam (1969-cavity detection), Kirk and Rauch (1977a—fracture detection; 1977b-karst hydrogeology), Ogden and Eddy (1984-fractures/caves), Ogden et al. (1991 -USTs)
Tomographic Imaging	Tamburi et al. (1985, 1988)
Self-Potential	
General	Ahmed (1963), Corwin (1990), HRB Singer (1971—abandoned mines), Bogoslovky and Ogilvy (1972-fissured media; 1977—landslides), Lord and Koerner (1980, 1987), Ogilvy and Bogoslovsky (1979), Ogilvy and Kuzima (1972)
Ground-Water Monitoring	Gilkeson and Cartwright (1983), Lange et al. (1986), Redwine et al. (1985), Rehm et al. (1985)
Contaminant Plumes	Corwin (1986), Hughes et al. (1986), Smith (1991)
Reservoir/Canal Leaks	Bogoslovsky and Ogilvy (1970a, 1970b, 1973, 1977), Ogilvy et al. (1969), Smith (1991), Yule et al. (1985)
Liner/Pond Leak Detection	Darilek and Parra (1988a,b), Darilek and Laine (1989), Fountain (1986), Laine and Miklas (1989), Parra (1988a,b), Peters et al. (1982a,b), Schultz and Duff (1985), Schultz et al. (1984a,b), Van et al. (1992), Wailer and Davis (1984)
Ground Water	Fournier (1989—volcanic area)
Karst	Erchul and Butler (1986), Lange and Quinlin (1988)

Table 3-4 Index to References on Induced Polarization Electrical Methods

Topic	References
Texts	Baizer and Lund (1983), Bertin and Loeb (1976), Bottcher (1952), Fink et al. (1990), Sumner (1976), Wait (1959, 1982)
Papers	Bleil (1953), Frische and von Buttlar (1957), Keevil and Ward (1962), Madden and Cantwell (1967), Marshall and Madden (1959), Seigel (1959), Sumner (1979), Taylor (1985), Vogelsang (1974), Ward (1980, 1988)
Frequency Domain	Barker (1974), Hallof (1964), Patella and Schiavone (1977), Zonge et al. (1972)
Time Domain	Bertin (1968), Patella and Schiavone (1977), Roy and Shikhar (1973), Zonge et al. (1972)
Complex Resistivity	Cleff (1991), Olhoeft (1984, 1990, 1992), Olhoeft and King (1991), Wheatcraft et al. (1984)
Subsurface Response	Barker (1975), Olhoeft (1985)
Ground Water	Adams et al. (1975), Bodmer et al. (1968), Mohamed (1970), Ogilvy and Kuzima (1972), Roy and Eliot (1980), Vacquier et al. (1957), Worthington (1975b); Texts with Brief Discussions: Rehm et al. (1985), U.S. Geological Survey (1977)
Field Applications	Ahgoran et al. (1947- cultural metallic refuse), Baker (1975), Bogoslovsky and Olgilvy (1970a), Hughes et al. (1986-brine toxic waste plume), HRB Singer (1971), Krumenacher and Taylor (1988-organic contaminants)
Contaminated Sites	Complex Resistivity: Olhoeft et al. (1986-hydrocarbons, 1992), Pitchford et al. (1988), Walther et al. (1983, 1986), Yong and Hoppe (1989); IP: Lord and Koerner (1980, 1987-1ow rating for detection of buried containers)

3.6 References

See Glossary for meaning of method abbreviations.

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CHAPTER 4
SURFACE GEOPHYSICS: ELECTROMAGNETIC METHODS

Electromagnetic measurements can be made in either the frequency domain or the time domain. (See Section 3.1 for a discussion of general characteristics of electromagnetic methods.) **Frequency domain** geophysical measurements sense the subsurface response to sinusoidal electromagnetic fields at one or more transmitted frequencies. **Time domain** geophysical measurements record the change in response as time passes after a transmitted signal has been abruptly turned off. The term electromagnetic induction (EMI) usually indicates use of frequency domain measurements. Time domain electromagnetic (TDEM) measurements, called **transient electromagnetic** (TEM) soundings, also involve electromagnetic induction. Although the use of TDEM methods at contaminated sites is a relatively recent development, they are far superior to EMI measurements in providing vertical resolution of soundings (see Section 4.2). The electrical method of induced polarization also can be used in either the time or the frequency domain (Section 3.5).

Frequency domain **electromagnetic induction** (EMI-Section 4.1) is the most commonly used surface geophysical method for detection of conductive contaminant plumes. **Time domain electromagnetics** (Section 4.2) has gained increasing popularity in ground-water studies, especially for the detection of freshwater-saltwater interfaces and saltwater intrusion because of its higher resolution and greater depth of penetration. Other major types of electromagnetic methods include **metal detection** (using EMI instruments designed specifically to detect buried metals-Section 4.3); **very low frequency (VLF) resistivity** (Section 4.4); and various **magnetotelluric** methods (Section 4.5). Metal detectors are commonly used at contaminated sites where buried pipelines and metallic wastes are known or suspected, and VLF resistivity is the next most frequently used EM method after electromagnetic induction for detection of conductive contaminant plumes.

4.1 Frequency Domain Electromagnetic Induction (EMI)

Electromagnetic induction methods (generally abbreviated as EM, although this abbreviation also is used specifically for frequency domain EM measurements) measure subsurface electrical conductivities by low-frequency electromagnetic induction (Benson et al., 1984). Table 4-1 identifies general references on electromagnetic induction methods. Often the term **terrain conductivity** is used to refer to measurements made using EMI methods. Electrical conductivity is a function of the type of soil and rock, its porosity, degree of connectivity, degree of saturation, and the electrochemistry of the fluids that fill the pore space. In most cases, the electrical conductivity (measured as millimhos per meter, or, more recently, milliSiemens per meter, mS/M) of the pore fluids will dominate the measurement. Also, dissolved species in contaminated water will alter its conductance compared to the natural ground water. Consequently, EM is an excellent technique for mapping contaminant plume boundaries, as well as a variety of other subsurface features with contrasting electrical properties.

EMI equipment used in ground-water contamination studies differs from the wide variety of EM equipment used in mineral exploration in that it is usually designed and calibrated to read directly in units of apparent conductivity. Figure 4-la shows the basic principle of operation: A transmitter coil generates a sinusoidal electromagnetic field that induces eddy currents in the earth below the instrument. A receiver coil then intercepts both the primary and the secondary electromagnetic fields created by the eddy current loops and produces an output voltage that is corrected for the primary field and the loop geometry and spacing. This voltage, within limits, is linearly related to subsurface conductivity. The reading represents the weighted cumulative sum of the conductivity variations from the surface to the effective depth of the instrument.

The effective depth for EMI is determined by the geometry and spacing of the transmitting and receiving coils (Figure 4-lb), with 60 meters representing a typical maximum depth. Readings to shallow depths can be made continuously since the coils are rigidly connected, whereas greater depth penetration requires stationary measurements (see Figure 1-3). Benson et al. (1984) is a useful source of additional introductory information about this method; Nabighian (1988, 1991) provides more detailed information. Section 1.3.1 in U.S. EPA (1993) summarizes advantages and disadvantages of EMI. In the last 10 years EMI probably has been

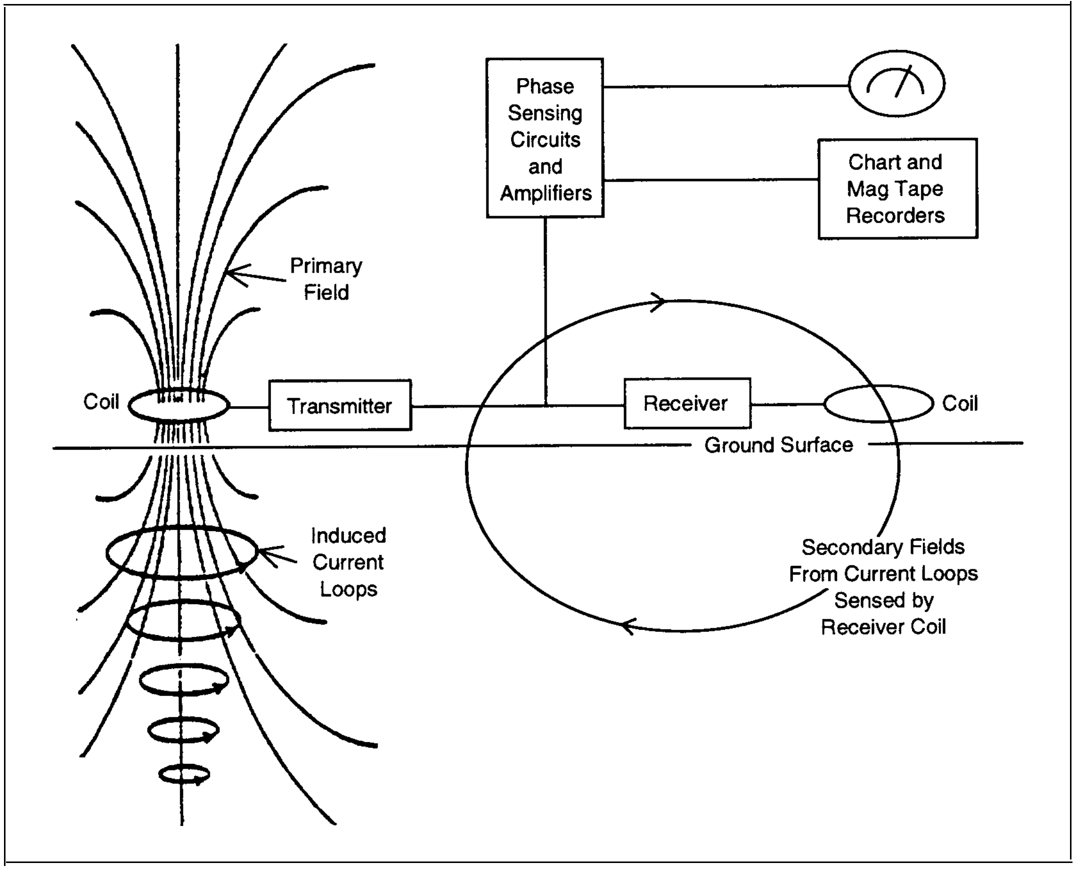

Figure 4-1a Electromagnetic induction: block diagram showing EMI principle of operations (adapted from Benson et al., 1984).

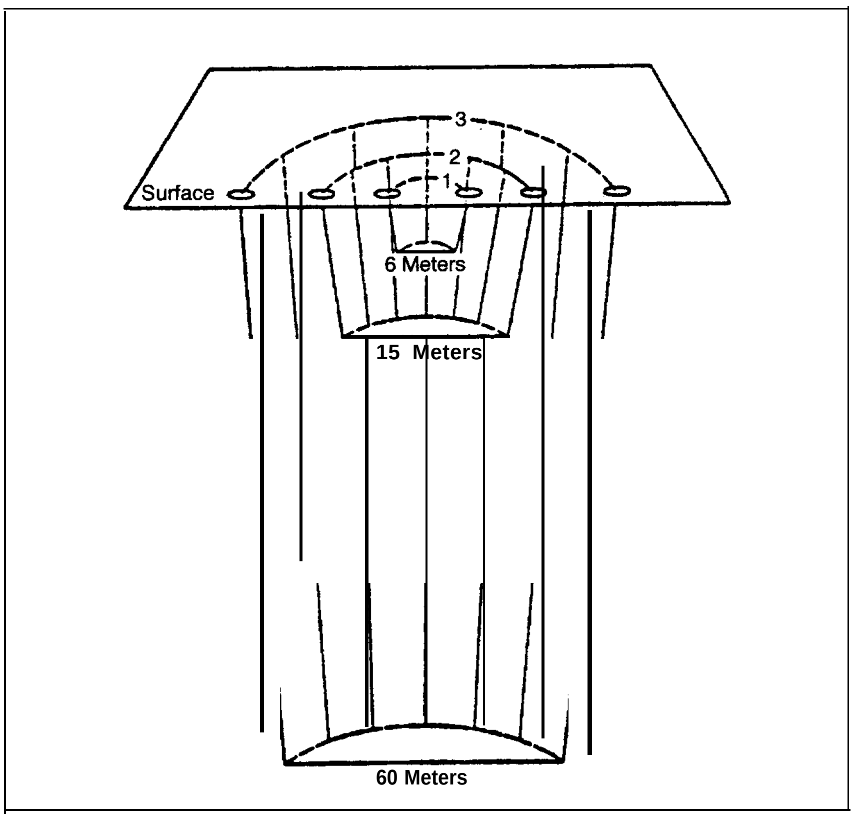

Figure 4-lb Electromagnetic induction: the depth of EMI soundings is dependent upon coil spacing and orientation selected (from Benson et al., 1984).

used more than any other geophysical method to map conductive contaminant plumes (Tables 4-2; see also Table A-l).

Table 4-1 identifies literature in which EMI and electrical resistivity methods have been compared. Rehm et al. (1985) reviewed literature reporting the success of DC methods and EMI in meeting objectives for hydrogeologic investigations. While both methods show a high success rate in meeting objectives, DC resistivity was unsuccessful more often than EMI (6 out 24 cases for DC resistivity compared to 1 out of 18 cases for EMI).

4.2 Time Domain Electromagnetic (TDEM)

Recent developments in time domain electromagnetic instrumentation (also called transient EM) with resolution capabilities in the shallow (<100 m) subsurface combines some of the best features of DC methods and EMI. In TDEM, a square, single-turn transmitter loop (of side length typically 10 to 20 m) is laid on the ground with the receiver coil nearby (Figure 4-2a). The transmitter initially causes a steady current to flow in the loop. This current is suddenly terminated, causing an essentially circular eddy current ring to flow at successively greater depths as shown in Figure 4-2b. Measurement of the decaying magnetic field from this descending eddy current yields data that can be interpreted in terms of the terrain resistivity as a function of depth. Thus the TDEM technique is useful for geoelectric sounding. Depth of exploration is determined by the dipole moment of the transmitter (product of current times area); the time of measurement of the decaying magnetic field; and the orientation, geometry, and spacing of the loops.

TDEM measurements have been used increasingly in the last decade for ground-water studies (Table 4-3), since the speed of operation, lateral resolution, and resolution of electrical equivalence (the situation where more than one layered earth model will fit the measured data to within the experimental error) are in general very good. Because the mathematics involved in the computer programs for analyzing TDEM measurement are more complicated than DC methods, however, erroneous interpretation is more likely, especially if nongeophysicists are using

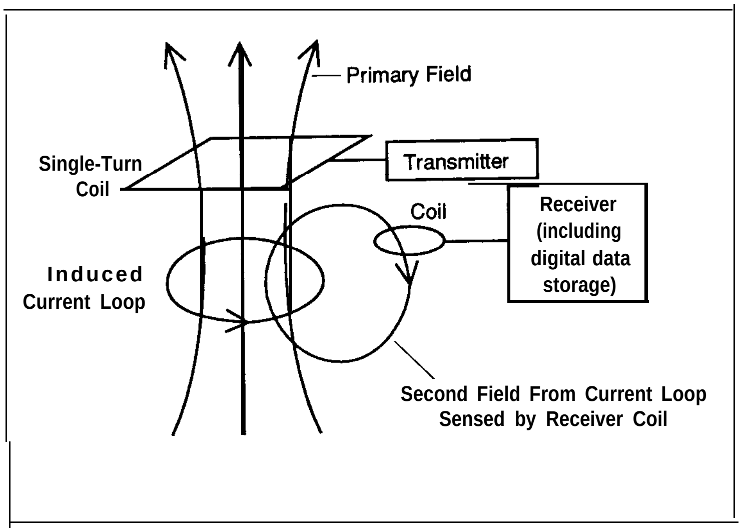

Figure 4-2a Time domain electromagnetic: block diagram showing TDEM principles of operation.

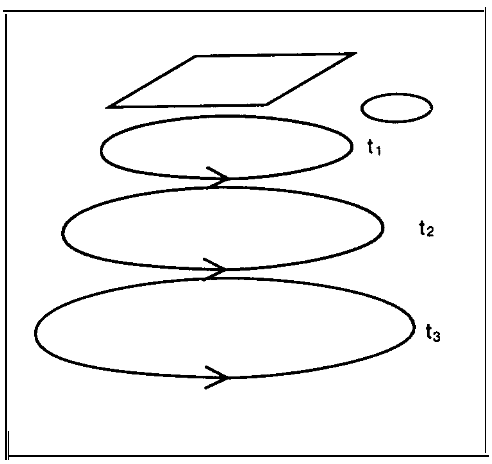

Figure 4-2b Time domain electromagnetics: the depth of TDEM soundings depends on transmitter current, loop size, and time of measurement.

the programs. Surface features can pose difficulties for placing the transmitter loop, and TDEM is less suitable for especially shallow applications (less than 150 m).

4.3 Metal Detection

Metal detectors operate on the same principles as electromagnetic induction, except that the instruments are specifically designed to sense increased conductivity resulting from either ferrous or nonferrous metals near the ground surface. The many different types of metal detectors available fall into three main classes: pipeline/cable locators, conventional “treasure hunter” detectors, and specialized detectors. The first two types are usually handheld and require one person to operate. Specialized detectors are designed for complex conditions and often require two operators, unless the device is truck-mounted.

The advantage of metal detectors is that they can sense nonferrous metals such as aluminum and copper, which cannot be detected with magnetometers. Their detection range is limited, however: up to 3 meters for single drums and 6 meters for large piles of metallic material. Section 1.3.3 in U.S. EPA (1993) summarizes advantages and disadvantages of metal detectors, and Benson et al. (1984) provide more detailed information on the use of metal detectors. Table 4-3 identifies a number of references concerning the use of metal detection or providing a discussion of the method in relation to investigations of contaminated sites.

4.4 Very Low Frequency Resistivity

Very low frequency (VLF) resistivity instruments measure the ratio of electrical to magnetic fields generated by military communication transmitters (around 15 to 25 kHz). The term very low frequency is somewhat confusing since, although the radio waves are indeed of a very low frequency, they are often of higher than those used in EM induction methods. The distribution of transmitting stations, their high power, and effects created by the ionosphere produce worldwide coverage of VLF transmissions (Stewart and Bretnall, 1986).

The depth of penetration of these waves is related to the resistivity of the subsurface materials. The depth of penetration for contaminant plumes (around 30 ohm-m) is around 20 meters, with penetration typically 35 to 60 meters in saturated overburden with higher resistivities (100 to 300 ohm-m) (Greenhouse and Harris, 1983).

Resistivity and phase angle (between the electric and magnetic fields) measurements are taken using electrodes driven into the ground at 10 meters apart. The principles of data interpretation are similar to those used in magnetotelluric methods.

An advantage of VLF measurements over EM and DC resistivity methods is that the remote transmitter is supplied free of charge and does not have to be carried by the survey crew. Although the measurement requires ground contact, only potential electrodes are employed, minimizing contact resistance problems. Given that potential electrodes are used, static effect problems (see below in relation to CSAMT) are a limitation associated with VLF resistivity; however, the ease of taking measurements allows a high spatial density, which helps minimize this effect. Since only two quantities are measured, resolving a two-layered earth requires that the resistivity of one of the layers be known or assumed. Another disadvantage is that measurements must be adjusted to account for differences in surface elevation before readings in sloping terrain can be compared. Where contaminant plumes are relatively shallow, VLF is an excellent method for investigating contaminated sites; as a result, it is the second most commonly used electromagnetic method for such applications after EMI (Table 4-3).

4.5 Magnetotelluric Methods

Telluric currents are natural electric currents that flow in the subsurface in response to ionospheric tidal effects and lightning associated with thunderstorms. Magnetotelluric (MT) geophysical methods involve the measurement of magnetic and electric fields associated with the flow of telluric currents (Cagniard, 1953). As noted in Table 1-3, a variety of MT methods have been developed audiofrequency MT (AMT) is the same as MT, except that audio frequencies are measured; audio frequency magnetic (AFMAG) methods measure the tilt angle of the total magnetic field on surface or in the air; and MT array profiling (EMAP) is MT enhanced with numerous measurements of the surface electric field to try to reduce errors attributable to static effects resulting from localized changes in conductivity of near-surface materials.

The main advantage of MT methods is that they can reach depths far greater than can be reached effectively using artificially induced currents. This is not particularly an advantage for site-specific investigations, although Strangway et al. (1980) reported on the use of shallow applications that might have some value in near-surface ground-water investigations. Table 4-3 identifies a number general references on MT methods. U.S. Geological Survey (1980) provides a brief discussion of potential applications for hydrogeologic studies.

Magnetotelluric principles are also involved in two EM methods using artificial sources: controlled-source audiomagnetotellurics (CSAMT) and VLF resistivity. CSAMT uses a remote transmitter combined with an AMT receiver. Use of CSAMT to detect brine contamination and for characterizing aquifers in fractured bedrock has been reported on a number of times (Table 4-3). Although attractive in theory, the static effect errors that plague MT surveys are also a source of error in CSAMT. In general, most other electrical and EM methods are more accurate and easier to use for shallow investigations.

