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

## A Reference Guide

Technology Transfer EPA/625/R-92/O07

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

September 1993

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# Notice

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## 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).

* 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

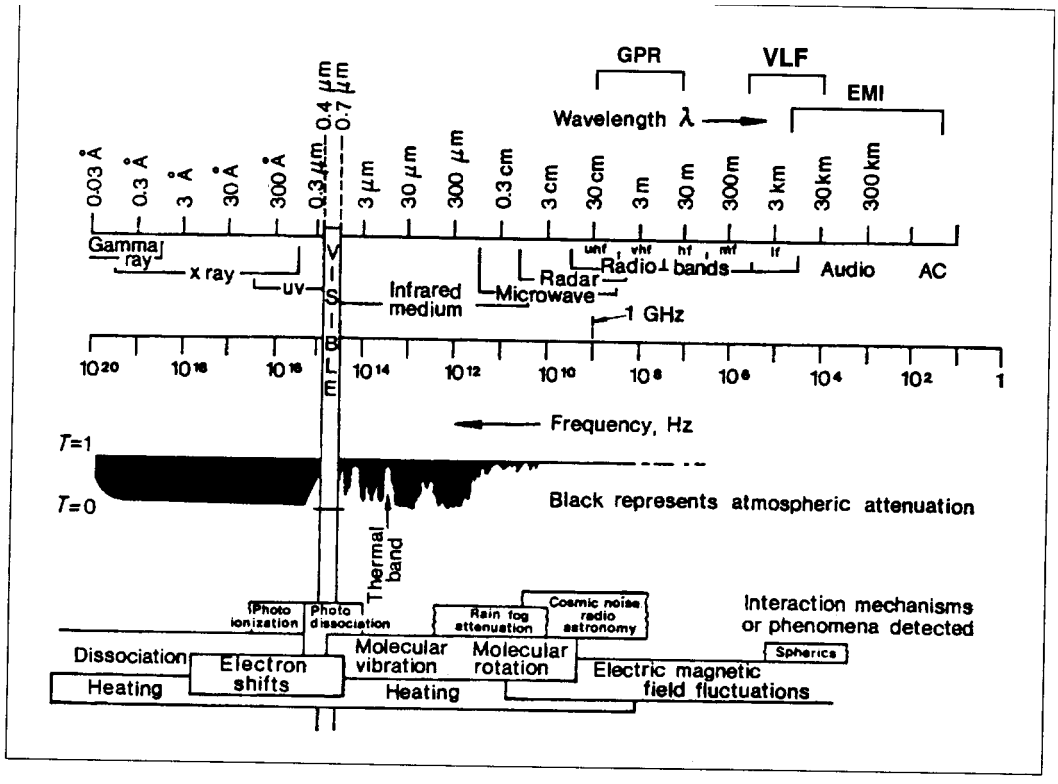


Figure 1-la The electromagnetic spectrum: customary divisions and portions used for geophysical measurements (adapted from Erdé1yi and Gá1fi, 1988).

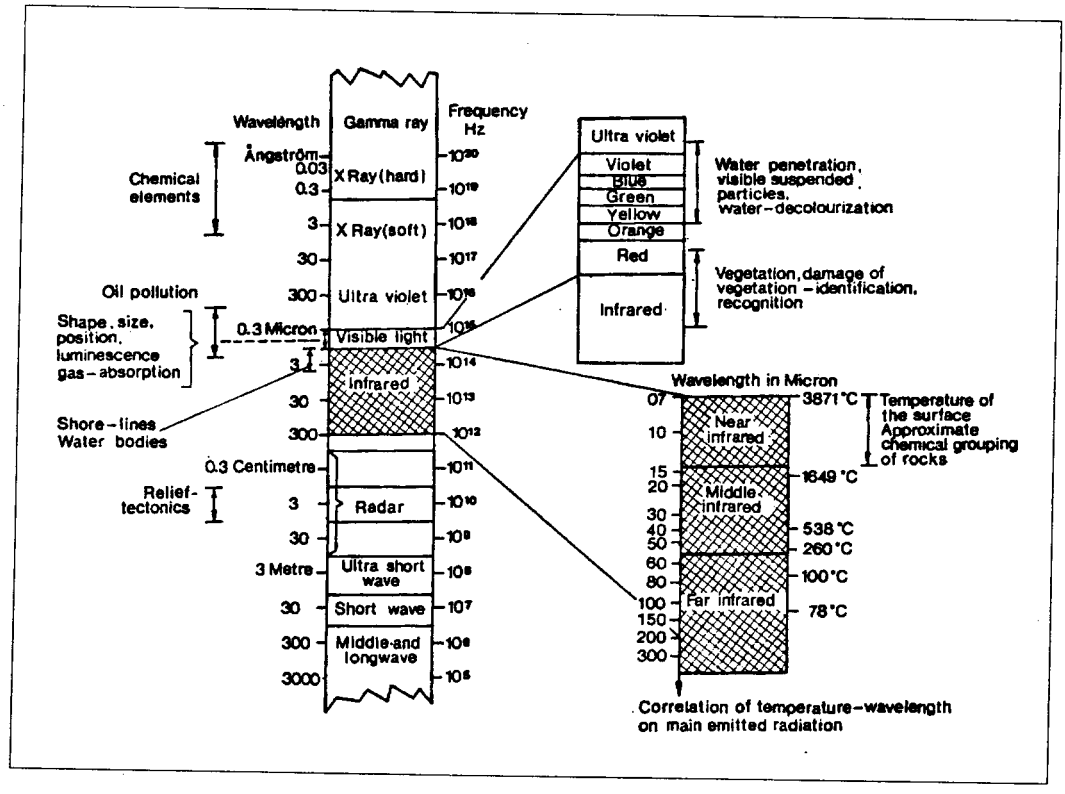


Figure 1-lb The electromagnetic spectrum: factors and phenomena influencing the radiation of electromagnetic waves (adapted from Erdé1yi and Gálfi, 1988).

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)<br>Induced Polarization (IP)<br>Complex Resistivity |
| | Electromagnetic |
| Telluric Current (TC)<br>Magnetotellurics (MT)<br>Audio-Frequency MT (AMT)<br>Audio-Frequency Magnetic (AFMAG)<br>MT Array Profiling (EMAP) | **Electromagnetic Induction** (EMI)<br>Time Domain EM (TDEM)[a]<br>Very Low Frequency (VLF) Resistivity<br>Controlled-Source Audiomagneto-Tellurics (CSAMT)<br>**Metal Detectors** (MD) |
| | Seismic/Acoustic |
| Acoustic Emission Monitoring | **Seismic Refraction** (SRR)<br>Shallow Seismic Reflection (SRL)[a]<br>Continuous Seismic Profiling (CSP)<br>Seismic Shear<br>Spectral Analysis of Surface Waves (SASW)<br>Side-Scan Sonar<br>Fathometer |
| | Other Methods |
| **Magnetometry**<br>Microgravimetry<br>Natural Geothermal[c]<br>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

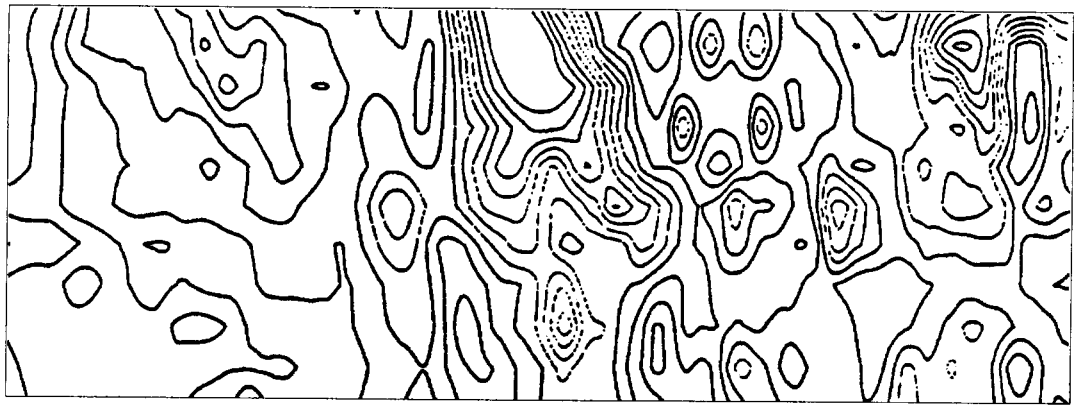

Figure 1-2a Ways of presenting areal geophysical measurements: an isopleth map of electrical conductivity measurement (from Benson et al., 1984a).

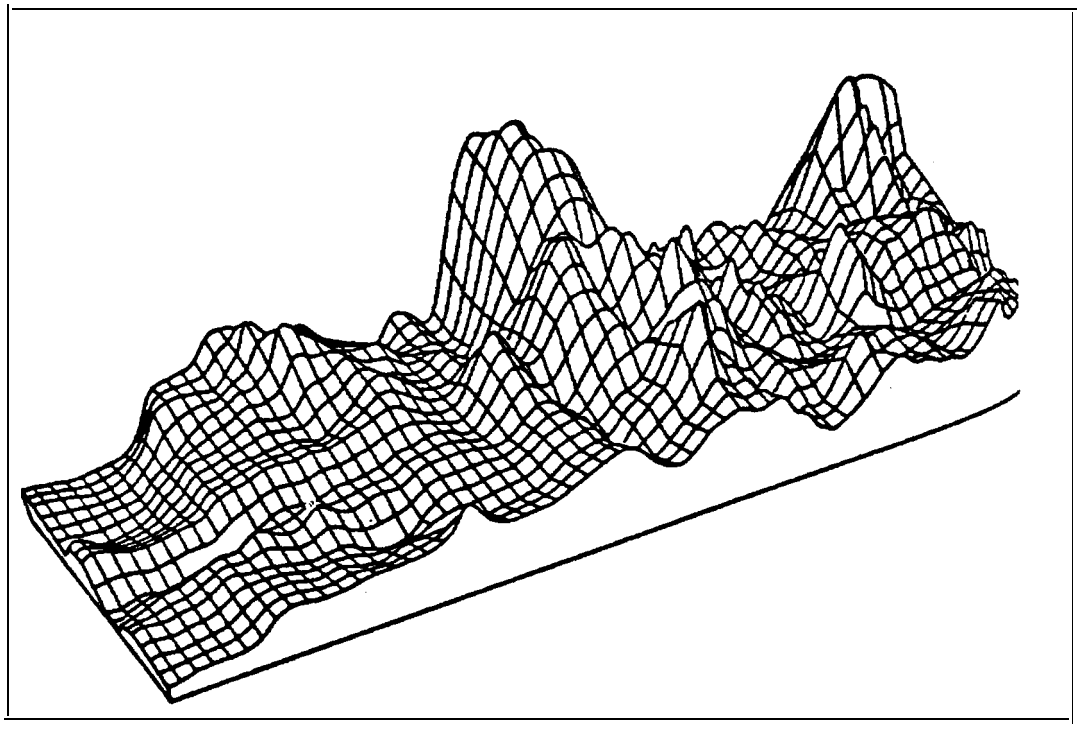

Figure l-2b Ways of presenting areal geophysical measurements: a 3-dimensional view of the data in Figure 1-2a (from Benson et al., 1984a).

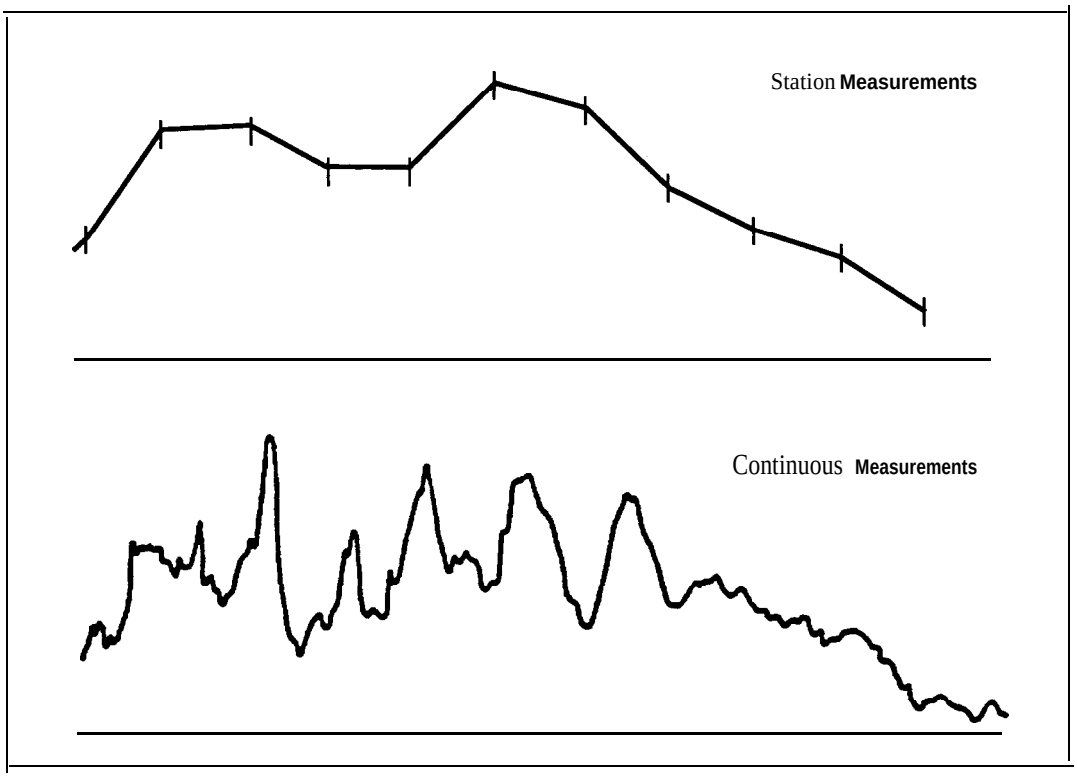


Figure 1-3 Discrete sampling versus continuous geophysical measurements (from Benson et al., 1984a).

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 |
|---|---|
| Texts/RePorts on Contaminated Site Applications | |
| 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 |
|---|---|
| Texts on Geologic and Entineering Applications | |
| 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. |
| Conferences/Symposia | |
| 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 |
|---|---|
| Papers on General Use of Geophysical Methods (cont.) | |
| 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]

Breusee, J.J. 1963. Modern Geophysical Methods for Subsurface Water Exploration. Geophysics 28(4):633-657. [ER]

Cichowicz N.L., R.W. Pease, Jr., P.J. Stellar, and H.J. Jaffe. 1981. Use of Remote Sensing Techniques in a Systematic Investigation of an Uncontrolled Hazardous Waste Site. EPA/600/2-81/l87 (NTIS PB82-103896). [ER, SRR, GPR, MD]

Cleff, R. (ed.). 1991. An Evaluation of Soil Gas and Geophysical Techniques for Detection of Hydrocarbons. API Publication No. 4509, American Petroleum Institute, Washington, DC. [GPR, EMI, ER, complex resistivity]

Collins, A.G. and A.I. Johnson (eds.). 1988. Ground-Water Contamination: Field Methods. ASTM STP 963, American Society for Testing and Materials, Philadelphia, PA, 485 pp. [Includes 5 papers on geophysical methods]

Costello, R.L. 1980. Identification and Description of Geophysical Techniques. USATHAMA Report DRXTH-TE-CR-80084. U.S. Army Toxic and Hazardous Materials Agency, Aberdeen Proving Ground, MD, 215 pp. [ER, GPR, SRR, BH] [Superseded by EC&T et al., 1990]

d'Arnaud Gerkins, J.C. 1989. Foundations of Exploration Geophysics. Elsevier, NY, 667 pp. [SRR, SRL, GR, MAG, SP, TC, MT, IP, ER, EMI, TDEM, radiation]

Dobecki, T.L. and P.R. Romig. 1985. Geotechnical and Ground Water Geophysics. Geophysics 50(12):2621-2636.

Dobrin, M.B. and C.H. Savit. 1988. Introduction to Geophysical Prospecting, 4th ed. McGraw-Hill, New York, 867 pp. [Earlier editions by Dobrin: 1960, 1965, 1976]. [SRR, SRL, CSP, GR, MAG, ER, SP, IP, EM I]

Ellyett, C.D. and D.A. Pratt. 1975. A Review of the Potential Applications of Remote Sensing Techniques to Hydrogeological Studies in Australia. Australian Water Resources Council Technical Paper No. 13, Canberra.

Emilsson, G.R. and J.C.B. Simonson. 1989. Integrated Geophysical and Geologic Techniques: Important First Steps in the Investigation of a Superfund Site in Southeastern Pennsylvania. In: Proc. (2nd) Symp. on the Application of Geophysics to Engineering and Environmental Problems, Soc. Eng. and Mineral Exploration Geophysicists, Golden, CO, pp. 354-367.

Environmental Consulting & Technology (EC&T), Inc., Technos, Inc., and UXB International, Inc. 1990. Construction Site Environmental Survey and Clearance Procedures Manual. U.S. Army Toxic and Hazardous Materials Agency, Aberdeen Proving Ground, MD. [GPR, EM I, MAG, MD, soil gas]

Erdé1yi, M. and J. Gálfi. 1988. Surface and Subsurface Mapping in Hydrogeology. Wiley-Interscience, New York, 384 pp. [Chapter 5 covers remote sensing, and Chapter 6 geophysical methods: GPR, ER, IP, EMI, SRR, SRL, GR, MAG, geothermal]

Evans, R. B., R.C. Benson, and J. Rizzo. 1982. Systematic Hazardous Site Assessments. In: Proc. (3rd) Nat. Conf. on Management of Uncontrolled Hazardous Waste Sites, Hazardous Materials Control Research Institute, Silver Spring, MD, pp. 17-22. [EMI, ER, GPR, MAG, MD, SRR]

Evans, R.B. and G.E. Schweitzer. 1984. Assessing Hazardous Waste Problems. Environ. Sci. Technol. 18(11):330A-339A. [EMI, ER, GPR, MAG, MD, SRR]

Eve, A.S. and D.A. Keys. 1954. Applied Geophysics in the Search for Minerals, 4th ed. Cambridge University Press, New York, 382 pp. [earlier editions 1929, 1931, 1938]. [MAG, ER, EM, GR, SRL, geothermal, radiometric]

Flatman, G. T., E.J. Englund, and D.D. Weber. 1986. Educational Needs for Hazardous Waste Site Investigations: Technology Transfer in Geophysics and Geostatistics. In: Proc. 7th Nat. Conf. on Management of Uncontrolled Hazardous Waste Sites, Hazardous Materials Control Research Institute, Silver Spring, MD, pp. 217-219.

French, R. B., T.R. Williams, and A.R. Foster. 1988. Geophysical Surveys at a Superfund Site, Waste Processing, Washington. In: Proc. (lst) Symp. on the Application of Geophysics to Engineering and Environmental Problems, Soc. Eng. and Mineral Exploration Geophysicists, Golden, CO, pp. 747-753.

Frischknecht, F. C., L. Muth, R. Grette, T. Buckley, and B. Kornegay. 1983. Geophysical Methods for Locating Abandoned Wells. U.S. Geological Survey Open-File Report 83-702, 211 pp.