Table 4-1 Index to General References on Electromagnetic Induction Methods

Topic	References
Texts	Hoyt (1974), Kaufman and Keller (1983), Kraus (1984), Nabighian (1988, 1991), Rokityanksi (1982), Verma (1982-three-layer interpretation data), Wait (1971, 1982); see also Table 1-4 for identification of general geophysics texts covering electromagnetic methods
Basic EM Theory	Jackson (1975), Kong (1975), Nabighian (1988), Stratton (1941), Wait (1985), Ward (1967a)
EM Wave Behavior	Chew (1990), Jordon (1963), Kong (1975), Lorrain and Carson (1970), McNeill (1990), Schelnukoff (1943), Wait (1970, 1981, 1985), Ward and Morrison (1971)
Review Papers	Bosschart (1970), Duran (1984-interferences), Lord and Koerner (1982), Ward (1967b, 1980), McNeil (1980b), Swift (1988)
Data Analysis	Boutwell and Lawrence (1988), Kufs et al. (1986), Lowrie and West (1965), Shope (1987), Spies and Eggers (1986), Vogelsang (1974-EM vs. IP), Wait (1962), Weber and Flatman (1986a,b), Wilt and Stark (1982)
Rock Conductivity	McNeill (1980a), Pfannkuch (1969); see also listing for references on subsurface electrical properties in Table 3-1
Nonconventional EMI	Beeson and Jones (1988), Goldman (1990), Johnson and Doborzynski (1988), Sternberg (1991), Sternberg et al. (1991)
EMI/ER Comparisons	Adams et al. (1988), Allen (1985), Allen et al. (1985), Benson et al. (1985, 1988), Bradley (1986), Brickell (1984), Butler and Llopis (1985), Cameron et al. (1981), Ehrlich and Rosen (1987), Emilsson and Wroblewski (1988), Evans and Schweitzer (1984), Fox and Gould (1984), Gilkeson and Cartwright (1982), Gilmer and Helbling (1984), Greenhouse and Harris (1983), Greenhouse et al. (1985), Jansen and Taylor (1989), Kelly et al. (1989), Knuth (1988), LeBrecque et al. (1984), Noel et al. (1982), Petersen et al. (1986), Pitchford et al. (1988), Roberts et al. (1989), Rodriquez (1984), Rudy and Caoile (1984), Rumbaugh et al. (1987), Russell (1990), Saunders and Stanford (1984), Stierman and Ruedisili (1988), Sweeney (1984), Tueci (1986), Vogelsang (1974), Walther et al. (1983), White and Brandwein (1982), White et al. (1984), Williams et al. (1984), Windschauer (1986), Woessner et al. (1989)

Table 4-2 Index to References on Applications of Electromagnetic Induction Methoda

Topic	References
Applications at Contaminated Sites	
Reports	Benson et al. (1984), EC&T et al. (1990), Pitchford et al. (1988), U.S. EPA (1987)
Reviews	Benson et al. (1982, 1991), Evans and Scwheitzer (1984), Fowler and Ayubcha (1986), Patra (1970), Pitchford et al. (1988), Saunder et al. (1991), White et al. (1984), Williams et al. (1984)
Ground-Water Quality Monitoring	Benson et al. (1985, 1988), Gilkeson and Cartwright (1982), Noel et al. (1982), Medlin and Knuth (1986)
Contaminated Sites	Adams et al. (1988), Barlow and Ryan (1985), Barton and Ivanhenko (1990), Bradley (1986), Carr et al. (1990), Cox and Saunders (1990), Duran and Haeni (1982), Feld et al. (1983), Fowler and Pasicznyk (1985), Fox and Gould (1984), Gilmer and Helbling (1984), Glaccum et al. (1982), Greenhouse and Slaine (1982, 1983, 1986), Hall and Pasicznyk (1987), Hankins et al. (1991), Knuth (1988-oil brine), Kufs et al. (1986), Lawrence (1984), Mills et al. (1987), Morgenstern and Syverson (1988a,b), Ringstand and Bugenig (1984), Roberts et al. (1989), Rodriguez (1984), Saunders and Cox (1987), Saunders and Stanford (1984), Scholl et al. (1984), Schutts and Nichols (1991), Slaine and Greenhouse (1982), Stierman and Ruedisili (1988), Walther et al. (1983), Weber and Flatman (1986a,b), White and Gainer (1985)
Contaminant Plumes	Brickell (1986), Emilsson and Wroblewski (1988), Greenhouse et al. (1985), LeBrecque et al. (1984), Mack and Maus (1986), McNeil (1982), Primeaux (1984, 1985), Rinaldo-Lee and Wagner (1985), Weber et al. (1984)
Landfill Leachate	Allen (1984), Ehrlich and Rosen (1987), Grady and Haeni (1984), Greenhouse and Harris (1983), Jansen et al. (1992), Kerfoot and Rumba (1985), McQuown et al. (1991), Roberts et al. (1989), Rudy and Caoile (1984), Rumbaugh et al. (1987), Russell (1990), Shope (1987), Stenson (1988), Sweeney (1984)
Buried Containers/Waste	Allen and Seelen (1992), Jordan et al. (1991), Lord and Koerner (1986, 1987a,b), Lord et al. (1982), Merin (1989-USTs), Rudy and Warner (1986-USTs), Schutts and Nichols (1991), Struttmann and Anderson (1989), Walsh (1989)
Soil salinity Mapping	Cameron et al. (1981), Corwin and Rhoades (1982, 1984), de Jong et al. (1979), Rhoades and Corwin (1981), Rhoades and Oster (1986), Williams and Baker (1982)

Table 4-2 (cont..)

Topic	References
Abdications at Contaminated Sites (cont.)	
Miscellaneous	Hydrocarbons: Davis (1991), Saunders and Cox (1987), Saunders and Germeroth (1985), Valentine and Kwader (1985, 1986); Acid Mine Drainage: Ladwig (1983,1984); Spray Irrigation Leachate: Allen et al. (1985); Brine/Salt Water: Chapman and Bair (1992), Lyverse (1989), Stewart (1982); Uranium Mill Tailings: Wightman et al. (1992)
Ground-Water Applications	
Ground-Water Texts	U.S. Geological Survey (1980), Redwine et al. (1985), Rehm et al. (1985)
Reviews	Benson (1991), McNeill (1988, 1991)
Case Studies	Arcone (1979), Butler and Llopis (1985), Drew et al. (1985), Duran (1987), Fitterman et al. (1991), Haeni (1986), Hoekstra (1978-permafrost), Hoekstra and Standish (1984), Jansen (1991), Kelly et al. (1989), Kachonoski et al. (1988), Koefoed and Biewinga (1976), Palacky et al. (1981), Payne (1991), Tucci (1986), Windschauer (1986), Woessner et al. (1989)
Soil Quality	McBride et al. (1990)
Hydraulic Conductivity	Taylor and Cherkauer (1984)
Recharge	Cook et al. (1992)
Other Applications	
Abandoned Mines	Friedel et al. (1990)
Abandoned Wells	Aller (1984)
Bedrock Topography	Ghatge and Pasicznyk (1986)
Geologic Structure	Telford et al. (1977)
Fracture/Faulted Rock	Adams et al. (1988), Jansen (1990), Jansen and Taylor (1988), Morgenstern and Syverson (1988a,b)

Table 4-3 Index to References on TDEM, VLF Resistivity, Metal Detection, and Magnetotelluric Methods

Topic	References
<u>TDEM</u>	
Texts	Felsen (1976), Kaufman and Keller (1983), Goldman (1990)
Review Papers	Kuo and Cho (1980), Nabighian and Macnae (1991), Strangway (1960-scale modeling)
Ground-Water Studies	Cook et al. (1992), Fitterman (1986, 1987), Fitterman and Stewart (1986), Fitterman et al. (1991), James et al. (1990), Hoekstra and Standish (1984), Hoekstra and Blohm (1990), Hoekstra and Cline (1986), Taylor et al. (1991), Taylor et al. (1992), Watson et al. (1990)
Contaminated Sites	Benson (1991), Hoekstra et al. (1992), Saunders et al. (1991)
Fresh-Salt Water Interface/Intrustion	Fitterman and Hoekstra (1984), Goldman et al. (1991), Hoekstra and Evans (1986), Hoekstra (1990), Hoekstra and Blohm (1990), Hoekstra et al. (1992), Maimone et al. (1989), Mills et al. (1987, 1988), Snow et al. (1990), Stewart and Gay (1986)
Brine Contamination	Frischknecht (1990), Raab and Frischknecht (1985)
<u>VLF Resistivity</u>	
General	Lankston and Hecker (1988), McNeill and Labson (1991), Paterson and Ronka (1971)
Contaminated Sites	Carr et al. (1990), Fitzgerald et al (1986), Grady and Haeni (1984), Greenhouse and Harris (1983), Greenhouse and Slaine (1983), Jansen and Taylor (1989), Koerner et al. (1982-buried containers), Meyer et al. (1990), Rodriguez (1984), Russell (1990), Slaine and Greenhouse (1982), Slaine et al. (1984), Stewart and Bretnall (1984, 1986)
Ground Water	Bernard and Valla (1991), Jansen and Taylor (1989), Watson et al. (1990)
Fracture Detection	Bernard and Valla (1991), HRB Singer (1971-abandoned mines), Jansen and Taylor (1988, 1989), Sinha (1989)
Geology	Telford et al. (1977-structure), Wynn (1979-buried paleochannel)
Weathered Zone	Poddar and Rather (1983)

Table 4-3 (cont.)

Topic	References
Metal Detection	
Contaminated Sites	Aller (1984), Benson et al. (1984, 1991), EC&T et al. (1990), Evans and Schweitzer (1984), Gilkeson et al. (1992), Koerner et al. (1982), Kufs et al. (1986), Lord and Koerner (1986, 1987a,b), Pease and James (1981), Pitchford et al. (1988), Westphalen and Rice (1992)
Magnetotelluric Methods	
Texts	Kaufman and Keller (1981), Porstendorfer (1975), Vozoff (1986), Wait (1982)
Review Papers	Strangway and Vozoff (1970), USGS (1980-TC, MT, AMT)
Telluric Currents (TC)	Alvarez (1991), Garland (l960), Pierce and Hoover (1986), U.S. Geological Survey (1980)
Magnetotellurics (MT)	Cagniard (1953), Strangway (1960), Vozoff (1991), Ward (1980), U.S. Geological Survey (1980)
Audiomagnetotellurics (AMT)	Adams et al. (1971), Strangway (1983), Strangway et al. (1973, 1980); Ground Water: Bazinet and Legault (1986), Pierce and Hoover (1986), U.S. Geological Survey (1980)
Controlled-Source Audiomagnetotellurics (CSAMT)	Zonge (1990), Zonge and Hughes (1991); Brine Contamination: Bartel (1989), Syed et al. (1985), Tinlin et al. (1988); Fractured Bedrock Aquifers: Lluria (1990), West and Ward (1988); In Situ Mining Leachate: Tweeton et al. (1991)

4.6 References

See Glossary for meaning of method abbreviations.

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Aller, L. 1984. Methods for Determining the Location of Abandoned Wells. EPA/600/2-83/123 (NTIS PB84-141530), 130 pp. Also published in NWWA/EPA Series, National Water Well Association, Dublin, OH. [air photos, color/thermal IR, ER, EMI, GPR, MD, MAG, combustible gas detectors]

Alvarez, R. 1991. Geophysical Determination of Buried Geological Structures and Their Influence on Aquifer Characteristics. Geoexploration 27:1-24. [tellurics, gravity]

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CHAPTER 5

SURFACE GEOPHYSICS: SEISMIC AND ACOUSTIC METHODS

Seismic methods are based on the timing of artificially generated acoustic signals propagated through the ground (or water and ground as in the case of continuous seismic profiling) and sensed by electromechanical transducers called geophones (if placed on the ground) or hydrophores (if placed in water). When seismic compressional waves (P waves) reach a lithologic contact with contrasting physical properties, they may be **reflected** back toward the surface or they may travel along the boundary contact before being **refracted** upward toward the surface or downward. Seismic methods are identified primarily by whether they detect reflected or refracted rays. Less commonly, seismic **shear waves** (S waves), in which particles move in a transverse direction relative to the propagation of the wave rather than back and forth as in a P wave (Section ***5.3.2),*** or Rayleigh-type surface waves (Section 5.3.3) are measured.

Seismic refraction (Section 5.1) has been most commonly used in ground-water and contaminated site investigations because of its relative simplicity and adaptability for shallow zone investigations. Relatively recent developments in **shallow seismic reflection** ***(Section 5.2)*** and **seismic shear** methods (Section 5.3.2) have resulted in increased use of these methods. **Continuous seismic profiling** (Section 5.3.1) and acoustic methods such as **side-scan sonar** and **fathometers** (Section 5.4.1) are used to characterize the subsurface below rivers, lakes, and impoundments. Seismic and acoustic methods used for design and engineering of structures and impoundments include **spectral analysis of surface waves** (Section 5.3.3) and **acoustic emission** monitoring (Section 5.4.2).

Since all seismic and acoustic methods measure only physical contrasts, they are unable to directly detect contaminant plumes or subsurface contaminants. Stratigraphic and geologic interpretations of high-resolution seismic techniques, however, can be very useful in guiding placement of boreholes for subsurface sampling and remediation.

5.1 Seismic Refraction

Although seismic refraction has generally lower resolution than seismic reflection, it generally has been the preferred seismic method in shallow hydrogeological investigations for a number of reasons (Zohdy et al., 1974):

- Refraction methods generally yield superior results in areas of thick alluvial or glacial fill and where large velocity contrasts exist, such as buried bedrock valleys.
- Personnel and equipment requirements are generally simpler and less expensive for refraction surveys than reflection surveys.

Tables 5-1 and 5-2 contain over 200 references on the use of seismic refraction for geologic, hydrogeologic, and contaminated site investigations. Because of recent advances in instrumentation and the development of new field techniques for shallow, high-resolution seismic reflection techniques have overcome most of the problems cited above; however, it can no longer be assumed that seismic refraction should be the method of choice (see Section 5.2).

Seismic refraction techniques are designed to obtain data on the near surface (typically to about 30 meters, although depths in excess of 200 meters can be achieved with more powerful seismic sources). Such techniques provide data on the refraction of seismic waves at the interface between subsurface layers and on their travel time within the layers. Properly interpreted, the refraction data make it possible to estimate the thickness and depth of geologic layers (including the water table) and to assess their properties. Also, changes in the lateral facies of aquifer material can sometimes be mapped with this method (Sendlein and Yazicigil, 1981).

Figure 5-1 shows a field layout for seismic refraction measurements. A seismic source creates direct compressional waves and refracted waves that are sensed by an array of geophones. A hammer is usually used as a signal source for near-surface investigations. Where more energy is required, firecrackers or small charges of explosives may be used (Criner, 1966). The seismograph records the time of arrival of all waves, using the moment the hammer hits the ground as time zero. The processing and interpretation of seismic refraction data require a great

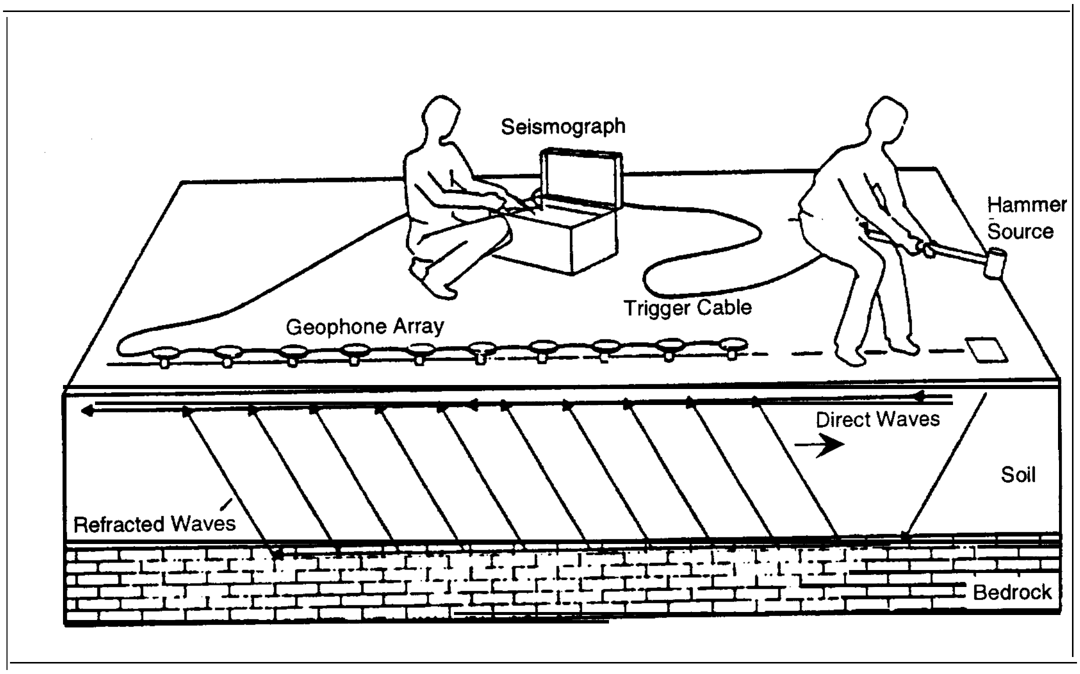

Figure 5-1 Field layout of a 12-channel seismograph showing the path of direct and refracted seismic waves in a two-layer soil/rock system (from Benson et al., 1984).

deal of skill; Figure 5-2 shows the required steps. First, the seismic signal is recorded on paper or with a computer. A single-channel seismograph plots the waveform against time (milliseconds) from a single geophone, and a multichannel instrument records waveforms from multiple geophones. Then, travel time is plotted against the source-to-geophone distance to produce a time/distance (T/D) plot. Finally, line segments, slope, and break points in the T/I) can be analyzed to identify the number of layers and depth of each layer. Figure 5-3 shows a number of idealized T/D plots for a variety of subsurface conditions. Benson et al. (1984), Haeni (1988a), and Zohdy et al. (1974) provide additional information on seismic refraction.

An important assumption in seismic refraction where multiple layers exist is that the velocity of seismic waves increases with depth. A layer with lower velocity below a higher velocity layer will not be detected because waves will be refracted downward. There may also be blind zones, layers that are not detected because they are relatively thin and velocity increases only slightly compared to the overlying layer (Soske, 1959). Sander (1978) examines the significance of blind zones in ground-water exploration. Tucker and Yorsten (1973) and Tucker (1982) discuss in detail the potential pitfalls in the use and interpretation of seismic refraction data.

5.2 Shallow Seismic Reflection

Most seismic reflection methods are designed to identify geologic contacts at depths greater than 200 feet (70 m). They have been used for many years by the petroleum industry to obtain stratigraphic and structural data on deeply buried sediments (Allen, 1980). These methods provide the highest level of accuracy and resolution in deep surface characterizations of any available geophysical method. The relatively recent development of high-resolution methods, such as the common-depth-point (CDP) techniques, can yield useful data at depths as shallow as 15 to 30 meters (Ayers, 1989). The common-offset method has been successfully used at interfaces as shallow as 2.7 meters (Birkelo et al., 1987), but a more typical minimum depth would be approximately 10 meters.

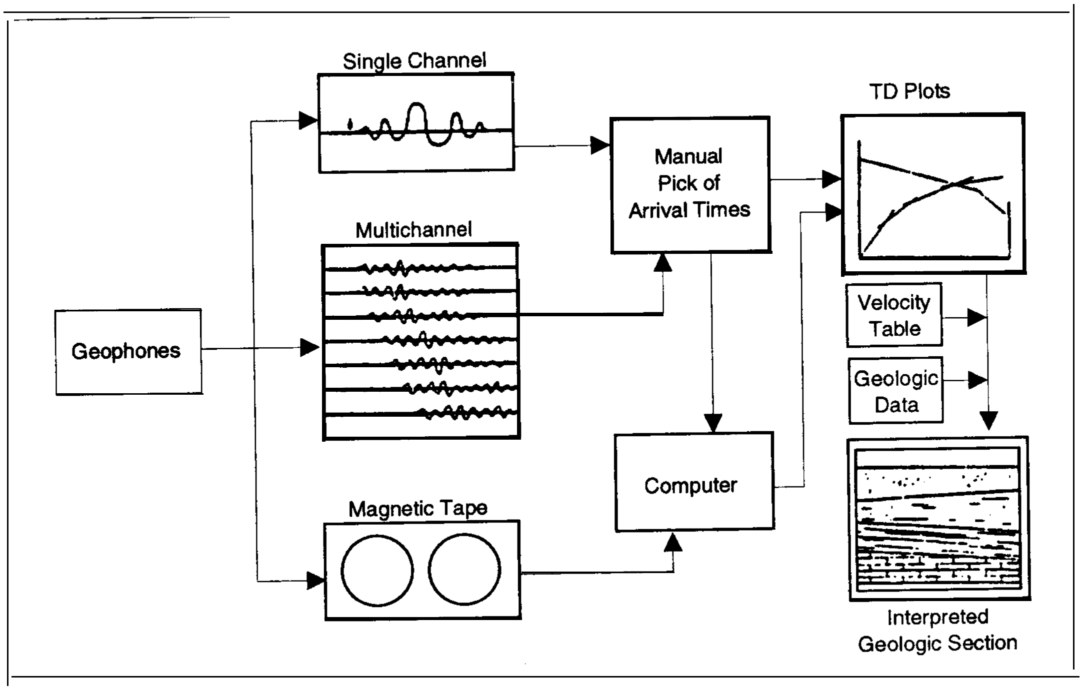

Figure 5-2 Flow diagram showing steps in the processing and interpretation of seismic refraction data (from Benson et al., 1984).

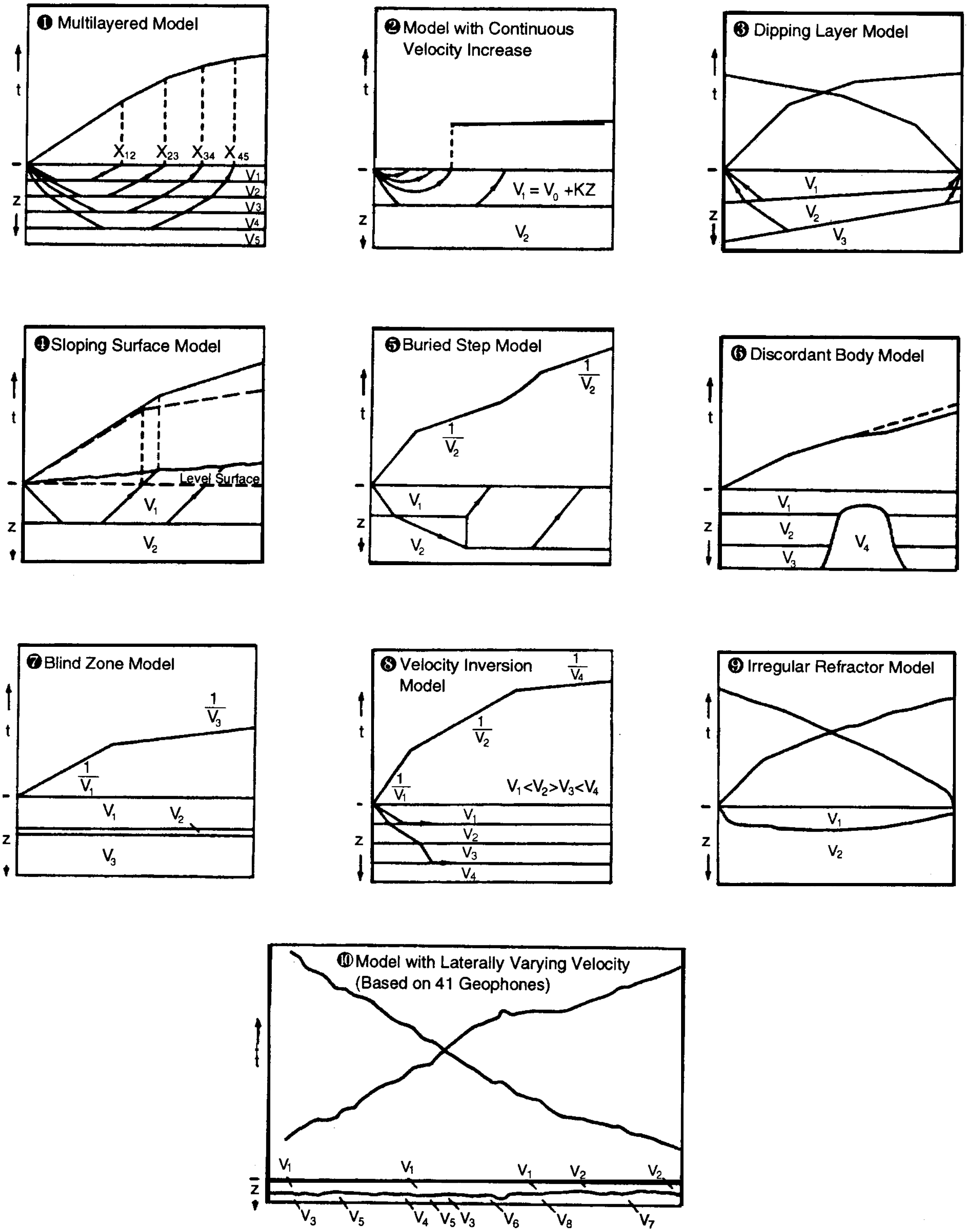

Figure 5-3 Schematic traveltime curves for idealized nonhomogenous geologic models (from Zohdy et al., 1974).