Garland, G.D. (ed.). 1989. Proceedings of Exploration 87. Special Volume 3, Ontario Geological Survey, Toronto, Canada, 914 pp. [77 papers covering surface, borehole, and airborne EM, IP, remote sensing, radiometric, and seismic methods]

Grant, F.S. and G.F. West. 1965. Interpretation Theory in Applied Geophysics. McGraw-Hill, New York, 583 pp. [ER, EM, SRL, SRR, GR, MAG, EMI]

Griffiths, D.H. and R.F. King. 1981. Applied Geophysics for Engineers and Geologists: The Elements of Geophysical Prospecting, 2nd ed. Pergamon Press, New York, 230 pp. [First edition 1965] [ER, EM, SRR, SRL, GR, MAG]

Hancock, J.C. and P.A. Wintz. 1966. Signal Detection Theory. McGraw-Hill, New York, 247 pp.

Handman, E.H. 1983. Hydrologic and Geologic Aspects of Waste Management and Disposal: A Bibliography of Publications by U.S. Geological Survey Authors. U.S. Geological Survey Circular 907, 40 pp. [15 references on geophysics]

Hansen, D.A., W.E. Heinrichs, Jr., R.C. Holmer, R.E. McDougall, G.R. Rogers, J.S. Sumner, and S.H. Ward (eds.). 1967. Mining Geophysics, Vol. II, Theory. Society of Exploration Geophysicists, Tulsa, OK, 708 pp. [EMI, ER, IP, MAG, GR]

Hatheway, A.W. 1982. Geological and Geophysical Techniques for Development of Siting and Design Parameters. In: Proc. Symp. on Low-Level Waste Disposal (Arlington, VA), M.G. Yalcintas (ed.), NUREG/CP-O028 Vol. 2, Oak Ridge National Laboratory, Oak Ridge, TN, pp. 33-50.

Heiland, C.A. 1937. Prospecting for Water with Geophysical Methods. Trans. Am. Geophys. Union 18:574-588. [ER ,EMI, GR, MAG, S, geothermal]

Heiland, C.A. 1940. Geophysical Exploration. Prentice-Hall, New York, 1013 pp. [Reprinted under the same title in 1968 by Hafner Publishing, New York] [S, ER, MAG, GR]

Helmstrom, C.W. 1968. Statistical Theory of Signal Detection. Pergamon Press, New York, 470 pp.

Hoekstra, P. and M. Blohm. 1988. Surface Geophysics for Mapping Faults, Shear Zones and Karstification. In: Proc. (lst) Symp. on the Application of Geophysics to Engineering and Environmental Problems, Soc. Eng. and Mineral Exploration Geophysicists, Golden, CO, pp. 598-620.

Hoekstra, B. and P. Hoekstra. 1990. Planning and Executing Geophysical Surveys. In: Proc. Fourth Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods. Ground Water Management 2:1159-1166. [EMI, ER, GPR, GR, MAG, SRR, SRL]

Howell, B.F. 1959. Introduction to Geophysics. McGraw-Hill, New York, 399 pp. [S, GR, MAG, thermal]

HRB-Singer, Inc. 1971. Detection of Abandoned Underground Coal Mines by Geophysical Methods. Project 14010, Report EHN. Prepared for U.S. EPA and PA Dept. of Env. Res. [VLF, IP, SP].

Jakosky, J.J. 1950. Exploration Geophysics. Trija Publishing Co., Los Angeles, 1195 pp. [S, ER, MAG, GR]

Johnson, A.I. and J.P. Gnaedinger. 1964. Bibliography. In: Symposium on Soil Exploration, ASTM STP 351, American Society for Testing and Materials, Philadelphia, PA pp. 137-155. [air photo interpretation (90 refs); ER and seismic (60 refs); electrical borehole logging (48 refs); nuclear borehole logging (40 refs), borehole camera (13 refs); neutron moisture measurement (50 refs)]

Johnson, W.J. and D.W. Johnson. 1986. Pitfalls of Geophysics in Characterizing Underground Hazardous Waste. In: Proc. 7th Nat. Conf. on Management of Uncontrolled Hazardous Waste Sites, Hazardous Materials Control Research Institute, Silver Spring, MD, pp. 227-232. [EMI, ER, GPR, MAG, SRR]

Karous, M. and S. Mareš. 1988. Geophysical Methods in Studying Fracture Aquifers. Charles University, Prague, 93 pp. [ER, EMI, SP, SRR, borehole]

Kearey, P. and M. Brooks. 1991. An Introduction to Geophysical Exploration, 2nd ed. Blackwell Scientific Publications, Boston, MA 296 pp. [First edition 1984] [SRR, SRL, GR, MAG, ER, SP, IP, EMI, VLF, AFMAG, TC, MT, AEM]

Lewis, M.R. and F.P. Haeni. 1987. The Use of Surface Geophysical Techniques to Detect Fractures in Bedrock—An Annotated Bibliography. U.S. Geological Survey Circular 987. [31 English language and 12 foreign language references]

Lord Jr., A.E. and R.M. Koerner. 1987. Nondestructive Testing (NDT) Techniques to Detect Contained Subsurface Hazardous Waste. EPA/600/2-87/078 (NTIS PB88-102405), 99 pp. [17 methods; EM I, GPR, MAG, MD best]

Lord, Jr., A.E, S. Tyagi, and R.M. Koerner. 1980. Non-Destructive Testing (NDT) Methods Applied to Environmental Problems Involving Hazardous Material Spills. In: Proc. Nat. Conf. on Control of Hazardous Materials Spills (Louisville, KY), Vanderbilt University, Nashville, TN, pp. 174-179. [17 methods]

MacLeod, I.N. and T.M. Dobush. 1990. Geophysics-More Than Numbers: Processing and Presentation of Geophysical Data. In: Proc. Fourth Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods. Ground Water Management 2:1081-1095.

McGinnis, L.D., R.C. Winter, S.F. Miller and C. Tome. 1988. Decision Making on Geophysical Techniques and Results of a Study at a Hazardous Waste Site. In: Proc. (lst) Symp. on the Application of Geophysics to Engineering and Environmental Problems, Soc. Eng. and Mineral Exploration Geophysicists, Golden, CO, pp. 691-712.

McKown, G.L. and G.A. Sandness, 1981. Computer-Enhanced Geophysical Survey Techniques for Exploration of Hazardous Wastes Sites. In: Proc. (2nd) Nat. Conf. on Management of Uncontrolled Hazardous Waste Sites, Hazardous Materials Control Research Institute, Silver Spring, MD, pp. 300-305.

Meinzer, O.E. 1937. The Value of Geophysical Methods in Ground Water Studies. Trans. Am. Geophys. Union 18:385-387.

Milsom, J. 1989. FieId Geophysics. Halsted Press, New York, 182 pp.

Morely, L.W. (ed.) 1970. Mining and Groundwater Geophysics/1967. Economic Geology Report 26. Geological Survey of Canada, Ottawa, Canada. [ER, EM, SRR, BH]

Nabighian, M.N. (ed.). 1988. Electromagnetic Methods in Applied Geophysics, Vol. 1, Theory. Society of Exploration Geophysicists, Tulsa, OK 528 pp.

Nabighian, M.N. (ed.). 1991. Electromagnetic Methods in Applied Geophysics, Vol. 2, Parts A and B, Applications. Society of Exploration Geophysicists, Tulsa, OK, Part A, pp. 1-520, Part B, pp. 521-992.

National Water Well Association (NWWA). 1971. Geophysics and Ground Water: A Primer: Part 1, An Introduction to Ground Water Geophysics; Part 2, Applied Use of Geophysics. Water Well Journal Part 1:25(7):43-60; Part 2: 25(8):35-50.

National Water Well Association (NWWA). 1984. NWWA/EPA Conference on Surface and Borehole Geophysical Methods in Ground Water Investigations (San Antonio, TX). National Water Well Association, Dublin, OH.

National Water Well Association (NWWA). 1985. NWWA Conference on Surface and Borehole Geophysical Methods in Ground Water Investigations (Fort Worth, TX). National Water Well Association, Dublin, OH.

National Water Well Association (NWWA). 1986. Surface and Borehole Geophysical Methods and Ground Water Instrumentation Conference and Exposition (Denver, CO). NWWA, Dublin, OH.

Neev, D. 1988. Application of Geophysical Methods for Subsurface Metal Screening A Case History. In: Proc. (lst) Symp. on the Application of Geophysics to Engineering and Environmental Problems, Soc. Eng. and Mineral Exploration Geophysicists, Golden, CO, pp. 713-721.

Nelson, J.S. 1988. Planning and Costing Geophysical Investigations for Engineering and Environmental Problems. In: Proc. (lst) Symp. on the Application of Geophysics to Engineering and Environmental Problems, Soc. Eng. and Mineral Exploration Geophysicists, Golden, CO, pp. 569-572.

Nettleton, L.L. 1940. Geophysical Prospecting for Oil. McGraw-Hill, New York, 444 pp. [GR, MAG, SRR, SRL, ER]

Nicholl, Jr., J.J. and K. Cain. 1992. Subsurface Characterization Using Integrated Geophysical Methods: A Case History. In: SAGEEP ’92, Society of Engineering and Mineral Exploration Geophysicists, Golden, CO, pp. 37-54.

O’Brien & Gere Engineering. 1988. Hazardous Waste Site Remediation: The Engineering Perspective. Van Nostrand Reinholdj New York. [SRR, SRL, ER, EM, GPR, MAG]

Ogilvy, A.A. 1970. Geophysical Prospecting for Ground Water in the Soviet Union. In: Mining and Groundwater Geophysics/1967, L.W. Merely (ed.), Geological Survey of Canada Economic Geology Report 26, pp. 536-543.