Seismic reflection surveys are generally similar to seismic refraction surveys in terms of instrumentation. Reflection surveys, however, usually are conducted with shorter spacing but with more geophones compared to refraction surveys of similar depths. In addition to recording the time of first arrival, in a reflection survey numerous arrivals of reflected waves are recorded at each geophone and multiple shots are used to create seismic waves, resulting in more data recorded and requiring more complex data processing. Table 5-3 identifies references on shallow seismic reflection methods, most of which have been published since 1980. Section 1.4.2 in U.S. EPA (1993) summarizes general advantages and disadvantages of seismic reflection.

5.3 Other Seismic Methods

Seismic methods with specialized applications include continuous seismic profiling, seismic shear surveys, and spectral analysis of surface waves. All three methods are discussed below.

5.3.1 Continuous Seismic Profiling (CSP)

CSP (also called marine seismic reflection, acoustical or continuous high-resolution subbottom profiling, and sonar seismic reflection) is a method originally developed and used in deep-water marine geology investigations and currently is used routinely for petroleum exploration. It differs from land-based seismic techniques in that usually one channel is used to detect signals. This method can be used to define hydrologic boundaries of shallow aquifers and in some cases can indicate the lithology of glacial deposits, provided that the area of interest is crossed by rivers, large streams, lakes, ponds, or estuaries (Morrissey et al., 1985).

In shallow water, high-resolution, single-channel, continuous seismic reflection equipment is towed through the water alongside or behind the survey boat. The energy source (electromechanical transducers, sparkers, or airguns) emits sounds into the water at a fixed frequency or within a range of frequency. The receiver, called a hydrophore, detects the reflected acoustic signals, which are processed in a manner similar to the land-based seismic reflection method to create a profile of the subsurface below the boat's line of travel. The position of the boat must be established and maintained throughout the survey relying on methods as various as the use of multiple survey crews siting the survey boat from land to the use of sophisticated microwave positioning systems. A grid pattern of survey lines allows a three-dimensional representation of the subsurface. A fathometer survey (Section 5.4.1) is usually conducted simultaneously to provide an indication of water depth that facilitates the calculations concerning thicknesses of subbottom strata.

Continuous seismic profiling is the most commonly used of the “minor” seismic methods in ground-water and contaminated site investigations (Table 5-4).

5.3.2 Seismic Shear Methods

Seismic shear methods record the time of arrival of seismic waves created at a point transverse to the line of the geophone array. When used in combination with seismic refraction data, the ground-water surface can be more readily differentiated from other lithologic contacts. Wrege et al. (1985) found that this method was more successful than conventional seismic refraction and reflection in detecting subsurface fissures that have developed where overpumping of ground water has caused subsidence. Table 5-4 identifies several recent studies reporting the use of seismic shear in hydrogeologic investigations and for fracture detection. Danbom and Domenico (1987) is a useful source for more detailed information on this method.

Basic instrumentation for seismic shear measurements is similar to the equipment used with seismic refraction and reflection methods except that layouts are modified to record the time of arrival of seismic shear waves (S waves), in which particles move in a transverse direction relative to the propagation of the wave rather than back and forth as in a compressional wave (P wave), which is observed in conventional seismic refraction and reflection. S waves are generated by delivering a sledgehammer blow to the soil at an angle to the ground surface or by using a set of three sequential explosive shots. Both reflection and refraction of S waves can be measured and analyzed.

5.33 Spectral Analysis of Surface Waves

Spectral analysis of surface waves (SASW) is used to measure dynamic soil properties, primarily for the purpose of evaluating soil strength and stability in response to stress from earthquakes. Cross-hole seismic methods also are used to measure these soil properties (see Section 7.3.3). The technique calls for the use of two vertical transducers placed on the ground surface at equal distances from an imaginary centerline. A vertical impulse is generated on the ground surface, and surface waves of the Rayleigh type are monitored as they propagate past the two transducers. Successive seismic impulses of different wavelengths allow the sampling of different depths of soil, with low frequency waves sampling greater depths.

Table 5-4 identifies a selection of references on the use of the SASW method. Although its use has not been reported in the ground-water and contaminated site characterization literature, potential applications of this method include geotechnical investigations for the design of structures at Resource Conservation and Recovery Act (RCRA) facilities and remediation-related activities.

5.4 Acoustic Methods

5.4.1 Sonar Methods

The term sonar is usually applied to the use acoustic signals to detect the interface between water and the water bottom surface as well as objects in water or lying on the bottom, although the term also has been used to describe continuous seismic profiling. These sonar methods are classified as acoustic rather than seismic because the signals that are detected do not travel through the earth (unlike continuous seismic profiling, which involves the detection of signals that travel through both water and the sediments below the water). Two sonar methods that have potential for application at contaminated sites where surface water is present include side-scan sonar and fathometer water bottom surveys.

Side-scan sonar involves using a boat to pull a towfish that contains transducers for sending bursts of high-intensity, high-frequency acoustic signals and for receiving the echoes from these signals. The signals are amplified and processed to create an image of the water bottom surface that may cover as much as several hundred meters on both sides of the survey line. The resolution of the image is sufficient to identify details such as bedrock outcrops, rough or smooth mud surfaces, sand surfaces, gravel or boulders, and collapsed features.

A fathometer is similar to side-scan sonar, except that it only records bottom topography directly below the instrument. A fathometer survey is required for accurate interpretation of continuous seismic profiles. Both instruments can be used in conjunction with an underwater magnetometer to locate metal containers at or below the sediment surface. Table 5-4 identifies some of the literature on the use of sonar methods; none of the material cited, however, is directly related to the investigation of contaminated sites.

5.4.2 Acoustic Emission Monitoring

Acoustic emission monitoring, also called the microseismic method, is a seismic method that uses a natural field signal source. It is classified as an acoustic method here because that is the term that is most commonly used for this method (see references identified in Table 5-4). Acoustic emission monitoring is mainly used to detect instabilities in engineered structures such as dams or impoundments.

The method involves the detection of subaudible sound waves caused by the release of stored elastic-strain energy in stressed materials (e.g., dislocations, grain boundary movement, and initiation and propagation of fractures through rather than between mineral grains). A wave guide (steel rod or plastic pipe), inserted in the ground or lowered down a borehole, transmits signals to a sensor. The sensor, an accelerometer, converts the mechanical wave energy to an electrical signal that is filtered and amplified, and a signal counter records a count each time the signal exceeds a threshold that is above the background noise level.

Acoustic emission installations require preliminary testing to distinguish background noise levels from such factors as wind, thunderstorms, barometric changes, power lines, operation of nearby machinery, passing airplanes, and vehicular traffic. Monitoring may be continuous or periodic.

5.5 Borehole Acoustic and Seismic Methods

A variety of borehole acoustic (i.e., acoustic velocity, acoustic-waveform, acoustic televiewer) and seismic (i.e., vertical seismic profiling uphole, downhole, seismic cone penetrometry; and cross-hole profiling) methods are covered in Chapter 7. Borehole acoustic velocity logs can be used to calibrate surface seismic surveys (Wrege, 1986).

Table 5-1 Index to General References on Seismic Refraction

Topic	References
General	
General Texts	Badley (1985), Dix (1952-oil prospecting), Haeni (1986c, 1988a-hydrogeology), Mooney (1984), Musgrave (1967), Palmer (1986), Redpath (1973), Waters (1981)
Analysis/ Interpretation	Berkhout (1985, 1988), Fagin (1991), Palmer (1980), Russell (1988), Slotnick (1959), Tucker (1982), Tucker and Yorsten (1973); Use of Computers: Ackermann et al. (1983), Haeni et al. (1987), Scott (1973, 1977a,b), Scott et al. (1972), Scott and Markiewicz (1990); Papers: Kanemori et al. (1992), Lankston (1988), Lankston and Lankston (1986), Meidav (1968)
Wave Theory Texts	Auld (1990), Berkhkout (1987), Bland (1988), Davis (1988), White (1965)
Other Texts/Reports Covering Seismic Retraction	Benson et al. (1984), Pitchford et al. (1988), Redwine et al. (1985), Rehm et al. (1985), U.S. EPA (1987), USGS (1980), Zohdy et al. (1974); see also Table 1-4 for identification of general geophysics texts covering seismics
Review Papers	Allen (1980), Burwell (1940), Dix (1960), Green (1974), Hasselström (1969), Hobson (1970), Linehan (1951), Stare (1962)
Theory	Dix (1939a,b), Evison (1952), Hawkins (1961—reciprocal method), Pullan and Hunter (1985), Sander (1978), Widess (1973)
Rock Properties	Auld (1990), Carmichael (1982)
Blind Zone/Limitations	Burke (1970), Domzalski (1956), Lankston (1989), Sander (1978), Soske (1959), Wallace (1970)
SRR-SRL Comparison	Adams (1992), Gahr et al. (1988), McDonald et al. (1992), Sauck (1991), Wrege (1986)
Seismic Sources	Criner (1966), Miller et al. (1986), Wang et al. (1992)

Table 5-2 Index to References on Applications of Seismic Refraction

Topic	References
Seismic Refraction Abdications: Ground Water	
Artificial Recharge	Bianchi and Nightingale (1975)
Quantitative Aquifer Properties*	Barker and Worthington (1973), Duffin and Elder (1979), Eaton and Watkins (1970), van Zijl and Huyssen (1971), Wallace and Spangler (1970), Worthington (1975a), Worthington and Griffiths (1975)
Glacial/Alluvial Aquifers*	Burwell (1940), Emerson (1968), Galfi and Pales (1970), Scott et al. (1972), Sjogren and Wager (1969)
Glacial/Alluvial Deposits over Bedrock*	Duguid (1968), Gill et al. (1965), Joiner et al. (1968), Lennox and Carlson (1967), Mercer and Lappala (1970), Peterson et al. (1968), Wachs et al. (1979)
Thick Alluvial Basins*	Ackermann et al. (1983), Arnow and Mattick (1968), Crosby (1976), Dudley and McGinnis (1976), Libby et al. (1970), Marshall (1971), Mattick et al. (1973), Mower (1968), Pankratz et al. (1978), Robinson and Costain (1971), Wallace (1970)
Alluvium-Sedimentary-Crystalline Rock*	Colon-Dieppa and Quinones-Marquez (1985), Scott et al. (1972), Torres-Gonzalez (1985), Visarion et al. (1976)
Stratified Drift-Dense Till-Crystalline Rock*	Johnson (1954), Mazzaferro (1980), Sander (1978), Scott et al. (1972)
Sand/Gravel-Thin Till-Crystalline Rock*	Birch (1976), Dickerman and Johnson (1977), Frohlich (1979), Grady and Handman (1983), Haeni (1978, 1986a), Haeni and Anderson (1980), Haeni and Melvin (1984), Mazzaferro (1980, 1986), Morrissey (1983), Sander (1978), Scott et al. (1978), Sharp et al. (1977), Tolman et al. (1983), Warrick and Winslow (1960), Winter (1984).
Aquifer-Bedrock Similar Velocity*	Broadbent (1978), Topper and Legg (1974)

Table 5-2 (cont.)

Topic	References
Seismic Refraction Applications: Ground Water (cont.)	
Variable-Thickness Lithic Sediments*	Pakiser and Black (1957)
Other Ground-Water Studies	Ackermann (1976-permafrost),* Ali (1985), Ayers (1988, 1989), Bonnini (1959), Butler and Llopis (1985), Carpenter and Bassarab (1964), Greenhouse et al. (1990), Harmon (1984), Hasselström (1969), Hinchey and Gould (1990), Hobson (1970), Hobson et al. (1962), Joiner and Scarborough (1969), Joiner et al. (1967), Kent and Sendlein (1972), Lankston et al. (1985), Laudon (1984), Laymen and Gilkeson (1989), Lennox and Carlson (1970), Linehan and Keith (1949), O'Brien and Stone (1984, 1985), Sauck (1991), Sendlein and Yazicigil (1981), Shields and Sopper (1969),* Stickel et al. (1952), Stierman et al. (1986), Sverdrup (1986), Taylor and Cherkauer (1984), Underwood et al. (1984), Urban and Pasquerell (1992-fractured rock), Van Overmeeren (1980, 1981), Wantland (1951), Wightman (1988), Wilson et al. (1970), Worthington (1975b), Wrege (1986), Zohdy (1965)
Seismic Refraction Applications: Contaminated Sites	
Contaminated Sites	Adams (1992), Adams et al. (1988), Allen and Rogers (1989), Benson et al. (1991), Bianchi and Nightingale (1975), Blackey and Stoner (1988), Bruehl (1983, 1984), Carpenter et al. (1991), Cichowicz et al. (1981), Ehrlich and Rosen (1987), Emilsson and Wroblewski (1988), Evans and Schweitzer (1984), Feld et al. (1983), Fowler and Ayubcha (1986), Gilmer and Helbling (1984), Hall and Pasicznyk (1987), Hennon et al. (1991), Leisch (1976), Pease and James (1981), Grady and Haeni (1984), James (1981), Roberts et al. (1989), Rodrigues (1987), Saunders and Stanford (1984), Walsh (1988), Williams et al. (1984), Yaffe et al. (1981)
Landfills	Carpenter (19%3), McQuown et al. (1991)
Monitoring Well Design	Gorin and Gilkeson (1991), Regan et al. (1987), Sendlein and Yazicigil (1981)
Waste Injection	Barr (1973)

Table 5-2 (cont.)

Topic	References
Seismic Refraction Applications: Subsurface Characterization	
Bedrock Valleys and Topography	Burgdorf and Richard (1984), Ghatge and Pasicznyk (1986), Nyquist et al. (1992), Pullan et al. (1987)
Coastal Areas	McDonald et al. (1992)
Karst	Imse and Levine (1985), LaMoreaux and Madison (1984)
Structure/Stratigraphy	Gardner (1939)
Subsurface Cavities	Cook (1964), Filler and Kuo (1989), Steeples et al. (1986)
Unconsolidated Deposits	Denne et al. (1984), Ehrlich and Rosen (1987), Johnson (1954), Hinchey and Gould (1990), Lennox and Carlson (1967), McGinnis and Kempton (1961), O'Brien and Stone (1984), Stierman et al. (1986), Tibbets and Scott (1972), Washburn (1992), Zehner (1973)

* Classification taken from Haeni (1988a). Annotations to references in these sections can be found in Haeni (1988a).

Table 5-3 Index to References on Seismic Reflection Methods

Topic	References
General	Knapp and Steeples (1986a,b), Johnson and Clark (1992), Lankston and Lankston (1983, 1988), Hunter and Pullan (1989), Pakiser and Warrick (1956), Ruskey (1982), Schepers (1975), Steeples and Miller (1988), Waters (1981)
Interpretation	Badley (1985), Kleyn (1983)
Applications	
Contaminated Sites	Adams (1992), Benson et al. (1991), Bikis and Lewis (1992), Irons and Lewis (1989, 1990), Miller and Steeples (1990), U.S. EPA (1987)
Engineering Investigations	McDonald et al. (1992)
Ground Water	Ayers (1988, 1989), Birkelo et al. (1987), Irons et al. (1991), Kleinschmidt and Pelton (1989), Lewis et al. (1990-monitoring well design), Sauck (1991), Slaine (1988), Steeples and Miller (1988), Wrege (1986); Texts: Redwine et al. (1985), USGS (1980)
Alluvium	Hasbrouck (1990a), Kopsick and Stander (1983), Lankston et al. (1985)
Structure/Stratigraphy	Allen et al. (1952), Gagne et al. (1985), Hunter et al. (1982, 1984), Richards (1960)
Bedrock	Miller et al. (1989), Singh (1986-shallow)
Coal Seams	Lepper and Ruskey (1976)

Table 5-4 Index to References on Miscellaneous Seismic and Acoustic Methods

Topic	References
Continuous Seismic Profiling	
General	Texts: Burdic (1991), Coates (1989), EG&G Environmental Equipment Division (1977), Hassab (1989—signal processing), Hersey (1963), Redwine et al. (1985-CSP and sonar), Sylwester (1983), Trabant (1984); Review Papers: Haeni (1986b, 1992)
Interpretation	Badley (1985), Ewing and Tirey (1961), Leenhart (1969), Roksandic (1978), Sangree and Widmier (1979), Tufekcic (1978)
Case Studies	Cardinell and Berg (1992), Cherkauer and Taylor (1988), Haeni (1986b, 1988b), Haeni and Melvin (1984), Hansen (1986), Hughes (1991, 1992-contaminated site), Missimer and Gardner (1976), Moody and Van Reenan (1967), Morrissey et al. (1985), Sjostrom et al. (1992), Van Overeem (1977), Van Reenan (1964), Wollansky et al. (1983)
Seismic Shear	
General	Texts/Symposia CH2M Hill (1991), Danbom and Domenico (1987), Dohr (1985), Woods (1985); Papers: Bates et al. (1992), Johnson and Clark (1992)
Bibliography	Ensley (1987)
Case Studies	Bates et al. (1991), Dobecki (1988), Hasbrouck (1986, 1987, 1990b, 1991), Wrege (1986), Wrege et al. (1985)
Fracture Detection	Bates et al. (1991), Martin and Davis (1987), Richard et al. (1991)
Spectral Analysis of Surface Waves	CH2M Hill (1991), Dobecki (1988), Stokoe and Nazarian (1985), Woods (1985)
Acoustic Emission Monitoring	Boyce et al. (1981), Davis et al. (1983, 1984), Descour and Miller (1989), Huck (1982), Koerner and Lord (1976, 1981), Koerner et al. (1976, 1978, 1981a, 1981b), Lord and Koerner (1980, 1987), Redwine et al. (1985), U.S. EPA (1979), Wailer and Davis (1984)
Sonar	Baxter and Mills (1992), Fish and Carr (1990), Lord and Koerner (1980, 1987), Saucier (1969, 1970), Redwine et al. (1985)

5.6 References

See Glossary for meaning of method abbreviations.

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CHAPTER 6
SURFACE GEOPHYSICS: OTHER METHODS

Four other major types of surface geophysical methods can be used in the study of ground water and contaminated sites. These involve ground penetrating radar (GPR-Section 6. 1), magnetometry (Section 6.2), gravity measurements (Section 6.3) and shallow geothermal measurements (Section 6.4.1). GPR is commonly used for site characterization (e.g., identifying depth to the water table and bedrock) and detection of buried wastes. Magnetic methods are widely used to detect buried metal objects, but also can be used for geologic characterization. Gravity is typically used for mapping bedrock topographies, especially buried valleys, and microgravity surveys can be used to detect subsurface cavities. Shallow geothermal methods have been used to study shallow ground-water flow systems and to monitor landfill leachate.

6.1 Ground Penetrating Radar and Related Methods

6.1.1 Terminology

Geophysical methods using the radio- and microwave portion of the electromagnetic spectrum probably have the most confusing terminology of any surface method (i.e., less consensus early on within the geophysics community). For example, **ground penetrating radar** (the most common term for this method in the literature) may be referred to as electromagnetic subsurface profiling (Morey and Harrington, 1972), electromagnetic pulse radar (Moffat and Puskar, 1976), pulsed microwave (Lord and Koemer, 1987a), or pulsed radio frequency (Koerner and Lord, 1986). Other names identified by Benson et al. (1984) include ground piercing radar, ground probing radar, and subsurface impulse radar.

Microwaves range from about 0.1 to 100 centimeters in wavelength (see Figure 2-1) (the term is something of a misnomer, since, although such wavelengths are small when compared to radio waves, they are extremely long when compared to wavelengths in the visible portion of the spectrum). Sensing in the microwave portion of the EM spectrum can be active or passive.

Passive microwave sensing systems rely on a lens or antenna that receives energy coming from an outside source and focuses it on a detector. Thermal infrared scanning (see Section 2.2), for example, is a passive microwave sensing system. Active microwave sensing systems involve a transmitter that provides an independent source of energy and a receiver that senses the reflected or echoed signal.

The term **radar** (an acronym derived from the phrase Radio Detection And Ranging) implies the use of an active energy source for sensing. Usually the signal is emitted as short, powerful bursts of energy called **pulses.** Less commonly, a **continuous wave** (CW) signal is used.

6.1.2 Ground Penetrating Radar

Ground penetrating radar (GPR) has been used at contaminated sites since the late 1970s (Table 6-1). The method involves use of a small antenna to radiate short pulses of high-frequency radio waves (ranging from around 10 MHz to 1,000 MHz) into the subsurface and a receiving antenna to record variations in the reflected return signal (Figure 6-1). The principles involved are similar to reflection seismology (see Section 5.2), except that electromagnetic energy is used instead of acoustic energy. Figure 6-2 illustrates the types of lithologic and stratigraphic interpretations that can be made using GPR images.

Dragging the antennae along the ground surface creates a continuous profile that gives the greatest resolution of all the surface geophysical methods discussed in this reference guide. Still, the depth of penetration is generally less than with other methods (1 to 25 meters, although hundreds of meters are possible in certain materials, such as salt domes) and is reduced by fluids, soils with high electrical conductivity, and fine-grained materials. Best overall penetration is usually achieved in dry, sandy, or rocky areas; poorer results are obtained in moist, clayey, or conductive soils. Davis et al. (1984) reported penetration to a depth of 25 meters in dry sandy soil. Attenuation is particularly severe in clay-rich soils and where water content exceeds 40 percent (Horton et al., 1981). Benson et al. (1984) provide more detailed information on the principles and applications of GPR.