Olhoeft, G.R. 1992a. Geophysics Advisor Expert System, Version 2.0. U.S. Geological Survey Open File Report 92-526, 21 pp. plus floppy disk. Also available from U.S. EPA Environmental Monitoring Systems Laboratory, PO Box 93478, Las Vegas, NV, 89193-3478; replaces Version LO (EPA/600/4-89/023), released in 1989. [ER, EMI, complex resistivity, SRR, SRL, GPR, GR, radiometric, soil gas]

Olhoeft, G.R. 1992b. Site Characterization Tools. In: Subsurface Restoration Conference, Third Int. Conf. on Ground Water Quality Research (June 21-24, 1992, Dallas, TX), National Center for Ground Water Research, Rice University, Houston, TX, pp. 29-31.

Olsson, O., 0. Duran, A. Jamtlid, and L. Stenburg. 1984. Geophysical Investigations in Sweden for the Characterization of a Site for Radioactive Waste Disposal—An Overview. Geoexploration 22:187-201.

Paillet, F.L. and W.R. Saunders (eds.). 1990. Geophysical Applications for Geotechnical Investigations. ASTM STP 1101, American Society for Testing and Materials, Philadelphia, PA 118 pp. [2 peer-reviewed papers on surface and 5 on borehole geophysics]

Pamsnis, D.S. 1975. Mining Geophysics, 2nd ed, revised and updated. Elsevier, New York, 395 pp. [second edition dated 1973]; [MAG, SP, EMI, TDEM, TC, ER, IP, GR, SRR, SRL, radiometric, BH]

Parasnis, D.S. 1979. Principles of Applied Geophysics, 3rd ed. Chapman and Hall, New York, 269+ pp. [earlier editions dated 1962, 1972]; [MAG, GR, ER, IP, EM, S]

Peterson, R., J. Hild, and P. Hoekstra. 1989. Geophysical Studies for the Exploration of Groundwater in the Basin and Range of Northern Nevada. In: Proc. (2nd) Symp. on the Application of Geophysics to Engineering and Environmental Problems, Soc. Eng. and Mineral Exploration Geophysicists, Golden, CO, pp. 425-435.

Phillipson, W.R. and D.A. Sangrey. 1977. Aerial Detection Techniques for Landfill Pollutants. In: Proc. 3rd Solid Waste Research Symp. (Management of Gas Leachate from Landfills), EPA/600/9-77/026 (PB272 595), pp. 104-114.

Pitchford, A. M., A.T. Mazzella, and K.R. Scarborough. 1988. Soil-Gas and Geophysical Techniques for Detection of Subsurface Organic Contamination. EPA/600/4-88/019 (NTIS PB88-208194). [EMI, ER, complex resistivity, GPR, SRR, SRL, MAG, MD, AEM, radiometric]

Redwine, J. et al. 1985. Groundwater Manual for the Electric Utility Industry, Volume 3: Groundwater Investigations and Mitigation Techniques. EPRI CS-3901. Electric Power Research Institute, Palo Alto, CA Chapter 3. [SRR, SRL, CSP, sonar, ER, SP, EMI, GPR, GR, BH]

Regan, J. M., M.S. Robinette, and T.R. Beaulieu. 1987. The Use of Remote Sensing, Geophysical, and Soil Gas Techniques to Locate Monitoring Wells at Hazardous Waste Sites in Ncw Hampshire. In: Proc. of the Fourth Annual Eastern Regional Ground Water Conference (Burlington, VT), National Water Well Association, Dublin, OH, pp. 577-591. [EMI, ER, GR, MAG, SRR, fracture trace]

Rehm, B.W., T.R. Stolzenburg, and D.G. Nichols. 1985. Field Measurement Methods for Hydrogeologic Investigations: A Critical Review of the Literature. EPRI EA-4301 Electric Power Research Institute, Palo Alto, CA. [Major methods: ER, EMI, SRR, BH; Other: IR, SP, IP/complex resistivity, SRR, GPR, MAG, GR, thermal]

Robinson, E.S. and C. Coruh. 1988. Basic Exploration Geophysics. John Wiley & Sons, New York, 562 pp. [SRR, SRL, GR, MAG, ER, IP, SP, TC, EMI, BH]

Schwarz, S.D. 1988. Application of Geophysical Methods to Groundwater Exploration in the Tolt River Basin, Washington State. In: Proc. (lst) Symp. on the Application of Geophysics to Engineering and Environmental Problems, Soc. Eng. and Mineral Exploration Geophysicists, Golden, CO, pp. 652-657.

Sharma, P.V. 1986. Geophysical Methods in Geology, 2nd ed Elsevier, New York, 428 pp. [First edition 1976] [S, GR, MAG, ER, geothermal]

Sheriff, R.E. 1968. Glossary of Terms Used in Geophysical Exploration. Geophysics 33(l): 181-228.

Sheriff, R.E. 1989. Geophysical Methods. Prentice Hall, Englewood Cliffs, NJ, 605 pp. [GR, MAG, ER, EM, SRR, geothermal, radiometric, BH]

Sheriff, R.E. 1991. Encyclopedic Dictionary of Exploration Geophysics, 3rd ed. Society of Exploration Geophysicists, Tulsa, OK, 376 pp. [lst ed. 1973, 2nd 1984]

Society of Exploration Geophysicists (SEG). Various dates. Annual Meeting Technical Program: Expanded Abstracts and Biographies. SEG, Tulsa, OK. [Publication for the 61st annual meeting in 1991 is a 2-volume set totaling 1707 pages]*

Society of Engineering and Mineral Exploration Geophysicists/Environmental and Engineering Geophysical Society (SEMEG/EEGS). 1988-present. Symposium on the Application of Geophysics to Engineering and Environmental Problems [lst, 1988; 2nd 1989; 3rd, 1990; 4th, 1991; 5th, 1992]. EEGS, Englewood CO.*

Taylor, R.W. 1984. Evaluation of Geophysical Surface Methods for Measuring Hydrological Variables in Fracture Rock Units. U.S. Bureau of Mine OFR-17-84 (NTIS PB84-158021), 145 pp.

Technos, Inc. 1992. Application Guide to the Surface Geophysical Methods. Technos, Inc., Miami, FL, 19 pp. [GPR, EMI, TDEM, VLF resistivity, ER, SRR, SRL, MAG, MD, GR, thermal, radiation)

Telford, W. M. N., L.P. Geldart, R.E. Sheriff, and D.A. Keys. 1990. Applied Geophysics, 2nd ed. Cambridge University Press, New York, 770 pp. [1st ed. 1976, reprinted 1982] [GR, MAG, SRR, SRL, ER, IP, SP, MT, EMI, TDEM, AEM, radioactive, BH]

Thomas, M.D. and D.F. Dixon (eds.). 1989. Proceedings of a Workshop on Geophysical and Related Geoscientific Research at Chalk River, Ontario. AECL-9085, Atomic Energy of Canada Limited. [25 papers on surface (GR, S, MAG, EM, ER, GPR) and borehole methods (electric, television, acoustic televiewer, spectral gamma)]

Tucci, P. 1989. Geophysical Methods for Water Resource Investigations in South and Central Arizona. In: Proc. (2nd) Symp. on the Application of Geophysics to Engineering and Environmental Problems, Soc. Eng. and Mineral Exploration Geophysicists, Golden, CO, pp. 368-383.

Tuttle, J.C. and G.H. Chapman. 1989. Field Analytical Screening, Reconnaissance Geophysical and Temporary Monitoring Well Techniques—An Integrated Approach to Pre-Remedial Site Characterization. In: Proc. 6th Nat. Conf. on Hazardous Wastes and Hazardous Materials, Hazardous Materials Control Research Institute, Silver Spring, MD, pp. 530-537. [EMI, ER, GPR, MAG, SRR, BH]

U.S. Army Corps of Engineers. 1979. Geophysical Exploration. Engineer Manual EM 1110-1-1802, Department of the Army, Washington, DC, 313 pp. [SRR, SRL, SASW, sonar, ER, GR, BH]

U.S. Department of Energy (DOE). 1990. Basic Research for Environmental Restoration. DOE/ER-0482T, Washington DC, 156 pp. [Discusses need for geophysics]

U.S. Environmental Protection Agency (EPA). 1987a. Surface Geophysical Techniques for Aquifer and Wellhead Protection Area Delineation. EPA/440/6-87/016 (NTIS PB88-229505).

U.S. Environmental Protection Agency (EPA). 1987b. A Compendium of Superfund Field Operations Methods, Part 2. EPA/540/P-87/001 (OSWER Directive 9355.0-14) (NTIS PB88-181557), 644 pp. [Remote sensing, EMI, ER, SRR, SRL, MAG, GPR, BH]

U.S. Environmental Protection Agency (EPA). 1992. Dense Nonaqueous Phase Liquids-A Workshop Summary, Dallas, Texas, April 16-18, 1991. EPA/600/R-92/030, 81 pp. [Section 4.2 provides brief description of geophysical techniques]

U.S. Environmental Protection Agency (EPA). 1993. Subsurface Field Characterization and Monitoring Techniques A Desk Reference Guide, Volume I: Solids and Ground Water. EPA/625/R-93/O03a. Available from EPA Center for Environmental Research Information, Cincinnati, OH. [Section 1 covers remote sensing and surface geophysical methods, Section 3 covers borehole geophysical methods]

U.S. Geological Survey (USGS). 1980. Geophysical Measurements. In: National Handbook of Recommended Methods for Water Data Acquisition, Chapter 2 (Ground Water), Office of Water Data Coordination, Reston, VA pp. 2-24 to 2-76. [TC, MT, AMT, EMI, ER, IP, SRR, GR, BH]

Valley, S.C. (ed.). 1965. Handbook of Geophysics and Space Environments. McGraw-Hill, New York.