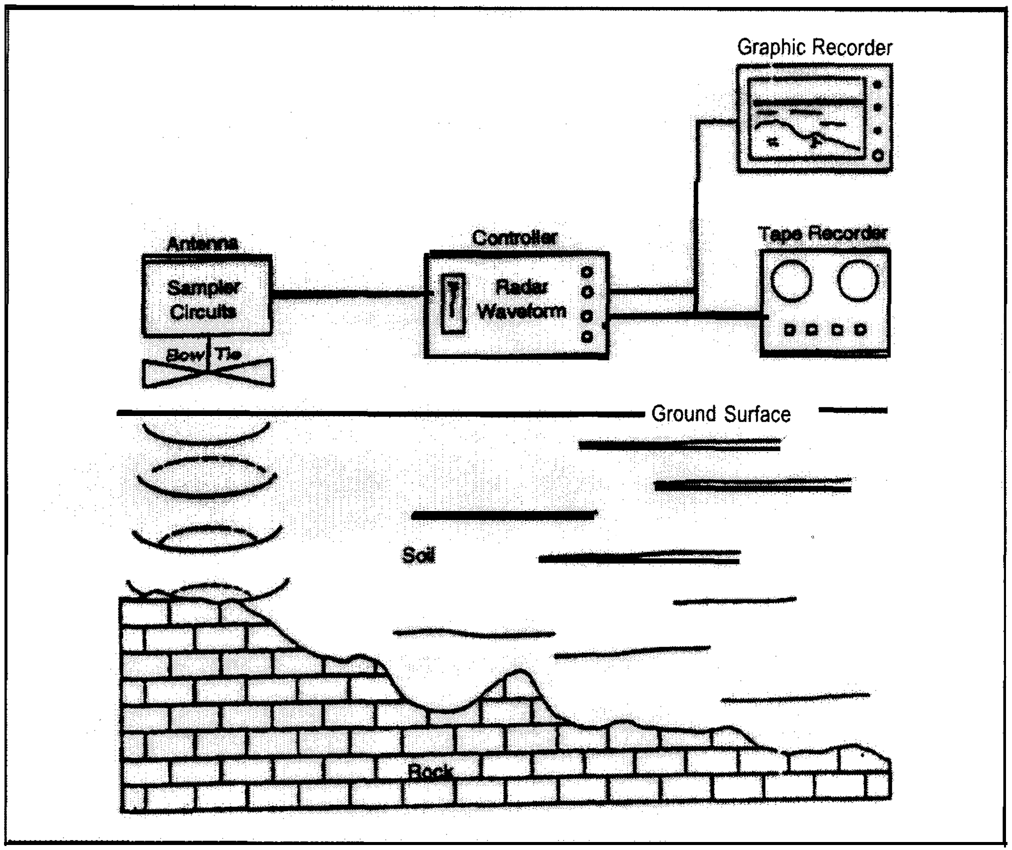

Figure 6-1 Block diagram of ground penetrating radar system. Radar waves are reflected from soil-rock interface (from Benson et al., 1984).

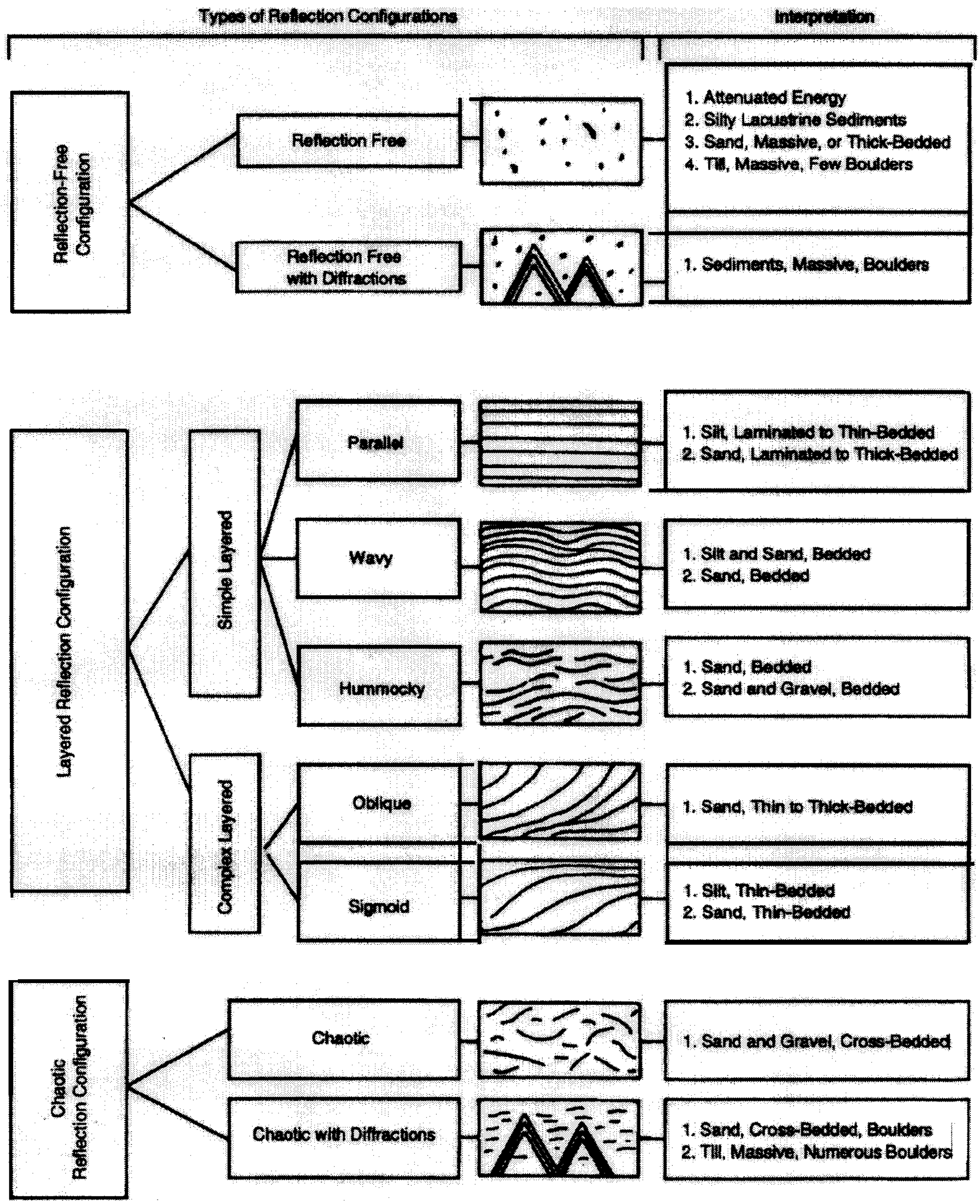

Figure 6-2 Reflection configurations on ground penetrating radar images indicating the lithologic and stratigraphic properties of sediments in the glaciated Northwest (Beres and Haeni, 1991).

The military provided the impetus for the development of GPR in the mid-1960s and early 197Os, primarily for use in detecting land mines and subsurface tunnels. Since then, GPR has been used increasingly in the mining industry (Pittman et al., 1984) and in geologic and soil investigations to characterize depth to water table, soil horizon and lithologic contacts, cavities, faults, and bedding joints and planes in rocks (Doolittle, 1987). Uses at contaminated sites include detection of buried containers and leaks, mapping of trench boundaries, and general subsurface characterization. GPR is the only consistently reliable method for detecting buried plastic containers (Lord and Koerner, 1987a).

Table 6-l lists over 30 studies reporting the use of GPR at contaminated sites and over 40 references on other applications, GPR is especially popular for soil characterization, since depth penetration limitations are usually not a problem.

6.2 Magnetometry

Magnetic measurements have long been used to map regional geologic structures and to carry out mineral exploration (Reford, 1980). Their main use in ground-water contamination studies is to locate buried metal drums that may be a source of contamination. Where drums are buried in shallow trenches, trench boundaries also can be located with magnetometer surveys (Gilkeson et al., 1986). A magnetometer locates ferrous metals (iron, steel, and nickel) in drums and buried pipelines, for instance, by measuring local perturbations in the strength of the earth's magnetic field. Single 55-gallon drums can be sensed up to a depth of 6 meters, and piles of drums up to 20 meters (Benson et al., 1984). Calculating the depth of buried objects with magnetometry is difficult, however.

Magnetometers measure either intensity of the earth's total magnetic field at a point or gradients in the magnetic field. **Proton precession** magnetometers use the precession of spinning protons after a coil is energized momentarily to measure the earth's total magnetic field. **Fluxgate** magnetometers measure a component of the earth's magnetic field, usually the vertical component. Two types of measurements are commonly made with magnetometers: total field measurements and gradient measurements. Proton magnetometers are usually configured for point total field measurements, which requires a closely spaced grid ‘of station measurements to provide complete coverage of a site. Fluxgate magnetometers are usually configured as **gradiometers,** which allow continuous measurement of the gradient in the magnetic field along a transect. Anomalous readings (measured as gammas) indicate the presence of ferrous metals.

Benson et al. (1984) provide additional information on the use of magnetometers at contaminated sites. Section 1.52 in U.S. EPA (1993) summarizes advantages and disadvantages of proton and fluxgate magnetometers. Table 6-2 lists references for additional information on the use of magnetic methods for geologic, hydrogeologic, and contaminated site investigations.

6.3 Gravimetrics

Gravimetry involves measurement in variations in the intensity of the earth’s gravitational field (expressed as acceleration in centimeters per second squared, or gals). Three principle classes of instruments are used in conventional gravity measurements: torsion balance, pendulum, and gravity meter or gravimeter (Lahee, 1961). All can detect anomalies as small as one-ten-millionth (milligals- $l0^{-3}$ gals) of the earth’s gravitational field. **Microgravimeters,** measuring in units of microgals (10” gals), are sufficiently sensitive that they can delineate cavities in the subsurface. This type of instrument usually is used in hydrogeologic and contaminated site investigations.

Station measurements along a transect or on a grid require great care in setting up the instrument, and the elevation of each station must be carefully surveyed. Gravity data obtained in the field must be corrected for elevation, rock density, latitude, earth-tide variations, and the influence of surrounding topographic variations. After corrections, measurements are plotted as Bouger anomaly maps, which look like topographic contour maps, and are interpreted in terms of the size, shape, and position of subsurface structures.

The most common use of gravity measurements for detecting bedrock valleys buried by unconsolidated glacial materials and conducting regional-scale ground-water investigations.. Use of gravity measurements for the characterization of fractures and the detection of subsurface cavities has been reported infrequently in the last 30 years; however, such measurements have been used at contaminated site at least a half-dozen times in the last 10 years (Table 6-3). For example, Roberts et al. (1989) obtained gravity data at a landfill in Tippecanoe County, Indiana, and compared this with gravitational estimates based on prelandfill topographic data to determine density variations within the fill material; Section 1.53 in U.S. EPA (1993) summarizes the advantages and disadvantages of gravity surveys.

6.4 Thermal Methods

Measurements of temperature variations in the subsurface can be used as both a near-surface and a borehole method. **Shallow geothermal** measurements are a relatively simple method for characterizing shallow ground-water flow and mapping contaminant plumes. **Borehole temperature logging** is a common borehole geophysical method, which is covered in this section on surface methods because there is not a clear dividing line between the two types of measurements and some of the literature is equally applicable to both types of measurements. Table 6-4 identifies references on soil temperature and other thermal property measurements, shallow geothermal ground-water applications, and borehole temperature logging.

6.4.1 Shallow Geothermal Measurements

Because water has a high specific heat capacity compared to most natural materials, its temperature changes slowly as it migrates through the subsurface. Consequently, shallow-earth temperatures can be related to the occurrence and flow of ground water (Cartwright, 1968a; Birman, 1969). Shallow, moving ground water produces lower temperatures compared to dry, shallow bedrock.

Shallow geothermal measurements are usually made by measuring subsurface temperatures at a selected depth (up to 40 inches) at numerous stations over a short time span. In the late 1960s and early 1970s a number of shallow geothermal ground-water studies were conducted (Table 6-4), and the method has been used infrequently at contaminated sites. Cartwright and McComas (1968) used soil temperature surveys at several landfills in northeastern

Illinois. These surveys indicated the presence of a halo of higher temperatures around the landfills, and indicated areas of surface recharge. Gilkeson and Cartwright (1983) review use of shallow geothermic methods for ground-water monitoring and describe several other examples of their use at contaminated sites.

6.4.2 Borehole Temperature Logging

Temperature measurement is one of the most commonly used borehole logging methods because it is simple and inexpensive. **A temperature log** involves recording temperature relative to depth with a temperature sensor, usually a thermistor mounted inside a cage or tube to protect it and to channel the fluid past the sensor. Temperature logs taken shortly after the cessation of drilling often provide an indication of the location of permeable strata. A **differential-temperature log** involves recording the rate of change in temperature relative to depth. Data can be obtained by computer calculation from a temperature log or by using a specially designed logging probe that utilizes either two sensors with a vertical spacing or one sensor and an electronic memory that compares the temperature at one time with those taken at previous times. A **radial differential temperature** tool uses two highly sensitive temperature probes that extend from the probe to contact the casing. As the probes are rotated, they measure differences in temperature at two points on the casing 180 degrees. apart. The probes also can detect cooler water flowing behind a casing that has not been properly sealed.

Table **6-1** Index to References on Ground Penetrating Radar

Topic	References
General	
Report/General Papers	Texts: Benson et al. (1984), EC&T et al. (1990), Morey and Harrington (1972), Lord and Koerner (1987a), Pilon (1992), Pitchford et al. (1988), Pittman et al. (1974), Rehm et al. (1985), Redwine et al. (1985), Skolnik (1990), Trabant (1984), Uhiksen (1982), U.S. EPA (1987); Papers: Annan and Cosway (1992), Bjelm et al. (1983), Daniels (1989), Lepper and Dennen (1990), Moffat and Puskar (1976), Morey (1974), Olhoeft (1984, 1988-bibliography), Roberts et al. (1992)
Symposia	Hänninen and Autio (1992), Lucius et al. (1990), Soil Conservation Service (1988)
Subsurface Dielectric Properties	Akhadov (1980), Daniel (1967), Hasted (1974), Hoekstra and Delaney (1974), Kracchman (1970), Tareev (1975), van Beek (1965), von Hippel (1954a,b); Papers: Saint-Amant and Strangway (1970), Olhoeft (1990)
Continuous Microwave	Koerner and Lord (1985), Koerner et al. (1978, 1981), Lord and Koerner (1982)
Applications: Subsurface Contamination	
Contaminated Sites	Barton and Ivanhenko (1991), Brewster et al. (1992 perchloroethylene), Cichowicz et al. (1981), Cosgrove et al. (1987), Douglas et al. (1992), Evans and Schweitzer (1984), Glaccum et al. (1982), Horton et al. (1981), Koerner et al. (1981), Kuo and Stangland (1986), Folwer and Ayubcha (1986), Hankins et al. (1991), Lawrence (1984), Osborne (199l-remote controlled), Pease and James (1981), Roberts et al. (1989), Russell (1990), Saunders et al. (1991), Smith and Markt (1988), Stanfill and McMillan (1985), Steams and Dialmann (1986), Underwood and Bales (1984 buried crystalline waste), White and Brandwein (1982)
Buried Containers	Allen and Seelen (1992), Bowder et al. (1982), Hager et al. (1991-USTs), Hatch (1987) Hogan (1988), Hu et al. (1992), Koerner et al. (1982), Lord and Koerner (1986, 1987a,b), Osborne (1991-remote controlled), Rudy and Warner (1986 USTs)
NAPL Detection	Annan et al, (1991), Cameron (1988), Cleff (1991), Daniels et al. (1992), Olhoeft (1986, 1992), Olhoeft et al. (1992), Redman et al. (1991), Stanfill and McMillan (1985)
Leak Detection	Koerner and Lord (1985), Koerner et al. (1978, 1981)
Sewage Plume	Wright et al. (1984)

Table 6-l (cont.)

Topic	References
Applications: Subsurface Characterization	
Soil Characteristics	Collins and Doolittle (1987), Collins et al. (1986), Doolittle (1982, 1983, 1987), Olson and Doolittle (1985), Puckett et al. (1986), Schellentrager et al. (1988), Shih and Doolittle (1984), Truman et al. (1988), Zobeck et al. (1985)
Bedrock Depth	Collins et al. (1989)
Fracture Detection	Imse and Levine (1985), Leckenby (1982) Olson and Doolittle (1985), Rubin and Fowler (1978), Ulriksen (1982)
Karst Terrane	Beck and Wilson (1988), Kuo and Stangland (1986)
Moisture Profiles	Houck (1984)
Subsurface Geology	Beres and Haeni (1991), Davis et al. (1984), Dolphin et al. (1978), Rubin and Fowler (1978), Wright et al. (1984)
Watershed Delineation	Asmussen et al. (1986)
Subsurface Openings	Cook (1956, 1975), Filler and Kuo (1989), Fountain (1976), Friedel et al. (1990), Leckenby (1982)
Ground Water	Beres and Haeni (1991), Davis et al. (1966), Johnson (1987), Sellman et al. (1983), Shih et al. (1986), Taylor and Baker (1988), Wright et al. (1984)
Water Bodies	Beres and Haeni (1989), Gorin and Haeni (1989), Haeni (1992), Haeni et al. (1987), Truman et al. (1991), Ulriksen (1982)
Wetlands	Watson et al. (1990)
GPR Applications: Miscellaneous	
Abandoned Well Location	Aller (1984)
Mining	Annan et al. (1988-potash mines), Cook (1973), Duckworth (1970), Pittman et al. (1984)
Glaciers	Harrison (1970), Watts and England (1976)

Table 6-2 Index to References on Magnetic Methods

Topic	References
Texts/Review Papers	Texts: Benson et al. (1984) Bozorth (195 I), Breiner (1973), EC&T (1990), Chikazumi (1964), Nettleton (1971, 1976) Rehm et al. (1985), U.S. EPA (1987), Zohdy et al. (1974); Papers: Hinze (1988) Kufs et al. (1986-statistical modeling of data), Palermo and Brickell (1984) Reford (1980); see also Table 1-4 for general geophysics texts covering magnetic methods
Applications	
Abandoned Well Location	Aller (1984), Martinek (1988)
Basalt Aquifers	Harmon (1984), Mabey and Oriel (1970)
Ground Water	Joiner et al. (1967), Ram Babu et al. (1991), Stierman et al. (1986) Wilson et al. (1970)
Bedrock Depth Topgraphy	Birch (1984), Ghatge and Pasicznyk (1986), Mabey and Oriel (1970) Ram Babu et al. (1991), Wire et al. (1984) Wynn (1979)
Contaminated Sites	Benson (1991), Allen and Rogers (1989), Blasting (1987), Carr et al. (1990), Evans and Schweitzer (1984), Feld et al. (1983), Fowler and Ayubcha (1986), Fowler and Pasicznyk (1985), Gilkeson et al. (1986) Gihner and Helbling (1984), Hitchcock and Harman (1983) Lord and Koerner (1986, 1987a,b), Palermo and Brickell (1984), Pitchford et al. (1988), Regan et al. (1987), Roberts et al. (1989) Smith and Markt (1988), White and Brandwein (1982)
Buried Drums/Metals	Allen and Seelen (1992), Barrows and Rocchio (1990), Emilsson and Morin (1989), Gilkeson et al. (1992), Hager et al. (1991-USTs), Hatch et al. (1987), Koerner et al. (1982), Lord and Koerner (1987a,b), Rudy and Warner (1986-USTs), Schlinger (1990-USTs), Schutts and Nichols (1991), Struttmann and Anderson (1989), Walsh (1989)
Other	Landslide Processes: Bogoslovsky and Ogilvy (1977); Abandoned Iron Ore Mining Area: Cohen et al. (1992)

Table 6-3 Index to References on Gravity Methods

Topic	References
Texts	Lahee (1961), Nettleton (1971, 1976) Rehm et al. (1985), Redwine et al. (1985), USGS (1980); see also Table l-4 for general geophysics texts covering gravimetric methods
Review Papers	Butler (1991), Hinze (1988) LaFehr (1980)
Microgravity Survey	Arzi (1975), Blivkovsky (1979), Fajkewicz (1976), Dahlstrand (1985) Imse and Levine (1985), Poeter (1989), Stewart and Wood (1986)
Applications	
Contaminated Sites	Benson. (1991), Bruehl (1983, 1984) Fowler and Ayubcha (1986), Kick (1989), Regan et al. (1987), Roberts et al. (1989), Rodrigues (1987)
Ground Water	Adams et al. (1975), Ali (1985), Ali and Whitely (1981), Carmichael (1976), Carmichael and Henry (1977), Eaton and Watkins (1970) Frohlich (1978), Joiner and Scarbrough (1969) Marshall (197 I), Mattick et al. (1973), Poeter (1989) Spangler and Libby (1968) Strange (1970) Van Overmeeren (1980, 1981), Wallace and Spangler (1970), West and Sumner (1972), Worthington. (1975) Wrege (1986)
Bedrock Topography/ Buried Valleys	Adams et al. (1975), Alvarez (1991), Burgdorf and. Richard (1984), Carmichael and Henry (1977), Denne et al. (1984), Ghatge and Pasicznyk (1986), Hall and Hajnal(1962),. Hansen (1984), Heigold et al. (1964), Henry (1984); Ibrahim and Hinze (1972), Lennox and Carlson (1967, 1970), Mabey (1960) Mabey and Oriel (1970), McGinnis et al. (1963) O'Brien and Stone (1984, 1985) Richard and Wolfe (1990), Stewart (1980), Van Overmeeren (1980), Wilson et al. (1983)
Unconsolidated Deposits	Tibbets and Scott (1972)
Fracture Zones	Imse and Levine (1985), Stewart and Wood (1986)
Karst/Cavities	Arzi (1977), Butler (1977, 1984), Colley (1963), Dahlstrand (1985), Fajkiewicz (1976) Fountain (1976), Omnes (1977)

Table 6-4 Index to References on Shallow and Borehole Thermal Methods

Topic	References
Texts	Eve and Keys (1954), Gougel (1976), Howell (1959), Jessup (1990), Rehm et al. (1985), Sharma (1986), Sheriff (1989), Bibliography: Summer (1971)
Basic Soil Thermal Properties	Carlslaw (1986), de Vries (1963, 1975), Kersten (1949), Lee (1965), Farouki (1981), Wierenga et al. (1969)
Soil Temperature	Buchan (199 I), Taylor and Jackson (1986a), Morrison (1983), Smith et al. (1960)
Measurement of Soil Thermal Properties	Beck et al. (1971), Flint and Childs (1987), Fuchs (1986), Fuchs and Hadas (1973), Hares et al. (1985), Horton et al. (1983), Jackson and Kirkham (1958), Jackson and Taylor (1986), Kimball and Jackson (1975), Kimball et al. (1976), Lettau (1971), Sophocleous (1979), Taylor and Jackson (1986b), Weaver and Campbell (1985)
Shallow Ground-Water Applications	
Measurement Methods	Misener and Beck (1960), Stevens et al. (1975)
Aquifer Thermal Storage Properties	Parr et al. (1983), Schaetele et al. (1980)
Ground-Water Detection	Bair and Parizek (1978-permeabihty variations), Birman (1969), Brown et al. (1983), Cartwright (1968a,b, 1974), Jansen (1990), Jansen and Taylor (1989), Kremar and Masin (1970), Parsons (1970); Unpublished Ph.D Theses: Cartwright (1973), O'Brien (1970), Supkow, (1971)
Subsurface Flow	Infiltration/Recharge: Boyle and Saleem (1979), Nightingale (1975), Randall (1986), Schneider (1962), Suzuki (1960); Ground-Water Flow: Brown et al. (1983), Cartwright (1970), Domenico and Palciauskas (1973), Jansen (1992), Lapham (1989), Schneider (1962), Stallman (1963, 1965); Temperature as Tracer: Davis et al. (1985), Keys and Brown (1978), Rorabaugh (1956), Sampayo and Wilke (1963)
Geology	Buried Valley Detection: Denne et al. (1984), Smith (1974); Fracture Detection: Howard et al. (1986), Jansen and Taylor (1988, 1989), Morin and Barash (1986), Silliman et al. (1987), Trainer (1968), Westphalen (1991), Williams et al. (1984), Yearsley et al (1990)
Contaminated Sites	Cartwright and McComas (1968), Gilkeson and Cartwright (1982, 1983), Gilkeson et al. (1984), Yazicigil and Sendlein (1982)

Table 6-4 (cont.)