Van Blaricom, R. 1980. Practical Geophysics for the Exploration Geologist. Northwest Mining Association, Spokane, WA 303 pp.

van der Leeden, F. 1991. Geraghty & Miller's Groundwater Bibliography, 4th ed. Water Information Center, Plainview, NY, 507 pp.

Van Eeckhout, E. and C. Calef (compilers). 1992. Workshop on Noninvasive Geophysical Site Characterization. LA-1231l-C, Los Alamos National Laboratories, Los Alamos, NM, 33 pp.

Wailer, M.J. and J.L. Davis. 1984. Assessment of Innovative Techniques to Detect Waste Impoundment Liner Failure. EPA/600/2-84/041 (NTIS PB84-157858), 148 pp. [28 methods assessed including ER, SRR, acoustic emission monitoring]

Ward S.H. (ed.) 1990a. Geotechnical and Environmental Geophysics Vol. I Review and Tutorial, Society of Exploration Geophysicists, Tulsa, 0K, 397 pp.

Ward S.H. (ed) 1990b. Geotechnical and Environmental Geophysics: Vol. II Environmental and Groundwater. Society of Exploration Geophysicists, Tulsa, OK, 309 pp. [34 papers, 13 on ER & EM; 14 on multiple methods; thermal, others]

Ward S.H. (ed.) 1990c. Geotechnical and Environmental Geophysics: Vol. III Geotechnical. Society of Exploration Geophysicists, Tulsa, OK, 352 pp. [23 papers, including cross-borehole resistivity, seismic shear, radio imaging]

Wruble, D.T., J.J. Van Ee, and L.G. McMillion. 1986. Remote Sensing Methods for Waste Site Subsurface Investigations and Monitoring. In: Hazardous and Industrial Solid Waste Testing and Disposal: Sixth Volume, R.A. Conway, et al. (eds.), ASTM STP 933, American Society for Testing and Materials, Philadelphia, PA pp. 243-256. [Airphotos, multispectral, thermal IR, surface geophysics]

Zohdy, A.A., G.P. Eaton, and D.R. Mabey. 1974. Application of Surface Geophysics to Ground-Water Investigations. U.S. Geological Survey Techniques of Water-Resource Investigations TWRI 2-D1, 116 pp. [ER, GR, MAG, SRR]

* 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.

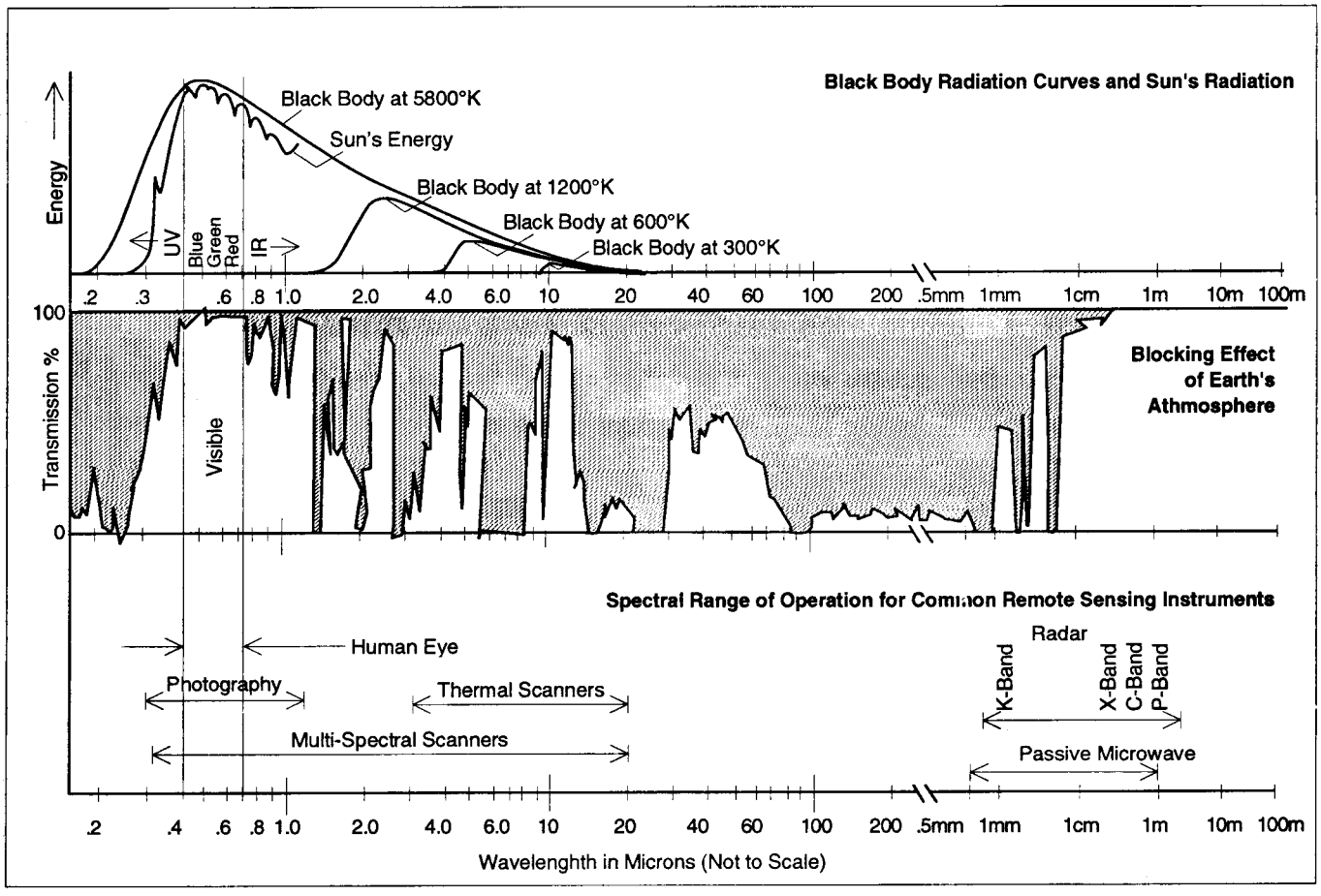


Figure 2-1 Portions of the electromagnetic spectrum used for remote sensing (Scherz and Stevens, 1970).

**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.*


Adams, W.M., F.L. Peterson, S.P. Mathur, L.K. Lepley, C. Warren, and R.D. Huber. 1971. A Hydrogeophysical Survey Using Remote-Sensing Methods from Kawaihae to Kailua-Kona, Hawaii. Ground Water 9(1):42-50. [ER, AMT, aerial thermal infrared, aeromagnetic]

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]

Arcone, A.A. 1979. Resolution Studies in Airborne Resistivity Surveying at VLF. Geophysics 44(5):937-946.

Avery, T.E. 1968. Interpretation of Aerial Photographs, 2nd ed. Burgess Publishing Company, Minneapolis, MN, 324 pp.

Baer, W.L. and P.M. Stokely. 1984. Incorporation of Hydrogeologic Data into United Sates Environmental Protection Agency/Environmental Photographic Interpretation Center Investigations of Hazardous Waste Sites. In: Proc. 5th Nat. Conf. on Management of Uncontrolled Hazardous Waste Sites, Hazardous Materials Control Research Institute, Silver Spring, MD, pp. 6-10.

Becker, A. 1990. Resistivity Mapping with Airborne Electromagnetic Induction Apparatus. In: Proc. (3rd) Symp. on the Application of Geophysics to Engineering and Environmental Problems, Soc. Eng. and Mineral Exploration Geophysicists, Golden, CO, pp. 1-28.

Burn, R.H. and V.R. Algaz. 1974. An Assessment of Remote Sensing Applications in Hydrologic Engineering. U.S. Army Corps of Engineers Hydrologic Center, Davis, CA, 55 pp.

Cameron, R.M. and K.S. Goodman. 1989. Detection and Mapping of Subsurface Hydrocarbons with Airborne Ground-Penetrating Radar. In: Proc. 3rd Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 137-149.

Chadwick D.G. 1973. Integrated Measurement of Soil Moisture by Use of Radio Waves. Utah Water Resource Laboratory, PB-227/5, 98 pp. [Thermal IR]

Ciciarelli, J. 1991. A Practical Guide to Aerial Photography. Van Nostrand Reinhold New York, 261 PP.

Colwell, R.N. 1983. Manual of Remote Sensing, 2nd ed. American Society of Photogrammetry, Fall Church, VA. [lst ed Reeves (1975)]

Cornillon, P. 1987. Report on the Usefulness of AVHRR and CZCS Sensors for Delineating Potential Disposal Operations at the 106-Mile Site. EPA/600/3-87/009 (NTIS PB87-168829). [Multispectral satellite imagery was not able to detect signs of ocean disposal]

Davis, E.M. and W.J. Fosbury. 1973. Application of Selected Methods of Remote Sensing for Detecting Carbonaceous Water Pollution. In: Remote Sensing and Water Resources Management, AWRA Proc. No. 17, American Water Resources Association, pp. 419-432. [Multispectral, IR]

Denny, C.S., C.R. Warren, D.H. Dow, and W.J. Dale. 1968. A Descriptive Catalog of Selected Aerial Photographs of Geologic Features of the United States. U.S. Geological Survey Professional Paper 590, 135 pp.