Topic	References
Borehole Temperature Logging	
Temperature Logs	Brown et al. (1983) Guyod (1946), Norris and Spieker (1962a,b), Nowak (1953), Peacock (1965), Sammel (1968), Trainer (1968)
Temperature Gradient J4P	Conaway (1977), Conaway and Beck (1977)
Fracture Connections	Sillman and Robinson (1989)
Vertical Velocity	Bredehoeft and Papadopulos (1965), Newman and McDuff (1988) Sorey (1971), Stallman (1963)
Borehole Case Studies	Emilsson and Arnott (1991), Howard et al. (1986), Michalski (1989) Morin and Barrash (1986), Silliman et al. (1987), Sutchffe and Joyner (1966), Williams et al. (1984), Westphaien (1991), Williams and Conger (1990), Yearsley et al. (1990)

6.5 References

See Glossary *for* meaning *of method* abbreviation.

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CHAPTER 7
BOREHOLE GEOPHYSICS

7.1 Overview of Downhole Methods

Borehole geophysics is the science of recording and analyzing continuous or point measurements of physical properties made in wells or test holes (Keys, 1990). The terms **borehole** and **downhole** are used interchangeably to refer to such measurements. Most specific borehole geophysical techniques have long been in use by the petroleum industry, where holes being logged are usually deep and filled with drilling muds or saline water. Many of these techniques are not suitable, or must be adapted, for use in freshwater aquifers, which are the focus of near-surface hydrogeological investigations. Nevertheless, suitable borehole geophysical methods can greatly enhance the geologic and hydrogeologic information obtained from water supply or monitor wells. The development of logging tools specifically designed for use in freshwater wells, such as the EM39 borehole conductivity meter (McNeill, 1986), and high-precision thermal and electromagnetic borehole flowmeters should contribute to greater use of downhole methods in the future.

7.1.1 Requirements of Borehole Methods

The characteristics of the borehole to be logged may place constraints on the type of borehole logging method that can be used—the primary consideration when identifying borehole logging methods of potential value for a specific situation. Table 7-1 lists important characteristics of 41 borehole logging methods with potential for application at contaminated sites. These characteristics include:

- Whether a casing is present. Electric methods, for example, require uncased holes.
- If cased, the type of casing. Borehole radar, for example, can be used with a polyvinyl chloride (PVC) casing, but not with a steel casing.

Table 7-1 Characteristics of Borehole Logging Methods (information for general guidance only)

Log Type/Section	Casing*	Min. Diam.** (in.)	Borehole Fluid	Radius of Measurement	Required Correction
Electrical Logs (7.3.1)[a]					
Spontaneous Potential (3.1.1)	Uncased only	1.5-3.0	Conductive fluid	Near borehole surface	Drilling fluid resistivity and borehole diameter for quantitative uses.
Single-Point Resistance (3.1.2)	Uncased only	1.5-2.0	Conductive fluid	Near borehole surface	Not quantitative; hole diameter effects significant.
Fluid Conductivity (3.1.3)	Uncased or screened	2.0-2.5	Conductive fluid	Within borehoIe	Calibration with fluid of known salinity; temperature correction.
Resistivity (3.1.4)	Uncased only	2.0-5.5	Conductive fluid	<1-60 in.	Drilling fluid resistivity, borehole diameter, and temperature log for quantitative uses.
Dipmeter (3.1.5)	Uncased only	?-6.0	Conductive fluid	Near borehole surface	Orientation; minimum of 6" diam. required for accurate joint/fracture characterization.
Induced Polarization (3.1.6)	Uncased only	2.0	Conductive	2-4 ft	Hole diameter.
Cross-Well AC Voltage (3.1.6)	Uncased only	?	Wet or dry	10s to 100s of meters	Borehole deviation.
Electromagnetic Logs (7.3.l)[a]					
Induction (3.2.1)	Uncased or nonmetallic	2.0-4.0	Wet or dry	30 in.	Effect of hole diameter and mud negligible.
Borehole Radar (3.2.2)	Uncased or nonmetallic	2.0-6.0	Wet or dry	meters	Borehole deviation (cross-hole).
Dielectric (3.2.3)	Uncased or nonmetallic	5.0	Wet or dry	30 in.	Conductive material skin depth, chlorine interference.
Nuclear Magnetic Resonance (3.2.4)	Uncased	7	Required	1.5 ft	Borehole fluid.
Surface-Borehole CSAMT (3.2.4)	Uncased only (?)	?	Wet or dry(?)	?	**?**
Nuclear Logs (7.3.2)[a]					
Natural Gamma (3.3.1)	Uncased or cased	1.0-2.0	Wet or dry	6-12 in.	None for qualitative uses. Hole diameter, casing (thickness, composition, size), and drilling fluid density for quantitative uses.
Gamma-Gamma (3.3.2)	Uncased or eased	2.5	Wet or dry	6 in.	Same as natural gamma with addition of formation fluid and matrix density corrections.
Neutron (3.3.3)	Uncased or cased	1.5-4.5	Wet or dry	6-12 in.	Same as natural gamma with addition of temperature, fluid salinity, and matrix composition corrections.
Gamma Spectrometry (3.3.4)	Uncased or cased	2.0-4.0	Wet or dry	6-12 in.	Similar to natural gamma

Table 7-1 (cont.)

Log Type/Section	Casing*	Min. Diam.** (in.)	Borehole Fluid	Radius of Measurement	Required Correction
Nuclear Logs (cont.)					
Neutron Activation (3.3.5)	Uncased or cased	2.0-4.0	Wet or dry	< Neutron	?
Neutron Lifetime (3.3.6)	Uncased or cased	2.0-4.0	Wet or dry	< Neutron	?
Acoustic and Seismic Logs (7.3.3)[a]					
Acoustic Velocity/* sonic** (3.4.1)	Uncased or bonded metallic	2.0-4.0	Required	Depends on frequency and rock velocity several feet	Hole diameter, formation fluid and matrix velocity corrections for quantitative uses.
Acoustic Waveform*** (3.4.2)	Uncased or bonded metallic	2.5-3.0	Required	> sonic	Same as sonic?
Acoustic Televiewer (3.4.3)	Uncased	3.0 min 16.0 max	Required	Borehole surface	Large number of equipment adjustments required during operation (calibration of magnetometer), borehole diameter response, borehole deviation.
Surface-Borehole Seismic (3.4.4)	Uncased or bonded cased	2.5-4.0	Wet or dry	Depends on geophone configuration	Borehole deviation, correction for geometric spreading of source energy geophones must be locked in dry holes.
Geophysical Diffraction Tomography (3.4.5)	Uncased or nonmetallic	2.5-4.0	Wet	100 ft	Borehole deviation.
Cross-Borehole Seismic (3.4.6)	Cased or uncased	2.0-3.0	Wet or dry	Depends on borehole spacing	Borehole deviation.
Miscellaneous Logging Methods (7.4.1)[a]					
Caliper (3.5.1)	Uncased or cased	1.5+	Wet or dry	Arm limit (usually 2-3 ft.)	None.
Temperature (3.5.2)	Uncased or cased****	2.0	Required	Within borehole	Calibration to known standard.
Mechanical Flowmeter (3.5.3)	*****	2.0-4.0	Required	*****	Borehole diameter for velocity and volumetric logging.
Thermal Flowmeter (3.5.4)	*****	2.0	Required	*****	Borehole diameter for velocity and volumetric logging.
EM Flowmeter (3.5.5)	*****	2.0	Required	*****	Borehole diameter for velocity and volumetric logging.
Single-Borehole Flow Tracing (3.5.6)	*****	1.75+	Required	*****	Changes in flow field with time.
Colloidal Boroscope (3.5.7)	*****	2.0	Required	*****	None.

Table 7-1 (cont.)

Log Type/Section	Casing*	Min. Diam.** (in.)	Borehole Fluid	Radius of Measurement	Required Correction
Miscellaneous Logging Methods (cont.)					
Television/Photography (3.5.7)	Uncased or cased	2.0+	Wet or dry	Borehole surface	None.
Gravity (3.5.8)	Uncased best	6.0	Wet or dry	10s to l00s of meters	Borehole diameter/inclination; other usual gravity corrections
Magnetic/Magnetic Susceptibility (3.5.8)	Uncased or nonmetallic	?	Wet or dry	1-2 ft	Hole diameter correction.
Well Construction Logs (7.4.2)[a]					
Casing Collar Locator (3.6.1)	Steel Casing	2.0+	Wet or dry	Casing collar, thickness	?
Cement and Gravel Pack Logs (3.6.2)	Cased	See specific logging methods discussed in this section.			
Borehole Deviation (3.6.3)	Uncased	Varies	Wet or dry	Borehole Surface	Magnetic declination.
Fluid/Gas Chemical Sensors[b]					
Eh, pH Probes (3.5.4)	Uncased/screened	2.0-6.0	Required	Within borehole	Calibration to known standards.
Ion-Selective Electrodes (3.5.5)	Uncased/screened	2.0-6.0	Required	Within borehole	Calibration to known standards.
Fiber Optic Chemical Sensors (5.5.6)	Uncased/screened	2.0	Wet or dry	Within borehole	Calibration to known standards.
Other Chemical Sensors (10.6.5)	Uncased/screened	2.0-6.0	Wet or dry	Within borehole	Calibration to known standards.

Boldface = Most frequently used techniques in ground-water investigations.

[a] Underlined number in parentheses indicates cross-reference to this guide; other numbers in parentheses are section numbers in U.S. EPA (1993) where additional information can be found on the specific methods.
[b] Borehole chemical sensors are not covered in this reference guide. See section numbers indicated in U.S. EPA (1993) for additional information on these techniques.
Note: Question mark (?) indicates that the information could not be found by the author in readily available sources.

* Unless otherwise specified, either plastic or steel casing is possible.
** Indicates range of minimum diameters for commercially available probes based on best available information. Various sources were used, with the survey by Adams et al. (1983) serving as the main source.
*** Wheatcraft et al. (1986) indicate that acoustic logs are suitable only for uncased boreholes. However, Thornhill and Benefield (1990) report using them for mechanical integrity tests of steel-cased injection wells.
**** Wheatcraft et al. (1986) indicate that casing is allowable for temperature logs. Benson (1991) indicates that casing should not be used. Uncased holes are required for identification of high-permeability zones. Cased hole uses would include measurement of geothermal gradient and cement bond logs (see Section 3.6.2).
***** Flow measurements are usually made in uncased holes or screened intervals of cased holes. Radius of measurement depends on permeability and whether natural or induced flow is measured. Natural flow will measure the properties of several well diameters; pumping will measure properties up to 25 to 35 well diameters (Taylor, 1989).

- Borehole diameter must be large enough for the instrument of interest. Some logs (e.g., dielectric and nuclear magnetic resonance logs) require borehole diameters that are considerably larger than are typically drilled for monitoring wells at contaminated sites.

- Whether borehole fluid (e.g., ground water or drilling fluid) is present. Electric logs, sonic logs, and any fluid characterization log require borehole fluid.

- The radius of measurement of specific methods can range from near the borehole surface (spontaneous potential and SP resistance logs) to more than 100 meters for borehole radar in highly resistive rock.

- Many logging methods require calibration or corrections for such factors as temperature, borehole diameter, and fluid resistivity.

The most commonly used borehole logging methods in hydrogeologic and contaminated site investigations involve spontaneous potential (SP), single-point resistance, fluid conductivity, natural gamma, gamma-gamma, neutron, sonic, caliper, temperature, and flowmeters. The nuclear logging methods listed in Table 7-1 are especially versatile because they can be used in cased monitoring wells.

7.1.2 Applications of Borehole Methods

A bewildering number of specific borehole logging methods are available, and papers describing new methods or innovative adaptation of older methods appear every year. Schlumberger (1974) lists almost four dozen, and Keys (1990) lists more than two dozen that have potential applications in ground-water investigations. Equally confusing to the uninitiated is the fact that the same logging technique may be called by several different names. For example the terms gamma-gamma and density are commonly used for the same log, and acoustic-waveform logs also are called variable density, three-dimensional (or 3D) velocity, and full waveform sonic logs (see Table 7-7). The summary tables covering major logging methods in later sections of this chapter list the most common alternative names for specific methods and the names of major variants of certain types of logs.

The 41 methods identified in Table 7-1 have been identified in U.S. EPA (1993) as having potential applications at contaminated sites. Table 7-2 identifies relevant borehole

Table 7-2 Summary of Borehole Log Applications

Required Information	Potential Logging Techniques
Lithology, Stratigraphy, Formation Properties	
General Lithology and Stratigraphic Correlation	Electric (SP, single-point resistance, normal and focused resistivity, dipmeter, IP, cross-well AC voltage); EM (induction, dielectric); all nuclear (open or cased holes); caliper logs made in open holes, borehole television.
Bed Thickness	Single-point resistance, focused resistivity (thin beds), gamma, gamma-gamma, neutron, acoustic velocity.
Cavity Detection	Caliper, acoustic televiewer, cross-hole radar, cross-hole seismic.
Sedimentary Structure Orientation	Dipmeter, borehole television, acoustic televiewer.
Large Geologic Structures	Gravity, surface-borehole/cross-hole seismic, cross-hole radar.
Total Porosity/Bulk Density	Calibrated dielectric, sonic logs in open holes; cross-hole radar; calibrated neutron, neutron lifetime, gamma-gamma logs, computer-assisted tomography (CAT) in open or cased holes; nuclear magnetic resonance, induced polarization, cross-hole seismic.
Effective Porosity	Calibrated long-normal and focused resistivity or induction logs.
Clay or Shale Content	Gamma log, induction log, IP log.
Relative Sand-Shale Content	Gamma, SP log.
Grain Size/Pore Size Distribution	Grain size: possible relation to formation factor derived from electric, induction or gamma logs; Pore size distribution: nuclear magnetic resonance: Soil macroporosity: computerized axial tomography (CAT).
Compressibility/Stress-Strain Properties	Acoustic waveform, uphole/downhole seismic, cross-hole seismic
Geochemistry	Neutron activation log, spectral-gamma log.
Aquifer Properties	
Location of Water Level or Saturated Zones	Electric, induction, acoustic velocity, temperature or fluid conductivity in open hole or inside casing. Neutron or gamma-gamma logs in open hole or outside casing.
Moisture Content	Calibrated neutron logs, gamma-gamma logs, nuclear magnetic resonance, computerized axial tomography (CAT).
Permeability/Hydraulic Conductivity	No direct measurement by logging. May be related to porosity, single borehole tracers methods (injectivity), 2-wave sonic amplitude, temperature, nuclear magnetic resonance. Estimation may be possible using vertical seismic profiling.
Secondary Permeability-Fractures, Solution Openings	Caliper, temperature, flowmeters (mechanical, thermal, EM), sonic, acoustic waveform/televiewer, borehole television logs, SP resistance, induction logs, cross-well AC voltage, surface-borehole CSAMT, vertical seismic profiling, cross-hole seismic.
Specific Yield of Unconfined Aquifers	Calibrated neutron logs during pumping.
Ground-Water Flow and Direction	
Infiltration	Temperature logs, time-interval neutron logs under special circumstances or radioactive tracers.

Table 7-2 (cont.)

Required Information	Potential Logging Techniques
Ground-Water Flow and Direction (cont.)	
Direction, Velocity, and Path of Ground-Water Flow	Thermal flowmeter single-well tracer techniques—point dilution and single-well pulse; multiwell tracer techniques.
Source and Movement of Water in a Well	Infectivity profile mechanical, thermal, EM flowmeters; tracer logging during pumping or injection; temperature logs.
Borehole Fluid Characterization	
Water Quality/Salinity	Calibrated fluid conductivity and temperature; SP log, single-point resistance, normal/multielectrode resistivity, neutron lifetime.
Water Chemistry	Dissolved oxygen, Eh, pH probes; specific ion electrodes.
Pore Fluid Chemistry	Induced polarization log, neutron activation (if matrix effects can be accounted for).
Mudcake Detection	Microresistivity, caliper, acoustic televiewer.
Contaminant Characterization	
Conductive Plumes	Induction log, resistivity, surface-borehole CSAMT.
Contaminant Chemistry	Specific ion electrodes, fiber optic chemical sensors.
Hydrocarbon Detection	Dielectric log, IP log.
Radioactive Contaminants	Spectral gamma log.
Dispersion, Dilution, and Movement of Waste	Fluid conductivity and temperature logs, gamma logs for some radioactive wastes, fluid sampler.
Buried Object Detection	Geophysical diffraction tomography.
Borehole/Casing Characterization	
Determining Construction of Existing Wells, Diameter and Position of Casing, Perforations, Screens	Gamma-gamma, caliper, collar, and perforation locator, borehole television.
Guide to Screen Setting	All logs providing data on the lithology, water-bearing characteristic, and correlation and thickness of aquifers.
Borehole Deviation	Deviation log, dipmeter, single-shot probe, dolly and cage tests.
Cementing/Gravel Pack	Caliper, temperature, gamma-gamma; acoustic waveform for cement bond; noise/Sonan log.
Casing Corrosion/Integrity	Borehole television/photography, under some conditions caliper or collar locator.
Casing Detection/Logging	Casing collar locator, borehole television/photography various electric, nuclear and acoustic logs.
Casing Leaks and/or Plugged Screen	Tracer and flowmeters.
Behind Casing Flow	Neutron activation and neutron lifetime logs.

methods for almost 40 specific applications in the following categories: lithology, stratigraphy, and formation properties; aquifer properties; ground-water flow and direction, borehole fluid characterization; contaminant characterization; and borehole/casing characterization. Table 7-14 indexes over 100 references on applications of borehole geophysics at contaminated sites, and for lithologic and hydrogeologic applications. Appendix A (Table A-2) provides summary information on 9 cases studies involving uses of borehole geophysics at contaminated sites.

7.1.3 Geophysical Well Log Suites

Rarely is a single logging method used since many logs require other logs for interpretation. Even when they are not mandatory, multiple logs may interact synergistically to provide more information than individual logs. For example, the minerals gypsum and anhydrite can be distinguished by interpreting gamma and neutron logs together. Figure 7-1 shows typical responses of three electrical logs (spontaneous potential, single-point resistance, and long-normal resistivity-see Section 7.3.1), two nuclear logs (gamma and neutron—see Section 7.3.2), and three other types of logs (acoustic velocity, caliper, and temperature). In the figure, the individual logs do not always show changes with a change in lithology, but for individual strata, one or more logs show changes in measured properties at the top and bottom of the formation. Figure 7-2 shows a similar suite of logs for a hypothetical hole in crystalline rock. Of particular interest in this figure is the ability of the logs to locate fractured and altered material that may serve as preferential flow paths for contaminated ground water. As with surface geophysical methods, most downhole methods require considerable training and skill in recording and interpreting data.

7.1.4 Guide to Major References

Table 7-3 provides information on over 30 general texts on borehole geophysical methods and log interpretation. Documents identified in this table published by Birdwell and Dresser Atlas are no longer available because these divisions are no longer providing geophysical logging services. Hydrogeologic and geophysical consulting firms, however, may have these documents in their files. Documents published by Schlumberger Educational Services (5000 Gulf Freeway, Houston, TX 77023) are available and periodically updated.