Deutsch, M., D.R. Wiosnet, and A. Ranjo (eds.). 1979. Satellite Hydrology (Fifth Annual William T. Pecora Memorial Symp. of Remote Sensing). American Water Resources Association, Minneapolis, MN, 730 pp.

DiNitto, R.G. 1983. Evaluation of Various Geotechnical and Geophysical Techniques for Site Characterization Studies Relative to Planned Remedial Action Measures. In: Proc. (4th) Nat. Conf. on Management of Uncontrolled Hazardous Waste Sites, Hazardous Materials Control Research Institute, Silver Spring, MD, pp. 130-134.

Dury, G.H. 1957. Map Interpretation. Pitman, London.

Dury, S.A. 1990. A Guide to Remote Sensing: Interpreting Images of the Earth. Oxford University Press, New York, 208 pp.

Ellyett, C.D. and D.A. Pratt. 1975. A Review of the Potential Applications of Remote Sensing Techniques to Hydrogeological Studies in Australia. Australian Water Resources Council Technical Paper No. 13, Canberra.

England A.W. and G.R. Johnson. 1977. Microwave Brightness Spectra of Layered Media. Geophysics 42(3):514-521.

Erb, T.L., W.R. Phillipson, W.L. Teng, and T. Liang. 1981. Analysis of Landfills with Historical Airphotos. Photogramm. Eng. and Remote Sensing 47:1363-1369.

Estes, J. E., D.S. Simonett, L.R. Tinney, C.E. Ezra, B. Bowman, and M. Roberts. 1978. Remote Sensing Detection of Perched Water Tables. California Water Resources Center Contribution No. 175, Univ. of California, Davis. [color IR, thermal IR, microwave]

Evans, B.M. and L. Mata. 1984. Aerial Photographic Analysis of Hazardous Waste Disposal Sites. In: Proc. (lst) Nat. Conf. on Hazardous Wastes and Environmental Emergencies, Hazardous Materials Control Research Institute, Silver Spring, MD, pp. 97-103.

Farrell, S.0. 1985. Evaluation of Color Infrared Aerial Surveys of Wastewater Soil Absorption Systems. EPA/600/2-85/039 (NTIS PB85-189074).

Fetter, Jr., C.W. 1980. Applied Hydrogeology. Charles E. Merrill Publishing, Columbus, OH.

Finkbeiner, M.A. and M.M. O'Toole. 1985. Application of Aerial Photography in Assessing Environmental Hazards and Monitoring Cleanup Operations at Hazardous Waste Sites. In: Proc. 6th Nat. Conf. on Management of Uncontrolled Hazardous Waste Sites, Hazardous Materials Control Research Institute, Silver Spring, MD, pp. 116-124.

Fisher, W.A. et al. 1966. Fresh Water Springs of Hawaii from Infrared Images. U.S. Geological Survey Hydrologic Atlas HA-218.

Fitterman, D.F. (ed.). 1990. Developments and Applications of Modern Airborne Electromagnetic Surveys. U.S. Geological Survey Bulletin 1925, 216 pp.

Frischknecht, F.C. 1990. Application of Geophysical Methods to the Study of Pollution Associated with Abandoned and Injection Wells. In: Proc. of a U.S. Geological Survey Workshop on Environmental Geochemistry, B.R. Doe (ed.), U.S. Geological Survey Circular 1033, pp. 73-77. [Aeromagnetic, TDEM]

Frischknecht, F.C. and P.V. Raab. 1984. Location of Abandoned Wells by Magnetic Surveys. In: Proc. 1st Nat. Conf. on Abandoned Wells-Problems and Solution, Environmental and Groundwater Institute, University of Oklahoma, Norman, OK, pp. 186-215. [Aeromagnetic]

Frischknecht, F.C., R. Gette, P.V. Raab, and J. Meredith. 1985. Location of Abandoned Wells by Magnetic Surveys-Acquisition and Interpretation of Aeromagnetic Data for Five Test Areas. U.S. Geological Survey Open-File Report 85-614-A, 64 pp.

Goodison, B.E. (ed.). 1985. Hydrological Applications of Remote Sensing and Remote Data Transmission. Int. Ass. Hydrological Sciences Pub. No. 145.

Hanna, W.F. (ed.). 1990. Geological Applications of Modern Aeromagnetic Surveys. U.S. Geological Survey Bulletin 1924, 106 pp.

Henry, E.C. 1992. Topography, Fracture Traces, Geology and Well Characteristics of the Unionville and West Chester 7.5 Minute Quadrangles, Chester County Pennsylvania. In: Ground Water Management 13:621-645 (Proc. of Focus Conf. on Eastern Regional Ground Water Issues).

Hill, J.M. and E.J. Dantin. 1984. Aerial Monitoring of Hazardous Waste Sites in Louisiana. In: Proc. (lst) Nat. Conf. on Hazardous Wastes and Environmental Emergencies, Hazardous Materials Control Research Institute, Silver Spring, MD, pp. 108-112.

Hoekstra, P., P.V. Sellman, and A. Delaney. 1975. Ground and Airborne Resistivity Surveys of Permafrost near Fairbanks Alaska. Geophysics 40:641-656.

Holz, R.K (ed.) 1973. The Surveillant Science: Remote Sensing of the Environment. Houghton Mifflin, Boston, 390 pp.

Howard, G.E. 1984. Airborne Television Applications for Emergency Response. In: Proc. (lst) Nat. Conf. on Hazardous Wastes and Environmental Emergencies, Hazardous Materials Control Research Institute, Silver Spring, MD, pp. 104-107.

Howe, H.L. 1958. Procedures for Applying Airphoto Interpretation in the Location of Groundwater. Photogramm. Eng. 24:25-49.

Huntley, D. 1978. On the Detection of Shallow Aquifers Using Thermal Infrared Imagery. Water Resources Research 14(6):1075-1083.

Idso, S. B., R.D. Jackson, and R.J. Reginato. 1975. Estimating Evapotranspiration: A Technique Adaptable to Remote Sensing. Science 189991-992.

Jackson, T.J. and T.J. Schmugge. 1986. Passive Microwave Remote Sensing of Soil Moisture. Advances in Hydroscience 14:123-159.

Jackson, T.J., T.J. Schmugge, and J.R. Wang. 1982. Passive Microwave Sensing of Soil Moisture Under Vegetative Canopies. Water Resources Research 18(4):1137-1142.

Jackson, T.J., T.J. Schmugge, and P. O'Neil. 1985. Remote Sensing of Soil Moisture from an Aircraft Platform Using Passive Microwave Sensors. In: Hydrological Applications of Remote Sensing and Remote Sensing Data Transmission, B.E. Goodison (ed), Int. Ass. Hydrological Sciences Pub. No. 145, pp. 529-540.

Jansen, J. and R. Taylor. 1988. Surface Geophysical Techniques for Fracture Detection. In: Proc. Second Conf. on Environmental Problems in Karst Terranes and Their Solutions (Nashville, TN), National Water Well Association, Dublin, OH, pp. 419-441. [EMI, VLF, thermal, fracture trace]

Johnson, A.I. and J.P. Gnaedinger. 1964. Bibliography. In: Symposium on Soil Exploration, ASTM STP 351, American Society for Testing and Materials, Philadelphia, PA, pp. 137-155. [90 references on air photo interpretation]

Kennedy, C.J. and J.S. Wogec. 1991. Use of Forward Looking Infrared Thermography for Site Assessment Work. Ground Water Management 6:745-750 (Environmental Site Assessment Conference).

Kondratyev, K.Y. 1969. Radiation in the Atmosphere. Academic Press, New York, 912 pp.

Landers, R.W. and H.V. Johnson. 1978. Photo Interpretation Keys for Hazardous Substances Spill Conditions. In: Control of Hazardous Material Spills, Information Transfer, Inc., Rockville, MD, pp. 124-127.

Lattman, L.H. 1958. Technique of Mapping Geologic Fracture Traces and Lineaments on Aerial Photographs. Photogramm. Eng. 24(4):568-576.

Lattman, L.H. and R.H. Matzke. 1961. Geological Significance of Fracture Traces. Photogramm. Eng. 27(3):435-438.

Lattman, L.H. and R.P. Nicholsen. 1958. Photogeologic Fracture-Trace Mapping in Appalachian Plateau. Am. Ass. Petrol. Geol. Bull. 42:2238-2245.

Lattman, L.H. and R.R. Parizek. 1964. Relationship Between Fracture Traces and the Occurrence of Ground Water in Carbonate Rocks. J. Hydrology 2:73-91.

Lattman, L.H. and R.G. Ray. 1965. Aerial Photographs in Field Geology. Holt Rinehart and Winston, New York, 221 pp.

Lee, K.H. 1991. Wetland Detection Methods Investigation. EPA/600/4-91/014 (NTIS PB91-217380). [Satellite, airborne radar and multispectral, black and white, color, color infrared airphotos]

Lee, K.H. 1992. Watershed Characterization Using Landsat Thematic Mapper (TM) Satellite Imagery Blackfoot River, Montana. EPA/600/4-91/027 (NTIS PB92-115237).

Lillesand H. and M. Kiefer. 1979. Remote Sensing and Image Interpretation. Wiley, New York.

Lord Jr., A.E., S. Tyagi, and R.M. Koerner. 1980 Nondestructive Testing (NDT) Methods Applied to Environmental Problems Involving Hazardous Material Spills. In: Proc. Nat. Conf. on Control of Hazardous Materials Spills (Louisville, KY), Vanderbilt University, Nashville, TN, pp. 174-179. [Review of 17 methods, including thermal infrared]

Lord Jr., A.E. and R.M. Koerner. 1987. Nondestructive Testing (NDT) Techniques to Detect Contained Subsurface Hazardous Waste. EPA/600/2-87/078 (NTIS PB88-102405), 99 pp. [17 methods including thermal infrared; EMI, GPR, MAG, MD best]

Lueder, D.R. 1959. Aerial Photographic Interpretation: Principles and Applications. McGraw-Hill, New York, 462 pp.

Lund, T. 1978. Surveillance of Environmental Pollution and Resources by Electromagnetic Waves. Nato Advanced Study Institutes Series C, Volume 45. Reidel Publishing Co., Boston, MA, 402 pp. [9 papers on land/water sensing using microwave and thermal IR]

Mabee, S.B., K.C. Hardcastle, and D.U. Wise. 1990. Correlation of Lineaments and Bedrock Fracture Fabric Implications for Regional Fractured-Bedrock Aquifer Studies, Preliminary Results from Georgetown, Maine. In: Ground Water Management 3:283-297 (7th NWWA Eastern GW Conference). [SLAR, air photos]

Mattick, R. E., F.H. Olmsted, and A.A.R. Zohdy. 1973. Geophysical Studies in the Yuma Area, Arizona and California. U.S. Geological Survey Professional Paper 726-D, 36 pp. [SRR, ER, GR, SRL, Aeromagnetic]

Meierhoff, M.L. and G.J. Weil. 1991. Underground Storage Tank Detection with Infrared Thermography. Ground Water Management 6:751-756 (Environmental Site Assessment Conference).

Merin, I.S. 1990. Identification of Previously Unrecognized Waste Pits Using Ground Penetrating Radar and Historical Aerial Photography. In: Proc. Fourth Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods. Ground Water Management 2:1049-1063.

Miller, V.C. and C.F. Miller. 1961. Photogeology. McGraw-Hill, New York.

Ottle, C, D. Vidal-Madjar, and G. Girard. 1989. Remote Sensing Applications to Hydrological Modeling. J. Hydrology 105:369-384.

Palacky, G.J. (cd.), 1986. Airborne Resistivity Mapping. Geological Survey of Canada Paper 86-22, 195 pp.

Palacky, G.J. and G.F. West. 1991. Airborne Electromagnetic Methods. In: Electromagnetic Methods in Applied Geophysics, Vol. 2, Applications, M.N. Nabighian (cd.), Society of Exploration Geophysicists, Tulsa, OK Part B, pp. 811-880.

Parizek, R.R. 1976. On the Nature and Significance of Fracture Traces and Lineaments in Carbonate and Other Terranes. In: Karst Hydrology and Water Resources, V. Yevjevich (cd.), Water Resources Publications, Fort Collins, CO, Vol. 1, pp. 3-1 to 3-62.

Pemberton, R.H. 1962. Airborne E1ectromagnetics in Review. Geophysics 28(5):691-713.

Phillipson, W.R. and D.A. Sangrey. 1977. Aerial Detection Techniques for Landfill Pollutants. In: Proc. 3rd Solid Waste Research Symp. (Management of Gas Leachate from Landfills), EPA/600/9-77/026 (PB272 595), pp. 104-114.

Plume, R.W. 1988. Use of Aeromagnetic Data to Define Boundaries of a Carbonate-Rock Aquifer in East-Central Nevada. U.S. Geological Survey Water Supply Paper 2330, 10 pp.

Poe, G.A., A.C. Stogryn, and A.T. Edgerton. 1971. Determination of Soil Moisture Content with Airborne Microwave Radiometry. Final Report 1684FR-1. Aerojet-General Corporation, El Monte, CA 169 pp. [Thermal IR]

Price, J.C. 1980. The Potential of Remotely Sensed Thermal Infrared Data to Infer Surface Soils Moisture and Evaporation. Water Resources Research 16(4):787-795.

Ray, R.G. 1960. Aerial Photographs in Geologic Interpretation and Mapping. U.S. Geological Survey Professional Paper 373, 320 pp.

Redwine, J. et al. 1985. Groundwater Manual for the Electric Utility Industry, Volume 3: Groundwater Investigations and Mitigation Techniques. EPRI CS-3901. Electric Power Research Institute, Palo Alto, CA. [Remote sensing, SRR, SRL, ER, SP, EMI, GPR, GR]

Rees, W.G. 1990. Physical Principle of Remote Sensing. Cambridge University Press, New York, 247 pp.

Reeves, R.G. 1968. Introduction to Electromagnetic Remote Sensing with Emphasis on Applications to Geology and Hydrology. AGI Short Course Lecture Notes. American Geological Institute, Washington, DC.

Reeves, R.G. (ed.). 1975. Manual of Remote Sensing. American Society of Photogrammetry, Falls Church, VA 2144 pp. [2nd ed. Colwell (1983)]

Regan, R.D. 1980. Remote Sensing Method. Geophysics 45(11):1685-1689.

Rehm, B.W., T.R. Stolzenburg, and D.G. Nichols. 1985. Field Measurement Methods for Hydrogeologic Investigations: A Critical Review of the Literature. EPRI EA-4301. Electric Power Research Institute, Palo Alto, CA. [Major methods: ER, EMI, SRR, BH; Other: infrared, SP, IP, complex resistivity, SRR, GPR, MAG, GR, thermal]

Rossiter, J.R. 1990. Geophysical and Remote Sensing Techniques for Detection and Measurement of Oil Slicks on Water. In: Proc. (3rd) Symp. on the Application of Geophysics to Engineering and Environmental Problems, Sot. Eng. and Mineral Exploration Geophysicists, Golden, CO, pp. 137-138.

Sabins, Jr., F.F. 1973. Recording and Processing Thermal Imagery. Photogramm. Eng. 39(8):839-844.

Sabins, Jr., F.F. 1978. Remote Sensing Principles and Interpretation. W.H. Freeman, San Francisco, CA, 426 pp.

Sangrey, D.A. and W.R. Phillipson. 1979. Detecting Landfill Leachate Contamination Using Remote Sensors. EPA/600/4-79/060 (NTIS PB80-174295), 78 pp.

Sauer, E.R. 1981. Hydrogeology of Glacial Deposits from Aerial Photographs. Photogramm. Eng. and Remote Sensing 46:811-822.

Scherz, J.P. 1971. Monitoring Water Pollution by Means of Remote Sensing Techniques. Remote Sensing Program Report No. 3. University of Wisconsin, Madison, WI, 27 pp.

Scherz, J.P. and A.R. Stevens. 1970. An Introduction to Remote Sensing for Environmental Monitoring. Remote Sensing Program Report No. 1, University of Wisconsin, Madison, WI, 80 pp.

Schmugge, T. and R.J. Gurney. 1986. Applications of Remote Sensing in Hydrology. In: Computational Methods in Water Resources, M.A. Celia et al. (eds.), Elsevier, New York, Vol. 1, pp. 383-388.

Schmugge, T.J., T.J. Jackson, and H.L. McKim. 1980. Survey of Methods for SoiI Moisture Determination. Water Resources Research 16:961-979. [Includes active microwave methods]

Sers, S.W. 1971. Remote Sensing in Hydrology A Survey of Applications with Selected Bibliography and Abstracts. Texas A&M University Remote Sensing Center, College Station, TX, 530 pp.

Setzer, J. 1966. Hydrologic Significance of Tectonic Fractures Detectable on Airphotos. Ground Water 4(4):23-27.

Sharp, R.S. 1970. Research Techniques in Nondestructive Testing. Academic Press, New York. [Thermal infrared sensing]

Shelton, G.A. 1984. Hazardous Waste Site Characterization Using Remote Sensing: An EPA Regional Office View. In: Proc. (1st) Nat. Conf. on Hazardous Wastes and Environmental Emergencies, Hazardous Materials Control Research Institute, Silver Spring, MD, pp. 113-116.

Sitton, M.D. and W.L. Baer. 1984. Graphically Integrating Aerial Photography and Hydrogeologic Data in Evaluating Groundwater Pollution Sources, Southington, CT. In: Proc. (lst) Nat. Conf. on Hazardous Wastes and Environmental Emergencies, Hazardous Materials Control Research Institute, Silver Spring, MD, pp. 198-200.

Smith, B., W. Heran, R. Bisdorf, and A.T. Mazzella. 1989. Evaluation of Airborne Geophysical Methods to Map Brine Contamination. EPA/600/4-89/003. U.S. EPA Environmental Monitoring Systems Laboratory, Las Vegas, NV.

Seer, G.J.R. 1980. Estimation of Regional Evapotranspiration and Soil Moisture Conditions Using Remotely Sensed Crop Surface Temperatures. Remote Sensing of Environment 9:27-45.

Soil Conservation Service (SCS). 1973. Aerial-Photo Interpretation in Classifying and Mapping Soils. U.S. Department of Agriculture Handbook 294.

Sonderegger, J.L. 1970. Hydrogeology of Limestone Terranes: Photogeologic Investigations. Geological Survey of Alabama Bulletin 94C.

Souto-Maior, J. 1973. Applications of Thermal Remote Sensing to Detailed Ground Water Studies. In: Remote Sensing and Water Resources Management, K.P.B. Thomson, R.K Lane, and S.C. Csallany (eds.), AWRA Proceedings Series No. 17, American Water Resources Association, Urbana, IL, pp. 284-298.

Strandberg, C.H. 1967. Aerial Discovery Manual. Wiley, New York.

Sucksdorff, Y. and C. Ottle. 1990. Application of Satellite Remote Sensing to Estimate Areal Evapotranspiration Over a Watershed. J. Hydrology 121:321-333. [thermal IR]

Svoma, J. and A. Pysek. 1985. Photographic Detection of Groundwater Pollution. In: Hydrological Applications of Remote Sensing and Remote Sensing Data Transmission, B.E. Goodison (cd.), Int. Ass. Hydrological Sciences Pub. No. 145, pp. 561-567.