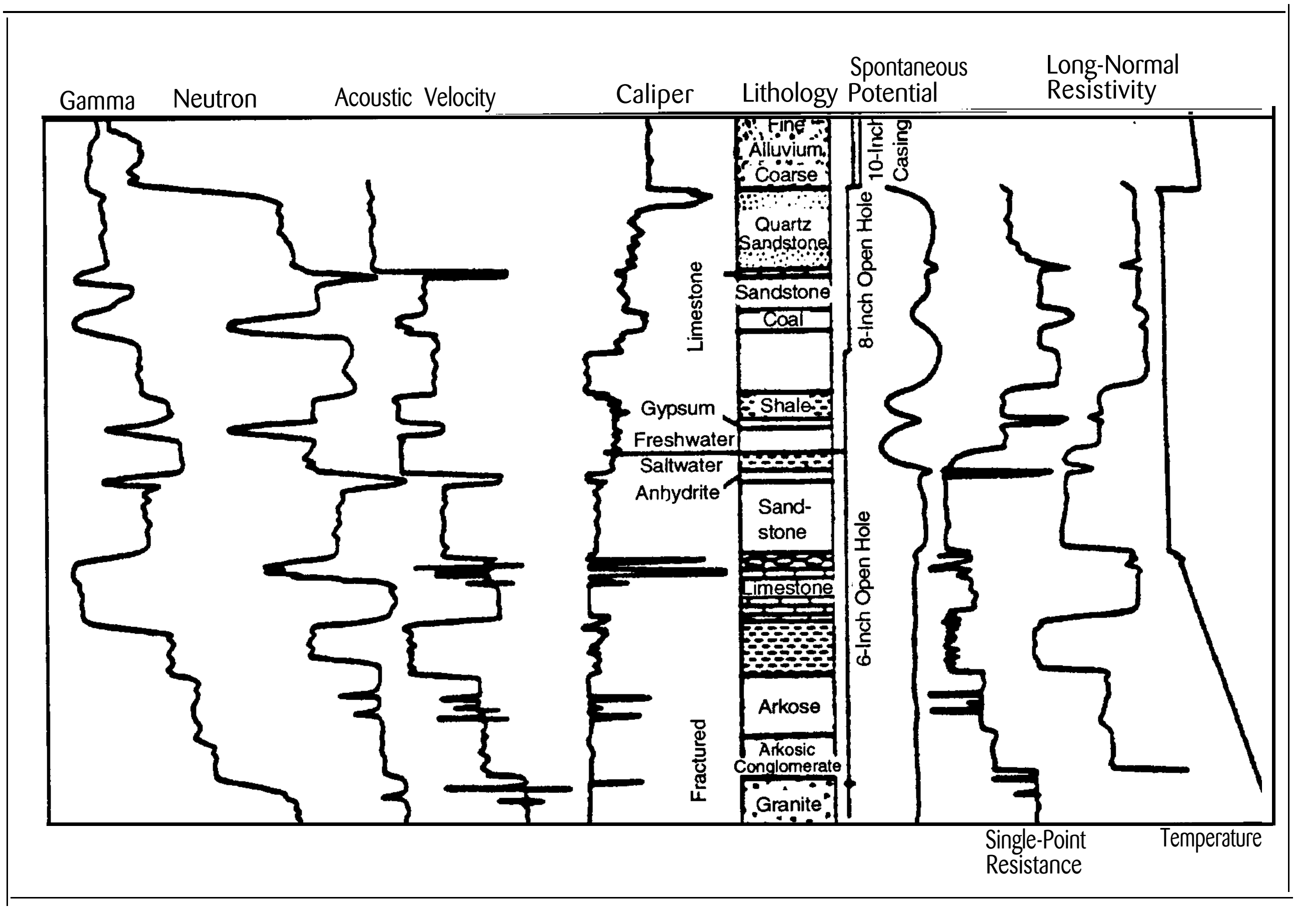

Figure 7-1 Typical response of a suite of hypothetical geophysical well logs to a sequence of sedimentary rocks (from Keys, 1990).

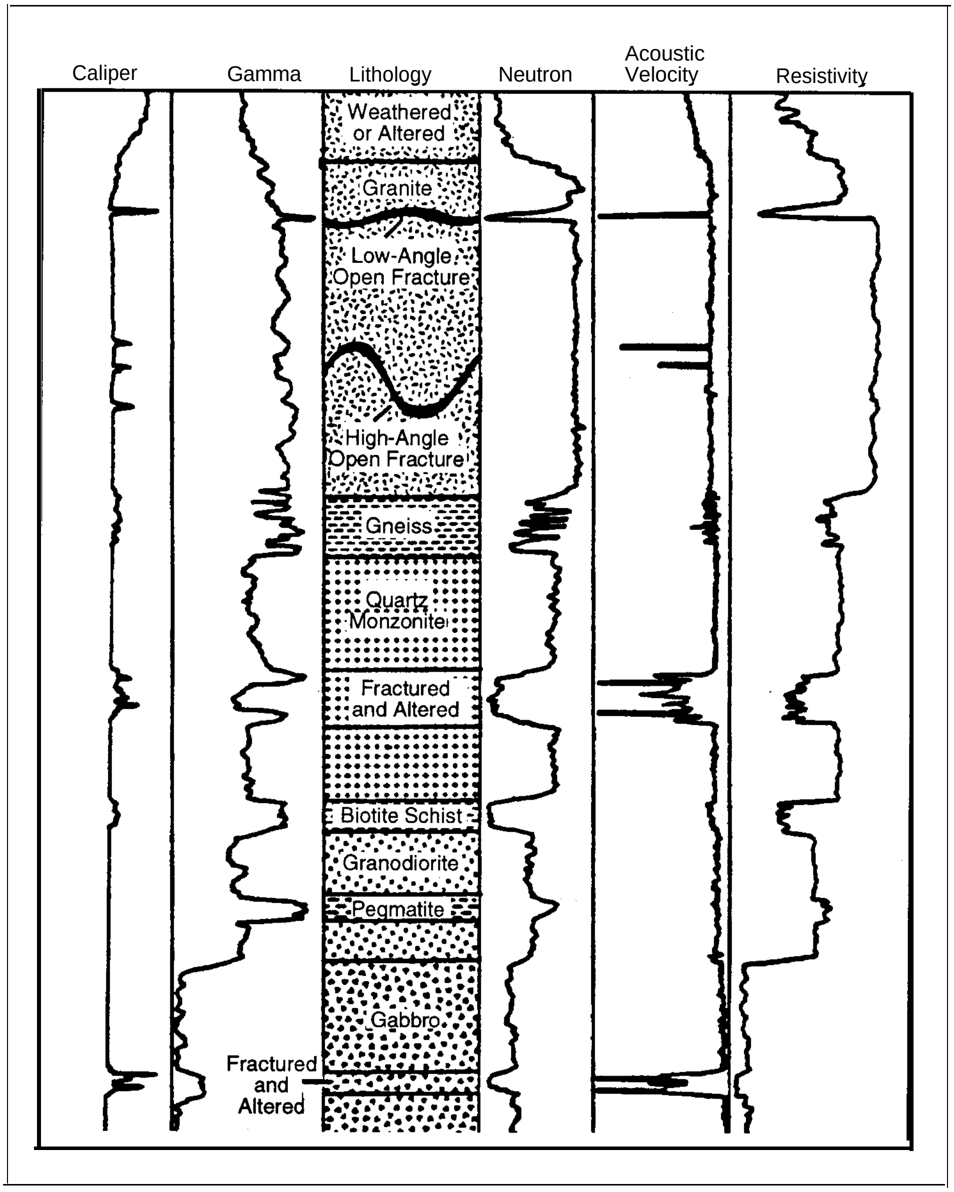

Figure 7-2 Typical response of a suite of hypothetical geophysical well logs to various altered and fractured crystalline rocks (from Keys, 1990).

Table 7-3 General Texts on Borehole Geophysical Logging and Interpretation

Reference	Description
Asquith and Gibson (1982)	Text on basic well log analysis for geologists.
Birdwell Division (1973)	Company that used to be in business of providing well logging services. 1973 guide on geophysical well log interpretation including SP, resistivity, gamma, gamma-gamma, neutron, fluid conductivity, temperature, and 3-D velocity. Hamilton and Myung (1979) provide summary information on major geophysical logging techniques.
Doveton (1986)	Text of log analysis for interpretation of subsurface geology with emphasis on computer models.
Dresser Atlas (1974, 1975, 1976, 1982)	Various publications by a company that used to be in the business of providing logging services: Log review (1974) covers induction, resistivity, acoustic velocity, gamma-gamma, neutron-gamma, diplog, neutron lifetime. Log interpretation fundamentals (1975) and charts (1979). Also, a home study course on well logging and interpretation (1982).
Ellis (1987)	Text on well logging resistivity, SP, induction, gamma, neutron, acoustic.
Foster and Beaumont (1990)	2-volume collection of reprints of papers on formation evaluation: I (log evaluation), II (log interpretation). Oriented toward petroleum applications.
Hearst and Nelson (1985)	Text on well logging for physical properties.
Helander (1983)	Text covering SP, resistivity, acoustic, and radioactivity logging and interpretation.
Hilchie (1982a)	Text on log interpretation oriented toward geologists and engineers: resistivity, SP, induction, acoustic, gamma, density, neutron, combined porosity, and focused resistivity logs.
Hilchie (1982b)	Text on advanced well log interpretation.
Labo (1987)	Text covering density, gravimetric, acoustic, seismic, and dipmeter logs.
LeRoy et al. (1987)	Edited volume with several chapters devoted to geophysical logging methods.
Lynch (1962)	Text on formation evaluation.
Nelson (1985)	Text covering use of downhole methods for characterization of fractured rock.

Table 7-3 (cont.)

Reference	Description
Pirson (1963, 1983)	1963 handbook on well log analysis and 1983 text on geologic well log interpretation.
Rider (1986)	Text on geological interpretation of logs: caliper, temperature, SP, resistivity, induction, gamma, spectral gamma, sonic/acoustic velocity, density.
Schlumberger (1989a&b, (1991)	Latest edition of Schlumberger Educational Services publications on log interpretation principles and applications covering uncased holes (1989a), and cased holes (1989b), and log interpretation charts (1991). See citations for methods covered. Earlier publications include Schlumberger (1972 and 1974).
Scott and Tibbets (1974)	Bureau of Mines information circular reviewing well log techniques for mineral deposit evaluation.
Serra (1984a,b)	Volume 1: acquisition of well log data; Volume 2: log interpretation. See citation for methods covered.
SPWLA (1978a, 1978b, 1990)	Series of reprint volumes containing papers on acoustic logging (1978a), gamma, neutron and density logging (1978b), and borehole imaging (1990).
Tearpocke and Bischke (1991)	Text on subsurface geological mapping using a variety of sources of information, including geophysical data.
Tittman (1986)	Well logging text covering electrical, nuclear, and sonic methods.
Wyllie (1963)	Text on fundamentals of well log interpretation. See citation for methods covered.

Table 7-4 provides information of texts/reports focusing on hydrogeologic/contaminated site applications, ground-water texts with chapters on borehole geophysical methods, and major conference series and symposia concerning borehole geophysical methods.

7.2 Special Considerations

7.2.1 Borehole versus In Situ Methods

In Situ sensing or logging methods involve the placement of disposable sensors (see, e.g., Greenhouse et al., 1985); reusable sensors (e.g., samplers and sensors used with cone penetrometers or other movable probes); or permanent sensors, which are installed in boreholes with cables running to the surface and backfilled. In situ sensors are most commonly used for chemical field screening and ongoing chemical monitoring of the vadose zone, while downhole logging methods are more commonly used for aquifer and lithologic characterization. This reference guide focuses on methods involving physical characterization of the subsurface using borehole instruments. U.S. EPA (1993) provides additional information on the use of cone penetrometers for physical characterization (Section 2.2), and the use of in situ and borehole chemical sensors (see Table 7-1, for sections in U.S. EPA 1993, dealing with specific types of sensors).

7.2.2 Surface-Borehole/Source-Receiver Configurations

Downhole and surface methods have become increasingly hybridized in recent years. For example, any method using a source-receiver layout (e.g., electrical resistivity, seismic and microwave radar) can be used in various combinations: surface-to-vertical borehole, surface-to-multiple boreholes, borehole-to-borehole. Recent developments in horizontal drilling technologies for subsurface monitoring and ground-water remediation also have made the use of surface-to-horizontal borehole configurations possible (Dickinson et al., 1987).

In surface-to-borehole configurations the signal source is usually at the surface with receivers in the borehole, as with vertical seismic profiling and geophysical diffraction

Table 7-4 Borehole Geophysics Texts, Reports, and Symposia Focusing on Hydrogeologic and Contaminated Site Applications

Topic/Reference	Description
Hydrogeologic/Contaminated Site Abdications	
U.S. Geological Survey Publications	Texts: Keys (1990) and Keys and MacCary (1971) are complementary texts on hydrogeologic applications of borehole geophysics; Reports: Bennett and Patten (1960) cover borehole geophysical methods for estimating specific capacity of mutltiaquifer wells. Johnson (1968) summarizes application of logging methods for hydrogeologic studies. Jorgenson (1989) discusses use of logs to estimate porosity, water resistivity, and intrinsic permeability. Patten and Bennett (1963) review application of electrical and nuclear logging to ground-water hydrology. See also Keys (1990).
U.S. EPA Publications	Section 8.4.3 of the compendium of Superfund field operations methods (U.S. EPA, 1987) and Section 3 of U.S. EPA (1993) cover borehole geophysics. Taylor et al. (1990) and Wheatcraft et al. (1986) review use of selected borehole geophysical methods at contaminated sites. Nielsen and Aller (1984) cover borehole methods for well integrity testing.
Emerson and Webster (1970)	Report prepared for Australian Water Resources Council on interpretation of geophysical logs in unconsolidated sediments.
Respold (1989)	Text on well logging in ground-water development published by International Association of Hydrogeologists.
Taylor and Dey (1985)	Bibliography on borehole geophysics as applied to ground-water hydrology. Organized in 70 subject headings.
Ground-Water Texts Covering Borehole Geophysics	
Bureau of Reclamation (1981)	Chapter 8 covers borehole logging and survey techniques for ground-water investigations.
Brown et al. (1983)	UNESCO research guide for ground-water studies. Section 9 covers borehole geophysics.
Campbell and Lehr (1973)	Text on water well technology. Chapter 9 covers borehole geophysics including SP, resistivity, gamma, caliper, fluid velocity, and acoustic. Extensive annotated bibliography.
Davis and DeWiest (1966)	Hydrogeology text. Chapter 8 covers borehole methods including SP, resistivity, acoustic, gamma, and neutron.

Table 7-4 (cont.)

Topic/Reference	Description
Ground-Water Texts Covering Borehole Geophysics (cont.)	
Driscoll (1986)	Text on ground water and wells. Chapter 8 covers borehole geophysical methods: resistivity, SP, gamma, gamma-gamma, neutron, acoustic, temperature, caliper, and fluid velocity.
Everett (1985)	Handbook focusing on coal and oil shale. Section 8 covers borehole geophysical methods: temperature, caliper, gamma, flow, radioactive tracer, 3-D velocity (acoustic waveform), acoustic, gamma-gamma, electric, acoustic televiewer.
Redwine et al. (1985)	EPRI ground-water manual. Section 5 covers borehole geophysical methods including SP, resistivity, gamma-gamma, neutron, caliper, borehole seismic methods, and temperature.
Rehm et al. (1985)	Section 5 covers hydrogeologic applications of surface and borehole geophysics and the bibliography in Section 6 contains 64 references on borehole logging.
Conferences/Symposia	
Canadian Well Logging Society (Various Dates)*	Biannual formation evaluation symposium series. Published volumes include 2nd (1968), 6th (1977), 7th (1979), 8th (1981), 9th (1983), 1lth (1987), 12th (1989), and 13th (1991).
Killeen (1985)	Proceedings of the 1983 international symposium on borehole geophysics for mining and geotechnical applications. Contains 40 papers.
MGLS Symposia Series (1985-1991)	Minerals and Geotechnical Logging Society biannual international symposia on borehole geophysics for minerals, geotechnical, and ground-water applications. Proceedings of 2nd symposium contains 7 papers on ground-water applications. MGLS is a chapter of SPWLA.
NWWA (1984, 1985, 1986)*	Conferences on surface and borehole geophysical methods in ground-water investigations. Both the 1984 and 1985 conference proceedings include 11 papers on borehole methods, and the 1986 conference proceedings includes 7 papers.
SPWLA (1960-present)*	Annual Logging Symposium transactions of the Society of Professional Well Log Analysts. 33rd annual symposium was held in 1992.

* See Appendix B.2 for addresses.

tomography, but the source also can be placed in the borehole with sensors at the surface, as with uphole seismic measurement. The type of model used for interpretation of the data will usually dictate the configuration required. In borehole-to-borehole configurations, the source is placed in one borehole and receivers are placed in one or more boreholes. When more than two boreholes are used, some methods (e.g., cross-hole seismic shear) require that the boreholes be aligned. Other cross-hole methods may not require alignment.

7.2.3 Tomographic Imaging

The application of tomographic imaging techniques, originally developed in the field of medicine, represents an important recent development in borehole geophysics (see general references identified in Table 7-9). Tomographic imaging is a type of waveform attenuation analysis that allows high-resolution imaging of subsurface inhomogeneities, such as stratigraphy, fracture detection, moisture variations, and buried objects. X-rays have been most commonly used for tomographic imaging and numerous terms have been used. **CAT,** which can stand for computerized axial tomography or computer-assisted tomography, scan is probably the most commonly used term; others include x-ray computed (computer) tomography, computed tomographic (CT) scanning, x-ray CT, gamma-ray attenuation CAT. Use of CAT scanning for near-surface characterization is in experimental stages.

The terms **geophysical diffraction tomography** (GDT) and variable density acoustic tomography have been applied to seismic tomographic imaging methods. GDT differs from other seismic methods in the way seismic signals are used and how the data received by the geophones or hydrophores are processed. Table 7-12 identifies a number of recent references on seismic tomographic methods. Tomographic principles can also be applied to cross-hole electrical resistivity and radar measurements, but this has been done infrequently (Table 7-10).

7.3 Major Types of Logging Methods

This section provides brief descriptions of the three major types of geophysical logging methods: electrical, nuclear, and acoustic/seismic. Summary tables in these sections provide a short description of each method and list hydrogeologic applications. At the end of this section, miscellaneous logging methods are covered.

7.3.1 Electrical and Electromagnetic Logging Methods

Electrical logging measures the flow of electric current in and adjacent to a well, using the same principles as various surface methods: electromagnetic induction (see Section 4.1); magnetotellurics (see Section 4.5), and microwave sensing (see Section 6.1). Table 7-5 describes 11 types of electrical and 4 types of electromagnetic logs and their potential for hydrogeologic applications, and Table 7-10 provides an index of references using these methods.

Fluid conductivity measurements are used to measure variations in salinity and locate saltwater leaks in artesian wells. Spontaneous potential logs, one of the most commonly used electrical logs, simply records the changes in current flow that result from changes in lithology. Single-point resistance and normal, focused and lateral resistivity logs all measure resistivity using the same principles as surface resistivity measurements. Resistivity logging methods have numerous variants depending on electrode configurations and spacings. These logs require conductive drilling mud or ground water with high salinities to work well and, consequently, are not well suited for near-surface investigations in freshwater aquifers. Normal resistivity logs, however, are widely used to measure variations in water quality.

Induction logs operate on the same principles as surface EM methods that measure conductivity (see Section 4.1). Since direct contact with a conductive medium is not required, induction logs are especially useful for logging the dry portion of boreholes where the water table is far below the surface (see, e.g., Turner and Black, 1989). Also, induction logs are also unaffected by the presence of plastic (e.g., polyvinyl choride) well casings, making them particularly useful for locating electrically conductive contaminant plumes in existing wells.

Nuclear magnetic resonance is often classified as a nuclear method, but it is actually a magnetic method that uses the same principle as the proton precession magnetometer (Section 6.2), except that the precession of protons (hydrogen atoms) in water molecules is measured in the formation after an induced magnetic field has been turned off. Nuclear magnetic resonance

Table 7-5 Summary of Electrical and EM Borehole Logging Methods in Hydrogeologic Studies

Method	Description	Hydrogeologic Applications
<u>Electric Logs</u>		
Fluid conductivity	A probe that records only the electrical conductivity of the borehole fluids by placing electrodes inside a protective housing.	Provides data related to the salinity (concentration of dissolved solids in the borehole fluid); used to locate sources of saltwater leaking into artesian wells; aids in interpretation of electric logs.
Spontaneous Potential (SP, self-potential)	Records the potentials or voltages that develop at the contacts between different lithologies.	Widely used in the petroleum industry for determining lithology, bed thickness, and salinity of formation water; generally not applicable for freshwater aquifers.
Single-Point Resistance	Measures the resistance in ohms between an electrode in a well and an electrode at the land surface, or between two electrodes in a well.	Excellent for information about changes in lithology; not influenced by bed thickness effects; cannot be used for quantitative interpretation of porosity and salinity.
Normal Resistivity (short normal, long normal)	Resistance is measured using four electrodes at various spacings on a single probe that is lowered down the hole.	Widely used in ground-water hydrology, primarily to determine water quality; quantitative interpretations require corrections for bed thickness, borehole diameter, and other factors.
Focused Resistivity (guard log, laterolog, dual laterolog)	Uses guard electrodes above and below the current electrode to force the current to flow out into the rocks surrounding the borehole.	Designed to measure the resistivity of thin beds or resistive rocks in wells containing conductive fluids; not generally available to water well loggers.
Lateral Resistivity	Similar to normal-resistivity electrode, but electrodes are more widely spaced on the probe.	Designed to measure resistivity of rock farther out from the borehole; suitable only for thick beds (> 40 feet); marginal for highly resistive rocks.
Microresistivity (microlog, contact log, microsurvey, microlateral, micronormal)	Numerous variations; all have short electrode spacing and pads or some kind of contact electrode to decrease the effect of borehole fluid.	Designed mainly to determine the presence or absence of mudcake; used primarily by the petroleum industry to determine the resistivity of the 3- to 5-inch zone affected by drilling muds.

Method	Description	Hydrogeologic Applications
Dipmeter	Includes a variety of wall-contact microresistivity probes; electrodes are on pads located 90 or 120 degrees apart and oriented with respect to magnetic north by a magnetometer in the probe.	Probably the best instrument for gathering information on the location and orientation of primary sedimentary structures over a wide variety of hole conditions; provides data on the strike and dip of bedding planes also on fractures (less precise).
Induced Polarization (IP)	Probe measures response of formation to an injected current (see Section 3.5). Requires water-filled hole.	Used to measure clay content and pore fluid chemistry and reactivity.
Hole-Hole/Hole-Surface Resistivity	Numerous configurations of source and receiver electrodes are possible.	Allows three-dimensional modeling of resistivity data to characterize subsurface inhomogeneities.
Cross-Well AC Voltage	A low frequency alternating current is introduced into the fracture system of 2 wells and the voltage between the currents and observation wells is measured.	Used to characterize the spatial variation in subsurface fracture systems (Robbins and Hayden, 1988)
<u>Electromagnetic Logs</u>		
Induction (dual induction, slimhole EM probe, borehole conductivity meter)*	Probe contains two coils: one for transmitting an alternating current into the surrounding rock, and a second for receiving the return signal; measures conductivity.	Designed for use in boreholes with no conductive material between the probe and the formation (oil-based drilling muds and air); generally not suitable for wells containing fresh water.*
Microwave sensing	A variety of methods use microwaves for sensing the subsurface single and cross-borehole radar (similar to GPR); dielectric log using continuous pulse microwave.	Pulsed microwave systems similar to applications for GPR (see Section 6.1); dielectric log has been used to measure the thickness of hydrocarbons floating on ground water (Holbrook, 1988).
Nuclear Magnetic Resonance	Similar to proton precession magnetometer, except response of protons in subsurface water is measured.	Measurement of porosity, moisture content, pore-size distribution, available water. Near-surface applications most common (see Section 7.3.1).
Surface-Borehole CSAMT	Similar to surface CSAMT (Section 4.5), except that borehole sensors are used.	Potential for mapping of subsurface conductive zones and three-dimensional characterization of fracture zones in deep boreholes.

* The recently developed EM39 induction logging tool is suitable for use in freshwater wells (McNeill et al., 1990).

Source Adapted from Keys (1990), Rehm et al. (1985), and Wheatcraft et al. (1986).

is more commonly used to measure soil moisture content in the near surface than for hydrogeologic investigations because a large diameter (minimum of 7 inches) is required for borehole logging.

7.3.2 Nuclear Logging Methods

Nuclear logging includes all methods that either detect the presence of unstable isotopes or create such isotopes in the vicinity of a borehole. Table 7-6 describes six types of nuclear logs, and Table 7-11 provides an index of references using these methods. Each type is potentially useful in hydrogeologic studies of the vadose and/or saturated zones because none require conductive media, as do most electrical logging methods. Most of these nuclear logs also allow quantitative interpretation of bulk density, porosity, salinity, and unsaturated moisture content. All of them are widely used in the petroleum industry, and neutron logs have been widely used in the study of soils. Gamma and neutron logs are probably the most common nuclear methods used in ground-water studies. Gamma spectrometry, gamma-gamma, and neutron activation have been used less frequently and should probably be considered more often. Nuclear logging tools with active radioactive sources require careful adherence to procedures for protecting the health and safety of users; their use is prohibited or restricted in some states.

7.3.3 Acoustic and Seismic Logging Methods

Table 7-7 provides information on three types of acoustic logs and various types of borehole seismic methods. Acoustic logging tools incorporate the signal source and the receiver on the same probe and are used in single boreholes. They are especially valuable for characterizing secondary porosity and fractures. Borehole seismic methods can use various surface-borehole or borehole-borehole source and geophone/hydrophone configurations. They are used primarily for stratigraphic, fracture, and geotechnical characterization. Table 7-12 provides an index of references related to acoustic and seismic methods.

Table 7-6 Summary of Nuclear Borehole Logging Methods in Hydrogeologic Studies*

Method	Description	Hydrogeologic Applications
Gamma (natural gamma)	Records total natural gamma radiation (primarily from K-40, U-238, and Th-232) from a borehole that is within a selected energy range.	The most commonly used nuclear log in ground-water applications; used for identification of lithology (clay and shale particularly) and stratigraphic correlation.
Neutron	Probe contains a source of neutrons and detectors that record neutron interactions in the vicinity of the borehole.	Widely used to measure saturated porosity and moisture content in the unsaturated zone; can also be used for lithology and stratigraphic correlation.
Gamma-Gamma (density)	Records the radiation at a detector from a gamma source in the probe after it is attenuated and scattered in the borehole and surrounding rock.	Primarily used to determine bulk density, porosity, and moisture content; distinguishes lithologic units; extensively used in the petroleum industry less frequently used for ground-water applications.
Gamma Spectrometry (spectra(l)-, spectro-, spectronomic-gamma)	Records the amount and energy level of gamma photons either on a continuous basis or at selected depths with a stationary probe. Types and amounts of radioisotopes can be measured.	Allows more precise identification of lithology than gamma log; permits identification of artificial radioisotopes that might be contaminating water supplies; widely used by petroleum industry should probably be used more frequently in ground-water investigations.
Neutron Activation (activation, thermal neutron)	Uses neutrons to "activate" stable isotopes in the borehole and identify the activated element by measuring the amount and energy level of emissions (see gamma spectrometry above).	Permits remote identification of elements present in the ground water and adjacent rocks; relatively new technique with potential for wide application in ground-water hydrology.
Neutron Lifetime (pulsed-neutron decay)	Uses a pulsed-neutron generator and a synchronously gated neutron detector to measure the rate of decrease of neutron population.	Used to measure salinity and porosity; can provide useful data through casing and cement; used by petroleum industry to date applications in ground water have been limited.

* Computerized axial tomography using x-rays and gamma rays has been tested in the laboratory, but not adapted for use in boreholes-see Section 7.2.3.

Source: Adapted from Keys (1990).

Table 7-7 Summary of Acoustic and Seismic Borehole Logging Methods in Hydrogeologic Studies

Method	Description	Hydrogeologic Applications
Acoustic Velocity (sonic, transmit time)	Records the travel time of an acoustic wave from one or more transmitters to receivers in the probe.	Useful for providing information on lithology and porosity, limited to consolidated materials in fluid-filled boreholes beginning to be more widely used in ground-water studies.
Acoustic Waveform (variable density, three-dimensional velocity, full waveform sonic)	Received acoustic signals are recorded digitally, or photographically using oscilloscope displays; the wave forms are analyzed (e.g., amplitude changes, velocity ratios).	Provides information on lithology and structure, various elastic properties can be determined; vertical compressibility of an aquifer can be estimated; fractures can be characterized. Not yet widely used in hydrogeologic studies.
Acoustic Televiewer (seisviewer)	An ATV probe uses a rotating transducer that serves as both transmitter and receiver of high frequency acoustic pulses. An oscilloscope and light-sensitive paper are used to create a 360 degree scan of the borehole wall.	Provides high-resolution information on the location and character of secondary porosity, such as fractures and solution openings; can also provide the strike and dip of fractures and bedding planes; not yet used extensively in ground-water studies because of cost and complexity.
Surface-Borehole Seismic (vertical seismic profiling/ VSP, uphole/ downhole)	Various configurations of surface and borehole geophone and seismic source arrays are possible.	VSP: detection of lithologic boundaries, fracture detection, estimation of permeability and hydraulic conductivity Uphole/Downhole:characterization of geotechnical properties.
Cross-Hole Seismic (cross-hole shear; cross-hole VSP)	Various configurations in which both seismic source and geophones are placed in boreholes.	Stratigraphy, porosity, fracture characterization, cavity detection, measurement of soil dynamic properties.
Geophysical Diffraction Tomography	Tomographic imaging principles applied to seismic data. Three configurations are possible for the seismic source: borehole-borehole, surface-borehole, and surface-to boreholes.	High-resolution possible; can detect isolated inclusions, lithologic boundaries, homogeneous areas.

7.4 Miscellaneous Logging Methods

7.4.1 Lithologic and Hydrogeologic Characterization Logs

Table 7-8 describes seven types of logs that may be useful for characterizing lithology and hydrogeology. Caliper logs have numerous variants but all are intended to measure borehole diameter. They provide essential data for interpreting other types of logs that are affected by variations in borehole diameter, and also generate some data on lithology and seeondary porosity. Fluid **temperature** can be measured as a gradient (also called thermal resistivity), or changes measured over time at one or more points can be tracked (as when injected water of a different temperature is used as a tracer). Chapter 6 (Section 6.4.2) contains further discussion of borehole temperature logging and Table 6-4 lists over 20 references on use of temperature logging.

Fluid flow measurements can locate zones of high permeability (fractures and solution porosity) and areas of leakage in artesian wells. The development of thermal and electromagnetic borehole flowmeters that can sense water movement either vertically or horizontally (or both) at very low velocities has greatly enhanced the ability to characterize variations in hydraulic conductivity in boreholes (see Table 7-13). Borehole **television** cameras have the advantage of allowing visual inspection of a borehole for such things as fracture detection and monitoring well integrity. Morahan and Dorrier (1984) describe the uses of television borehole logging in ground-water monitoring programs.

Borehole **magnetometers** operate on the same principles as surface magnetometers (Section 6.2). Magnetometer probes can be especially useful when drilling is required in areas where the presence of buried ferrous metal wastes is suspected. In such situations, lowering the probe to the bottom of the hole approximately every 5 feet may provide advanced warning of the presence of buried drums that are outside the detection limit of surface instruments.

Borehole gravity is probably the least commonly used borehole method in contaminated site and hydrogeologic applications, and its use has been reported only infrequently (Table 7-13).

Table 7-8 Summary of Miscellaneous Borehole Logging Methods in Hydrogeologic Studies*

Method	Description	Hydrogeologic Applications
Caliper	A probe that measures borehole diameter; many types are available mechanical, electrical, acoustic, one to four arms.	Provides some information on lithology and secondary porosity; essential to guide the interpretation of other types of logs that are affected by borehole diameter.
Fluid Temperature	Temperature probes are used to record temperature or the rate of change in temperature vs. depth (see Section 6.4.2)	Widely used in ground-water studies for information on movement of natural or injected water, permeability; distribution, and relative hydraulic head.
Flowmeters (mechanical/spinner log, thermal, electromagnetic)	Flow measurement with logging probes most commonly is done mechanically with an impeller flowmeter; thermal and EM flowmeters are relatively recent developments that allow more precise readings.	Used to measure vertical flow in boreholes, locate intervals of leakage in artesian wells, identify fractures producing and accepting water, locate zones of high permeability; one of the most useful logging methods available for the study of ground water.
Single-Borehole Tracing	Various methods (injector-detector, injection-withdrawal, borehole dilution) measure direction and speed of water movement using tracers.	Similar to flowmeters (above).
Television/ Photography	Borehole television and cameras allow visual inspection of borehole both sidewards and downwards.	Information on frequency, size, and orientation of fractures; vertical correlation of rock cores where voids are present; inspection of monitoring well integrity.
Magnetic	Probes operating on same principles as surface magnetometers.	Changes in lithology; check for buried ferrous metal containers in boreholes before the next depth increment is drilled.
Gravity	Microgravity instrumentation designed for borehole use.	Complements surface gravity data for structural and stratigraphic interpretation.

* See Section 7.4.2 for discussion of well construction logging methods.

Sources: Adapted from Keys (1990) and Wheatcraft et al. (1986).

7.4.2 Well Construction Logs

Well construction logging is useful for planning cementing operations, installing of casing and screens, performing hydraulic testing, and guiding the interpretation of other logs (Keys, 1990; Nielsen and Aller, 1984). The major types of well construction logs are casing logs, for locating cased intervals in wells; cement and gravel pack logs, for locating cement and gravel pack in the annular space outside a casing; and borehole deviation logs, for determining whether a well deviates from the vertical.

A number of specific borehole logging methods can be used for well construction logging (see Table 7-2). Most electric logs and gamma-gamma logs will show a sharp deflection at the bottom of steel casing. High-resolution caliper logs are excellent for locating threaded couplings, the bottom of the inside string of casing, and, sometimes, corroded steel casing.

A caliper log made before the casing is installed is helpful for planning the cementing or installation of gravel pack. Temperature logs can locate cement grout while it is still warm from chemical reactions during curing. A special type of acoustic log called a **cement bond log** can be used to determine the location of cement behind the casing and, under some conditions, the quality of the bonding to easing and rock.

The deviation of boreholes and wells from the vertical is common. While this tendency is not commonly measured by water well loggers, it may be important for ensuring the proper functioning of logging probes and accurate interpretation of log data. Augered boreholes less than 100 feet deep reportedly have deviated such that transmittance logs between boreholes have been adversely affected (Keys 1990). Single-shot probes that provide one measurement of the deviation angle and azimuth at a predetermined depth are the least expensive method for obtaining borehole-deviation information. The disadvantage is that the probe must be brought to the land surface and reset after each measurement.

Table 7-9 Index for General References on Borehole Geophysics

Topic	References
Bibliographies	Prenksy (various dates), Rehm et al. (1985), Taylor and Dey (1985), University of Tulsa (1985), van der Leeden (1991)
Glossary	Society of Professional Well Log Analysts (1985)
s/R	
General	Dresser Atlas (1974, 1982), Ellis (1987), Guyed and Shane (1969), Hamilton and Myung (1979), Hallenberg (1983), Hearst and Nelson (1985), Helander (1983), Kelly (1969), LeRoy et al. (1987), Labo (1987), Lynch (1962), Nelson (1985), Scott and Tibbets (1974), Serra (1984a), Telford et al. (1990), Tittman (1986)
Log Interpretation	Asquith and Gibson (1982), Birdwell Division (1973), Dresser Atlas (1975, 1979, 1982), Doveton (1986), Foster and Beaumont (1990), Hallenberg (1984), Hilchie (1982a,b), Pirson (1963, 1983), Rider (1986), Schlumberger (1972, 1974, 1989a,b, 1991), Serra (1984b), SPWLA (1979), Tearpock and Bischke (1991), Wyllie (1963)
Imaging/Tomography	Borehole Imaging: Lines and Scale (1997), SPWLA (1990-borehole imaging); Tomography: Davis (1989), Desaubies et al. (1990), Stewart (1991), Lines and Scales (1987), Tweeton (1988)
Quality Control	Bateman (1985), Theys (1991)
Borehole Logging Symposia	Canadian Well Logging Society (various dates), Killeen (1985), Minerals and Geotechnical Logging Society (1985-89), NWWA (1984, 1985, 1986), SPWLA (1960 to present), Thomas and Dixon (1989)
Ground-Water Applications	
Texts/Reports	Bennett and Patten (1960), Emerson and Webster (1970), Hodges and Teasdale (1991), Johnson (1968), Jorgenson (1989), Keys (1990), Keys and MacCary (1971), Patten and Bennett (1963), Respold (1989), Taylor and Dey (1985), Technos (1992)
Ground-Water Texts with Sections on Borehole Geophysics	Beesley (1986), Bureau of Reclamation (1981), Brown et al. (1983), Campbell and Lehr (1973), Davis and DeWiest (1966), Driscoll (1986), Everett (1985), Kovács et al. (1982), Redwine et al. (1985), Rehm et al. (1985), U.S. Army Corps of Engineers (1979)

Table 7-9 (cont.)

Topic	References
Ground-Water Abdications (cont.)	
Contaminated Site Texts	Taylor et al. (1990), Technos (1992), U. S. EPA (1987, 1993), Wheatcraft et al. (1986)
Review Papers	Benson (1991), Collier and Alger (1988), Crowder and Irons (1989—economic considerations), Darr et al. (1990), Dickinson et al. (1987), Evans (1970), Johnson (1968), Jones and Buford (1951), Jones and Skibitzke (1956), Keys (1967a,b, 1968), Linck (1963), Mickam et al. (1984), Nelson (1982), Paillet (1989a), Pfannkuch (1966), Pickett (1970), Segesman (1980), Stegner and Becker (1988), Stowell (1989a,b), Taylor (1989), Taylor et al. (1985)

Table 7-10 Index for References on Electric and EM Borehole Logging Methods

Topic	References
Texts	Dakhnov (1962), Guyed (1952, 1957a, 1958, 1965), Guyed and Pranglin (1959), Hilchie (1979), Kaufman and Keller (1989—induction), Patten and Bennett (1963), Ross and Ward (1984); Bibliography Johnson and Gnaedinger (1964)
ER/EM Tomography	Daily and Owen (1991), Dines and Lytle (1979, 1981), Sandberg et al. (1991); see also Table 7-9
Electrical	
Electric Logs	Baffa (1948), Barnes and Livingston (1947), Collier (1989a—resistivity log selection), Croft (1971), Greenhouse et al. (1985), Guyed (1957b, 1965, 1966), Guyod and Pranglin (1959), Hanson (1967), Ineson and Gray (1963), Jones and Buford (1951), Kwader (1985), Lindsey (1985), Lytle et al. (1979), MacCary (1971), Michalski (1989), Patton and Bennet (1963), Peterson and Lao (1970), Poland and Morrison (1940), Pryor (1956), Roy (1975), Turcan (1962, 1966), Turcan and Winslow (1970), Walstrom (1952); Focused Resistivitv: Moran and Chemali (1985), Roy (1982); Interpretation: Alger (1966-fresh water), Atkins (1961), Carter (1966)
Self-Potential	Frimpter (1969), Gonduin and Scale (1958), Kendall (1965), Morris (1957), Vonhof (1966)
Fluid Conductivity	Emilsson and Arnott (1991), Michalski et al. (1992), Pedlar et al. (1990, 1992), Sutcliffe and Joyner (1966), Tellam (1992), Tsang and Hufschmied (1988), Tsang et al. (1992), Williams and Conger (1990)
Dipmeter	Bigelow (1985)
Borehole-Surface Resistivity/IP	Asch and Morrison (1989), Asch et al. (1986-contaminated site), Bevc and Morrison (1991), Daniels (1977, 1983), Le Masne and Poirmeur (1988), Olhoeft and Scott (1980-complex resistivity), Poirmeur and Vasseur (1988), Wilt and Tsang (1985a,b)
Cross-Well Resistivity	Daily and Owen (1991—tomography), Robbins and Hayden (1988)
Electromagnetic	
Review	Dyck (1991)
EM (Induction) Logs	Snelgrove and McNeill (1985), McNeill (1986, 1989), McNeill and Bosnar (1988), McNeill et al. (1990), Peterson (1991), Taylor and Wheatcraft (1986), Taylor et al. (1988, 1989), Wyllie (1960)

Table 7-10 (Cont.)

Topic	References
Electromagnetic (cont.)	
Cross-Borehole Radar	Davis et al. (1984), Dines and Lytle (1979, 1981), Holser et al. (1972), Leckenby (1982), Lytle et al. (1979, 1981), Olhoeft (1988), Olhoeft et al. (1992), Sandberg (1991), Wright et al. (1984)
Nuclear Magnetic Resonance	Abragam (1961), Jackson (1984), Keys (1990), Morrison (1983), Schlichter (1963)
Other EM Methods	Borehole CSAMT. West and Ward (1988); Dielectric Collier (1989b), Freedman and Vogiatzis (1979), Keech (1988), Serra (1984a); Disposable E Log: Greenhouse et al. (1985)

Table 7-11 Index for References on Nuclear Logging Methods

Topic	References
General	
Texts	Belcher et al. (1952), Gardner and Roberts (1967), Guyod (1965), IAEA (1968, 1971), Killeen (1982—gamma), Morrison (1983), Patten and Bennett (1963), SPWLA (1978a); Protection: Blizard (1958), U.S. Nuclear Regulatory Commission (1985)
Review Papers	Baffa (1948), Duval (1980, 1989), Ellis (1990), Keys (1967a), Russell (1941); Bibliography; Johnson and Gnaedinger (1964); Protection: Fujimoto et al. (1985)
Specific Logging Methods	
Gamma	Guyed (1965, 1966), Ellis (1990), Killeen (1982), Killow (1966), Lee et al. (1984), Norris (1972), Markstrom (1992), Mickam et al. (1984), Rabe (1956), Reed (1985), Wahl (1983), Woodyard (1984)
Gamma-Gamma (Density)	Ellis (1990), Newton et al. (1954), Pickell and Heacock (1960), Poeter (1987, 1988-neutron, gamma-gamma), Scott (1977), Tittman and Wahl (1965), Yearsley et al. (1990a, 1991)
Gamma Spectrometry	Text: Adams and Gasparini (1970); Other: Ellis (1990), Quirein et al. (1982), Rutkowski and Taylor (1990), Schneider (1982), Serra et al. (1980), Stromswold and Wilson (1981), Taylor (1986), Thomas and Dixon (1989)
Neutron	Bleakley et al. (1965), Jones and Schneider (1969), MacCary (1971), Meyer (1962), Poeter (1987, 1988), Reed et al. (1983-vadose zone), Senger (1985), Schimschal (1981), Teasdale and Johnson (1970), Tittman et al. (1968), Tittle (1961). U.S. EPA (1993) provides an index of over 90 references on neutron logging for moisture measurement.
Neutron Lifetime	Thornhill and Benefield (1990, 1992)
Radioactive Tracers	Moltyaner (1989), Wiebenga et al. (1967)

Table 7-12 Index for References on Acoustic and Seismic Logging Methods

Topic	References
<u>Acoustic Logs</u>	
General	Guyed and Shane (1969), SPWLA (1978b),
Acoustic Velocity/ Waveform	Haase and King (1986), Paillet and White (1982), Paillet et al. (1986), Pickett (1960), Thornhill and Renefield (1990), Yearsley et al. (1990b, 1991)
Acoustic Televiewer	Collier and Ridder (1992), Haase and King (1986), Kierstein (1984), Pailett et al. (1985), Schaar (1992), Thomas and Dixon (1989), Westphalen (1991), Williams and Conger (1990), Zemanak et al. (1969, 1970)
Water Levels	Alderman (1986), Ritchey (1986)
<u>Borehole Seismic Methods</u>	
Seismic Profiling (VSP)	Texts: Balch and Lee (1984), Gal'perin (1979), Hardage (1985), Toksoz and Stewart (1984); <u>Papers</u>: Beydoun et al. (1985), Carswell and Moon (1989), Cybriwsky et al. (1984), Hennon et al. (1991), Imse and Levine (1985), King et al. (1989), Levine et al. (1984), Majer et al. (1988), Paillet et al. (1986), Stewart et al. (1981), Streitz (1987), Suprahitho and Greenhalgh (1986)
Cross-Hole Seismic	<u>Cross-Hole Shear</u>: Bates et al. (1991), CH2M Hill (1991), Hoar and Stokoe (1977), Stokoe (1980), Stokoe and Nazarian (1985), Woods (1978), Woods and Stokoe (1985); <u>Other Cross-Hole</u>: Bois et al. (1972), Butler and Curro (1981), Jackson et al. (1992), Jessop et al. (1992), McCann et al. (1986), Pratt and Worthington (1988)
Diffraction Tomography	Anderson and Dziewonski (1984), Bates et al. (1991), Devaney (1984), Jackson et al. (1992), Jessop et al. (1992), King and Witten (1989, 1990), Mahannah et al. (1988), Pratt and Worthington (1988), Tweeton (1988), Tweeton et al. (1991), Tura et al. (1992), Wong (1991), Wu and Toksoz (1987); see also Table 7-9

Table 7-13 Index for References on Miscellaneous Logging Methods

Topic	References
Flow Measurement	
Borehole Dilution	Dexter and Kearly (1988), Halevy et al. (1967), Leap and Kaplan (1988), McLinn and Palmer (1988, 1989), Taylor et al. (1988)
Brine Tracing	Williams et al. (1984), Patten and Bennett (1962), Yearsley et al. (1990b)
Thermal Flowmeters	Chapman and Robinson (1962), Guthrie (1986), Hess (1982, 1984, 1986, 1989), Hess and Paillet (1989), Kerfoot (1982, 1984, 1988, 1992), Kerfoot and Kiely (1989), Kerfoot et al. (1991), Melville et al. (1985), Molz et al. (1990), Paillet (1989b), Paillet et al. (1987), Williams and Conger (1990), Rehfeldt (1989)
EM Flowmeter	Young and Waldrop (1989), Young and Pearson (1990)
Mechanical Flowmeters	Erickson (1946), Fiedler (1928), Hess and Wolf (1991), Molz et al. (1989), Patten and Bennett (1962), Syms (1982)
Other Methods	
Temperature	See listing for Borehole Temperature Logging in Table 6-4.
Caliper	Edwards and Stroud (1966), Hilchie (1982), Lattman and Parizek (1964), Mickam et al. (1984), Lee et al. (1987), Parizek and Siddiqui (1970), Sutcliffe and Joyner (1966), Syms (1982)
Borehole Cameras	Jensen and Ray (1965), Johnson and Gnaedinger (1964-bibliography), Mullins (1966), Sturges (1967), Trainer and Eddy (1964-borehole periscope)
Borehole Televison	Briggs (1964), Callahan et al. (1963), Gernand (1991), Gorder (1963), Huber (1982), Kearl et al. (1992-colloidal horoscope), Lloyd (1970), Michalski et al. (1992), Morahan and Dorrier (1984), Thomas and Dixon (1989), Zemanek et al. (1969, 1970)
Borehole Gravity	Head and Kososki (1979), Hearst and Carlson (1982), Labo (1987), Robbins (1986)
Magnetic Susceptibility	Scott et al. (1981)

Table 7-14 Index for References on Applications of Borehole Geophysics in Hydrogeologic and Contaminated Site Investigations

Topic	References
Contaminated Site Applications	
Case Studies	Adams et al. (1983), Adams et al. (1988), Asch et al. (1986), Crowder and Irons (1988), Crowder et al. (1987), Davison et al. (1982-nuclear waste storage), Dearborn (1988), DiNitto (1983), Deluca and Buckley (1985), Hess et al. (1984), King et al. (1989—buried wastes), Michalski (1989), Mahannah et al. (1988), Michalski et al. (1992), Montgomery et al. (1985), Olhoeft et al. (1992-DNAPL spill), Poeter (1988), Ring and Sale (1987), Robbins (1986), Tests (1988), Rutkowksi and Taylor (1990-radioactive contamination), Sciacca (1991), Schneider and Greenhouse (1992), Sloto et al. (1992), Turner and Black (1989), Tweeton et al. (1991—in situ mining leachate), U.S. EPA (1987), Westphalen (1991), Wheatcraft et al. (1987), Williams and Conger (1990), Wilt and Tsang (1985)
Ground-Water Monitoring	Morahan and Dorrier (1984), Voyteck (1982)
Lithologic Characterization	
Fractured Rock	Adams et al. (1988), Bates et al. (1991), Beydoun et al. (1985), Brother et al. (1990), Carswell and Moon (1989), ColIier and Ridder (1992), Cybriwsky et al. (1984), Dearborn (1988), DeLuca and Buckley (1985), Haase and King (1986), Havranek and Smith (1989), Hess (1984, 1986), Hess and Paillet (1989), Holzhausen and Egan (1986), Howard ***et*** al. (1986), Imse and Levine (1985), Jones et al. (1984), Lee et al. (1984), Levine et al. (1984), Majer et al. (1988), Merin (1992), Michalski et al. (1992), Morin and Barrash (1986), Nelson (1985), Paillet (1984, 1989b), Pailett et al. (1985, 1986, 1987), Richardson et al. (1989), Robbins and Hayden (1988), Ross and Ward (1984), Sandberg et al. (1991), Schaar (1992), Silliman et al. (1987), Stewart et al. (1981), Tsang et al. (1992), Tura et al. (1992), Westphalen (1991), Williams et al. (1984), Yearsley et al. (1990b)
Solution Cavities	Bates et al. (1991)
Stratigraphy/Structure	Davis et al. (1984), Potts (1991), Senger (1985-glacial), Sciacca (1991), Spencer (1985)
Lithology	Biella et al. (1983), Norris (1972), Woodward (19841), Wyllie (1960)

Table 7-14 (cont.)

Topic	References
Aquifer Characterization Applications	
Ground-Water Studies	Crosby and Anderson (1971), Dyck et al. (1972), Greenhouse et al. (1990), Hanson (1967), Head and Merkel (1977), Keys and Brown (1971, 1973—artificial recharge), Lee et al. (1984), Heeley and Marshall (1985), MacCary (1983), Mickam et al. (1984), Newman and McDuff (1988), Taylor (1986), Taylor and Wheatcraft (1986), Wrege et al. (1986), Perched Water Table: Poeter (1987, 1988)
Permeability/ Hydraulic Conductivity	Blankennagel (1968-hydraulic testing), Bredehoeft (1964-permeability), Croft (1971), Henrich (1986-transmissive layers), Hess (1989), Hufschmied (1986), Jorgenson (1989), Kwader (1984a), Levine et al. (1984), Morin and Barrash (1986-fracture flow), Paillet et al. (1987), Pedlar et al. (1990), Rabe (1956), Rehfeldt (1989), Schimschal (1981), Sutcliffe and Joyner (1966-packer testing), Taylor et al. (1988), Tsang et al. (1992), Young and Pearson (1990)
Other Hydraulic Properties	Porosity B1eakley et al. (1965), Jorgenson (1989), MacCary (1984a), Pickett (1960), Taylor et al. (1988), Tittman et al. (1966), Worthington (1976); Specific Yield: Johnson (1967), Jones and Schneider (1969), Levine et al. (1984); Other: Bennett and Patten (1960-specific capacity), Diodato and Parizek (1992), Gernand (1991), MacCary (1984b-formation factor), Meyer (1963— storage coefficient), Moltyaner (1989—aquifer parameters)
Water Quality	Alger (1966), Barnes and Livingston (1947), Brown (1971), Guyed (1957, 1966), Kwader (1984b, 1985, 1986), MacCary (1980), Peterson (1991), Poland and Morrison (1940), Poole et al. (1989), Pryor (1956), Turcan (1962, 1966), Turcan and Winslow (1970), Vonhof (1966), Worthington (1976)
Aquifers with High Secondary Porosity	Carbonates: Chombart (1960), Collier (1992), Cregon and Moir (1961), Haase and King (1986), Lee et al. (1984), Head and Merkel (1977), MacCary (1971, 1978, 1980, 1983, 1984a), Parizek and Siddiqui (1970); Basalts Crosby and Anderson (1971), Peterson and Lao (1970)
Well Construction	Jann (1966-borehole alignment), Kendall (1965-corrosion detection), Killow (1966-behind casing flow), Linck (1963), Norris (1972), Yearsley et al. (1990a-monitoring well completion); Casing Detection: Frimpter (1969), Marsh and Parizek (1968), Ross and Adcock (1969) Cement Bond Logs:Bade (1963), Pickett (1966), Upp (1966), Landry (1992), Yearsley et al. (1991); Injection Well Integrity Testing: Nielsen and Aller (1984), Thornhill and Benefield (1990, 1992)

7.5 References

See Glossary for meaning of method abbreviations.

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APPENDIX A

CASE STUDY SUMMARIES FOR SURFACE AND BOREHOLE GEOPHYSICAL METHODS

This appendix provides summary information on case studies involving the use of surface (Table A-1) and borehole (Table A-2) geophysical methods at contaminated sites. The following information is provided for each reference: (1) location (if specified), (2) contaminants involved, (3) geology and depth to water table, where given, (4) geophysical methods used and (5) citation. Six geophysical methods are listed in the methods column: SR (seismic refraction), ER (electrical resistivity), EMI (electromagnetic induction), GPR (ground penetrating radar), M (magnetics), and G (gravity). An "x" is placed in the appropriate column for each method used at the site. If other methods were used the name of the method is provided in the space available.

The case studies are listed in alphabetical order by author (last column), and reference citations immediately follow each table. Only geophysical applications at contaminated sites are included in this appendix. Other references on the use of surface geophysical methods for geologic and hydrogeologic investigations can be found in the index reference table in the chapter that covers the method of interest.

Table A-1 Ground-Water Contamination Case Studies Using Surface Geophysical Methods

Location	Contaminant	Geology	Methods SR	ER	EMI	GPR	M	G	Reference
Central Maryland	LUST (fuel oil and gasoline)	Alluvial aquifer (l0-35 ft) over fractured gneiss	x	x	x				Adams et al. (1988)
Metamora landfill, Michigan (Superfund)	Buried drums, heavy metals and organics	300 ft of complex glacial deposits over sandstone aquifer	x	x			x		Allen and Rogers (1989)
New Jersey	Sodium chromate and sodium hydroxide	115 ft sand aquifer over clay		x					Berk and Yare (1977)
Easton, Pennsylvania	Siting of ash disposal impoundment	Alluvial and glacial outwash over karst	x						Blackey and Stoner (1988)
Northeast Illinois	4 sanitary landfills	Various unconsolidated glacial and outwash deposits		x ThermaI					Cartwright and McComas (1968)
North Bay, Ontario	Landfill leachate	30-45 ft of glaciolacustrine silty sands over igneous				x			Cosgrave et al. (1987)
Southern New Jersey	Landfill leachate	Sand and gravel aquifer	x		x				Emilsson and Wroblewski (1988)
Various unspecified locations	Buried wastes, landfill leachate	Unconsolidated material	x	x	x	x	x		Evans and Schweitzer (1984)
Wilsonville, Illinois	Buried drums with hazardous wastes	90 ft of glacial till over shale					x		Gllkeson et al. (1986)
Las Vegas, Nevada	Hydrocarbon spill	Alluvium, water table 0-30 ft		x	x				Glaccum et al. (1983)
Borden, Ontario	Landfill leachate	90 ft sand aquifer		x	x				Greenhouse and Harris (1983)
Morns County, New Jersey	Industrial waste (VOCs and iodide)	8-60 ft glacial sands, silts, and clays over gneiss	x		x				Hall and Pasicznyk (1987)
West Kensington landfill, Rhode Island	Landfill Ieachate	Sand and gravel aquifer		x					Kelly (1976)
Northeastern Ohio	Oil-field brine	Sandstone aquifer		x	x				Knuth (1988)
Clarion, Clinton, and Butler Counties, PA	Acid mine drainage	Coal strip mine spoils			x				Ladwig (1983)
West Point, Kentucky	Oil-field brine	Sand and gravel aquifer			x				Lyverse (1989)
Monterey County, California	Salt-water intrusion	sand and gravel aquifers 180-500 ft deep			x				Mills et al. (1987)

Table A-1 (cont.)

Location	Contaminant	Gcology	Methods SR	ER	EMI	GPR	M	G	Reference
Southeastern Idaho	Metals manufacturing waste disposal ponds	Fractured and faulted basalt aquifer			x				Morgenstern and Syverson (1988)
Reno, Nevada	Saline water	Volcanic lavas and tuffs ground water at 250 ft			x				Ringstad and Bugenig (1984)
Tippecanoe County, Indiana	Landfill Ieachate, buried metals	Clay-rich glacial till over sand and gravel aquifer	x	x	x	x	x	x	Roberts et al. (1989)
Braccbridge, Ontario	Landfill leachate (TCE contamination)	Glacial sand and gravel over granite	x				x		Rodrigues (1987)
Saukville, Wisconsin	Fly ash Ieachate	Glacial sand and gravel aquifer over dolomite		x					Rogers and Kean (1980)
Northwest Missouri	Landfill leachate	Missouri River floodplain		x	x				Rudy and Caoile (1984)
Eastern North Carolina	Jet fuel leak	Alluvial sands and clays			x				Saunders and Cox (1987)
Newark International Airport, New Jersey	Jet fuel leak	50-75 ft silt, sand, and clay over shale			x				Saunders and Germeroth (1985)
Citrus and Collier Counties, Florida	Saltwater intrusion	Floridan aquifer (carbonate)		x	x				Stewart (1982)
Landfill (unspecified)	Landfill leachate	Not specified			x				Stewart and Bretnall (1986)
Four locations (unspecified)	Industrial waste, landfill leachate	Variable		x					Stellar and Roux (1975)
75 km east of San Francisco, California	Landfill leachate	3-10 ft of soil over sandstone		x	x				Sweeney (1984)
Western Massachusetts	Landfill leachate	sand and gravel aquifer	x	x	x				Walsh (1988)
Utah	Uranium mill tailings	Sandstone			x				White and Gainer (1985)

Table A-2 Ground-Water Contamination Case Studies Using Borehole Geophysical Methods

Location	Contaminant	Geology	Ground-Water Investigation Methods	
Central Maryland	LUST (fuel oil and gasoline)	AlluviaI aquifer (10-35 ft) over fractured gneiss	Caliper, gamma, vertical seismic, borehole camera	Adams et al. (1988)
Rocky Mountain Arsenal, Denver Colorado	Injected hazardous chemicals	Alluvium over inter-bedded sandstone and shale	SP, induced polarization, normal and focused resistivity, neutron, gamma-gamma, gamma, caliper, fluid resistivity, temperature, full waveform sonic	Crowder et al. (1987)
Northeastern Massachusetts (Superfund)	Landfill leachate, organics	Fractured gneiss	Caliper, SP resistance, fluid resistivity & temp., gamma, neutron, ATV	Dearborn (1988)
Florida	Waste-injection monitor well	Sands and clays over limestone at about 1,400 ft	Electric, fluid resistivity, caliper velocity, gamma	Foster and Goolsby (1972)
Albuquerque NM (Superfund)	VOCs	Unconsolidated sands and gravels with beds of silt and clay	Caliper, spinner, brine injection, resistivity, temperature	Ring and Sale (1987)
Arlington, Oregon RCRA facility	—	Interbedded basalts and sedimentary rock, water table at 100-200 ft	Gamma, gamma-gamma, neutron activation	Testa (1988)
Western U.S.	Heavy metal contamination from a gas processing plant.	15-105 ft of alluvial soils over limestone; water table at 480 ft	Dual induction, gamma- and spectro-gamma, neutron	Turner and Black (1989)
Northeast U.S.	Vocs	Glacial deposits over crystalline bedrock	Caliper, SP, SP resistance, gamma, gamma-gamma, neutron, ATV, temperature	Westphalen (1991)
New York	TCE, PCE	(1) Mesozoic sediments, (2) Precambrian metamorphic rocks	Caliper, SP resistance, fluid resistivity, gamma, ATV, temperature, thermal flowmeter	Williams and Conger (1990)

Table A-2 Ground-Water Contamination Case Studies Using Borehole Geophysical Methods

Location	Contaminant	Geology	Ground-Water Investigation Methods	
Central Maryland	LUST (fuel oil and gasoline)	Alluvial aquifer (10-35 ft) over fractured gneiss	Caliper, gamma, vertical seismic, borehole camera	Adams et al. (1988)
Rocky Mountain Arsenal, Denver Colorado	Injected hazardous chemicals	Alluvium over inter-bedded sandstone and shale	SP, induced polarization, normal and focused resistivity, neutron, gamma-gamma, gamma, caliper, fluid resistivity, temperature, full waveform sonic	Crowder et al. (1987)
Northeastern Massachusetts (Superfund)	Landfill leachate, organics	Fractured gneiss	Caliper, SP resistance, fluid resistivity & temp., gamma, neutron, ATV	Dearborn (1988)
Florida	Waste-injection monitor well	Sands and clays over limestone at about 1,400 ft	Electric, fluid resistivity, caliper velocity, gamma	Foster and Goolsby (1972)
Albuquerque NM (Superfund)	VOCs	Unconsolidated sands and gravels with beds of silt and clay	Caliper, spinner, brine injection, resistivity, temperature	Ring and Sale (1987)
Arlington, Oregon RCRA facility	—	Interbedded basalts and sedimentary rock, water table at 100-200 ft	Gamma, gamma-gamma, neutron activation	Testa (1988)
Western U.S.	Heavy metal contamination from a gas processing plant.	15-105 ft of alluvial soils over limestone; water table at 480 ft	Dual induction, gamma- and spectro-gamma, neutron	Turner and Black (1989)
Northeast U.S.	VOCs	Glacial deposits over crystalline bedrock	Caliper, SP, SP resistance, gamma, gamma-gamma, neutron, ATV, temperature	Westphalen (1991)
New York	TCE. PCE	(1) Mesozoic sediments, (2) Precambrian metamorphic rocks	Caliper, SP resistance, fluid resistivity, gamma, ATV, temperature, thermal flowmeter	Williams and Conger (1990)

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See glossary for meaning of method abbreviations.

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Williams, J.H. and R.W. Conger. 1990. Preliminary Delineation of Contaminated Water-Bearing Fractures Intersected by Open-Hole Bedrock Wells. Ground Water Monitoring Review 10(4):118-126. [Gamma, SP resistance, caliper, fluid-resistivity, temperature, acoustic televiewer, thermal flowmeter]

APPENDIX B
TECHNICAL INFORMATION SOURCES

This appendix provides (1) the names of individuals who may be able to provide technical assistance in evaluating or selecting geophysical methods at contaminated sites (Section B.1), (2) addresses and phone numbers of organizations that publish journals, symposium proceedings, and other geophysics-related publications (Section B.2), and (3) the addresses of major U.S. Environmental Protection Agency libraries and information on holdings.

B.1 Technical Assistance

Technical assistance on questions concerning use of geophysical methods is available to EPA personnel from a number of EPA laboratories and regional offices:

Environmental Systems Monitoring Laboratory, Las Vegas, NV (Aldo Mazzella, FTS 545-2254; 702/798-2254) (Lary Jack, FTS 545-2367; 702/798-2373)

Region V, Chicago, IL (Mark Vendl, 312/886-0405; Jim Ursic, 312/353-1526)

The following individuals with the U.S. Geological Survey also may be able to answer questions by telephone:

Gary Olhoeft, Denver, CO (303/236-1302)

Peter Haeni, Hartford, CT (203/240-3060)

B.2 Organizations and Journals

American Society for Testing and Materials, 1916 Race Street, Philadelphia, PA 19103-1187 (215/299-5585).

Canadian Well Logging Society (CWLS), 640 5th Avenue S. W., Suite 229, Calgary, Alberta, T2P OM6 (403/269-9366). Publisher of CWLS Journal.

Environmental and Engineering Geophysical Society (EEGS, formerly Society of Engineering and Mineral Exploration Geophysicists), P.O. Box 4475, Englewood, CO 80155 (303/771-6101). Publisher of SAGEEP proceedings and Journal of Applied Geophysics (formerly Geoexploration).

National Ground Water Association (NGWA—formerly National Water Well Association), 6365 Riverside Drive, Dublin, OH, 43017 (800/551-7379). Publisher of Ground Water and Ground Water Monitoring and Remediation (formerly Ground Water Monitoring Review).

National Technical Information Semite (NTIS, U.S. Department of Commerce, Springfield, VA 22161 (800/336-4700). Copies of out-of-print government documents.

Society of Exploration Geophysicists (SEG Book Order Department), P.O. Box 702740, Tulsa, OK 74170-2740 (918/493-3516). Publisher of Geophysics.

Society of Professional Well Log Analysts (SPWLA), 6001 Gulf Freeway, Suite C129, Houston, TX 77023 (713/928-8925). Publisher of Log Analyst.

European Association of Exploration Geophysicists (Journal Subscription Department, Marston Book Services, P.O. Box 87, Oxford UK). Publisher of Geophysical Prospecting.

American Geophysical Union (2000 Florida Avenue, NW, Washington, DC 20009, 202/939-3200). Publisher of Water Resources Research.

The Journal of Hydrology is published by Elsevier Science Publishers (Journal Department, P.O. Box 211, 1000 AE Amsterdam, Netherlands).

B.3 EPA Libraries

Headquarters Library, PM-211A 401 M St. SW, Room 2094, Washington DC 20460; (202/382-5921). 25,000 books/documents, 625 journals, 365,000 microfiche documents.

Region 1 Library/LIB, JFK Federal Building, Boston, MA 02203; (617/565-3300). 22,000 books/documents, 175 journals, 90,000 microfiche.

Region 2 Library, 26 Federal Plaza, Room 402, New York, NY 10278; (212/264-2881). 7,000 books/documents, 50 journals, 155,000 microfiche.

Region 2 Field Office Library, MS-245, 2890 Woodbridge Avenue, Building 209, Edison, NY 08837; (201/321-6762). 8,000 books/documents, 60 journals, 100,000 microfiche.

Region 3 Information Resource Center, 3PM52, 841 Chestnut Street, Philadelphia, PA 19107; (215/597-0580). 24,000 books/documents, 225 journals, 120,000 microfiche.

Region 4 Library, G6, 345 Courtland Street, NE, Atlanta, GA 30365-2401; (404/347-4216). 48,000 books/documents, 220 journals, extensive microfiche collection.

Region 5 Library, 230 Dearborn Street, Room 1670, Chicago, IL 60604; (312/353-2022). 27,000 books/documents, 325 journals, 110,000 microfiche.

Region 6 Library, 1445 Ross Avenue, First Interstate Bank Tower, Dallas, TX 75202-2733; (214/655-6444). 16,000 books/documents, 76 journals, microfiche.

Region 7 Library, 726 Minnesota Avenue, Kansas City, KS 66101; (913/551-7358). 16,000 books/documents, 110 journals, 150,000 microfiche.

Region 8 Library, 8PM-IML, 999 18th Street, Suite 500, Denver, CO 80202-2405; (303/293-1444). No listing of holdings.

Region 9 Library, 75 Hawthorne Street, San Francisco, CA 94105; (415/744-1510). 77,000 books/documents, 250 journals, >450,000 microfiche.

Region 10 Library, MD-108, 1200 Sixth Avenue, Seattle, WA 98101; (206/553-1289). 23,000 books/documents, 150 journals, 95,000 microfiche.

Andrew W. Breidenbach Environmental Research Center Library, 26 West Martin Luther King Drive, Cincinnati, OH 45268-4545; (513/569-7707). 19,000 books/documents, 600 journals, >300,000 microfiche.

Robert S. Kerr Environmental Research Laboratory, P.O. Box 1198, Kerr Lab road, Ada, OK 74820; (405/332-8800). 4,000 books, 60 journals, 76,000 hardcopy/microfiche documents.

National Enforcement Investigations Center Library, Building 53, Box 25227, Denver Federal Center, Denver, CO 80225; (303/236-5122). 2,000 books, 100 journals, numerous microfiche.

Environmental Monitoring Systems Laboratory Library, 944 E. Harmon Avenue, Las Vegas, NV 89119; P.O. Box 93478, Las Vegas, NV 89193-3478; 702(798-2648). Extensive microfiche collection.

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