Thomson, K.P.B., R.K Lane, and S.C. Csallany (eds.). 1973. Remote Sensing and Water Resources Management. AWRA, Proceedings Series No. 17, American Water Resources Association, Urbana, IL, 436 pp.

Trainer, F.W. 1967. Measurement of the Abundance of Fracture Traces on Aerial Photographs. U.S. Geological Survey Professional Paper 575-C, pp. C184-C185.

Trainer, F.W. and R.L. Ellison. 1967. Fracture Traces in the Shenandoah Valley, Virginia. Photogramm. Eng. 32(2):190-199.

Ulaby, F.T., R.K Moore, and A.K Fung. 1982. Microwave Remote Sensing: 3 Vols. Addison-Wesley, Reading MA.

U.S. Environmental Protection Agency (EPA). 1986. Test Methods for Evaluating Solid Waste, 3rd ed., Vol. II Field Manual Physical/Chemical Methods. EPA/530/SW-846 (NTIS PB88-239223); First update, 3rd ed., EPA/530/SW-846 .3-l (NTIS PB89-148076); available as subscription from U.S. Government Printing Office (GPO stock no. 955-001-00000-1). [2nd edition published in 1982 (NTIS PB87-120291); Revised Chapter 11 (Ground-Water Monitoring), covering remote sensing and geophysical methods, should be available in 1993]

U.S. Environmental Protection Agency (EPA). 1987. A Compendium of Superfund Field Operations Methods, Part 2. EPA/540/P-87/001 (OSWER Directive 9355.0-14) (NTIS PB88-181557), 644 pp. [remote sensing, EMI, ER, SRR, SRL, MAG, GPR, BH]

U.S. Geological Survey (USGS). 1982. Evaporation and Transpiration. In: National Handbook of Recommended Methods for Water Data Acquisition. USGS Office of Water Data Coordination, Reston, VA pp 8-1 to 8-57. [Reviews thermal IR remote sensing methods for estimating evapotranspiration]

Vacquier, V., N.C. StaenlanA R.G. Henderson, and I. Zeitz. 1951. Interpretation of Aeromagnetic Maps. Geological Society of America Memoir 47.

Verstappen, H.Th. 1977. Remote Sensing in Geomorphology. Elsevier, New York.

Vizy, K.N. 1974. Detecting and Monitoring Oil Slicks with Aerial Photos. Photogramm. Eng. 40(6):697-708.

Warren, W.M. and C.C. Wielchowsky. 1973. Aerial Remote Sensing of Carbonate Terranes in Shelby County, Alabama. Ground Water 11(6): 14-26. [color infrared, SLAR]

Watson, K, and R.D. Regan (eds.). 1983. Remote Sensing. Geophysics Reprint Series No. 3. Society of Exploration Geophysicists, Tulsa, OK, 581 pp.

Williams, Jr., R.S. and T.R. Ory. 1967. Infrared Imagery Mosaics for Geological Investigations. Photogramm. Eng. 33(12):1377-1380.

Wilson, T.M., J.A. Gordon, A.E. Ogden, and J.D. Reinhard. 1990. Detection of Failing Septic Tanks in East Tennessee Utilizing Infrared Color Aerial Photographs. In: Ground Water Management 3:177-188 (7th NWWA Eastern GW Conference).

Wiltala, S.W. and T.G. Newport. 1963. Aerial Observations of Ice Cover to Locate Areas of Groundwater Inflow to Streams. U.S. Geological Survey Professional Paper 450-E, pp. E148-E149.

Wise, D.U. and T.A. McCrory. 1982. A New Method of Fracture Analysis: Azimuth versus Traverse Distance Plots. Geol. Soc. Am. Bull 93:889-897.

Wobber, FJ. 1967. Fracture Traces in Illinois. Photogramm. Eng. 33(5):499-506.

Wolfe, E.W. 1971. Thermal IR for Geology. Photogramm. Eng. 37:43-52.

Wolfe, P.R. 1974. Elements of Photogrammetry. McGraw Hill, New York, 562 pp.

Wood C.R. 1972. Groundwater Flow. Photogramm. Eng. 38(4):347-352.

Wruble, D.T., J.J. Van Ee, and L.G. McMillion. 1986. Remote Sensing Methods for Waste Site Subsurface Investigations and Monitoring. In: Hazardous and Industrial Solid Waste Testing and Disposal: Sixth Volume, R.A. Conway, et al. (eds.), ASTM STP 933, American Society for Testing and Materials, Philadelphia, PA, pp. 243-256. [Airphotos, multispectral, thermal IR, surface geophysics]

Yates, S. R., A.W. Warrick, A.D. Matthias, and S. Musil. 1988. Spatial Variability of Remotely-Sensed Surface Temperatures at Field Scale. Soil Sci. Soc. Am. J. 52:40-45. [thermal IR]

Zeil, P., P. Volk, and S. Saradeth. 1991. Geophysical Methods for Lineament Studies in Groundwater Exploration: A Case History for SE Botswana. Geoexploration 27:165-177. [aeromagnetic, satellite imagery, VLF]

# 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):

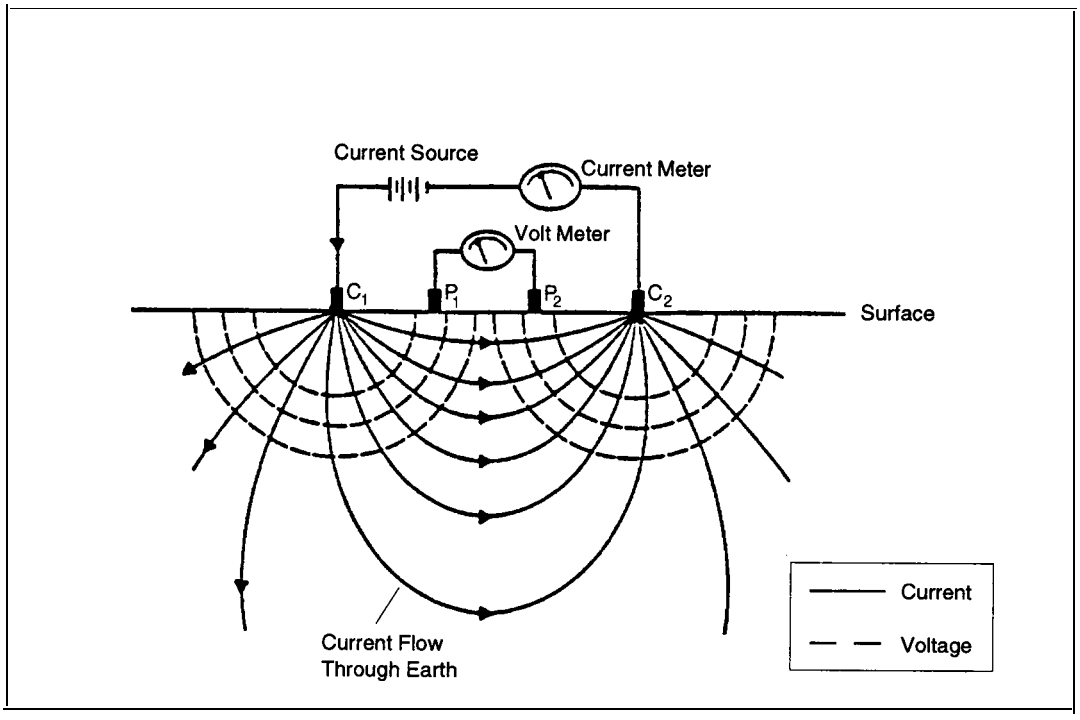


Figure 3-1 Diagram showing basic concept of resistivity measurement (from Benson et al., 1984).

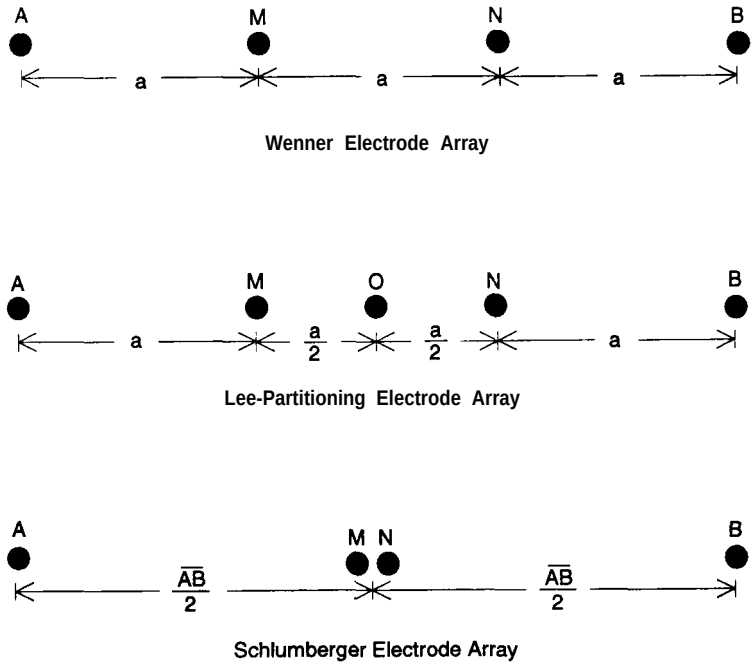


Figure 3-2 Wenner, Lee-Partitioning, and Schlumberger electrode arrays. A and B are current electrodes, M, N, and O are potential electrodes; a, $\frac{a}{2}$, and $\frac{\overline{AB}}{2}$ are electrode spacings (from Zohdy et al., 1974).

- 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

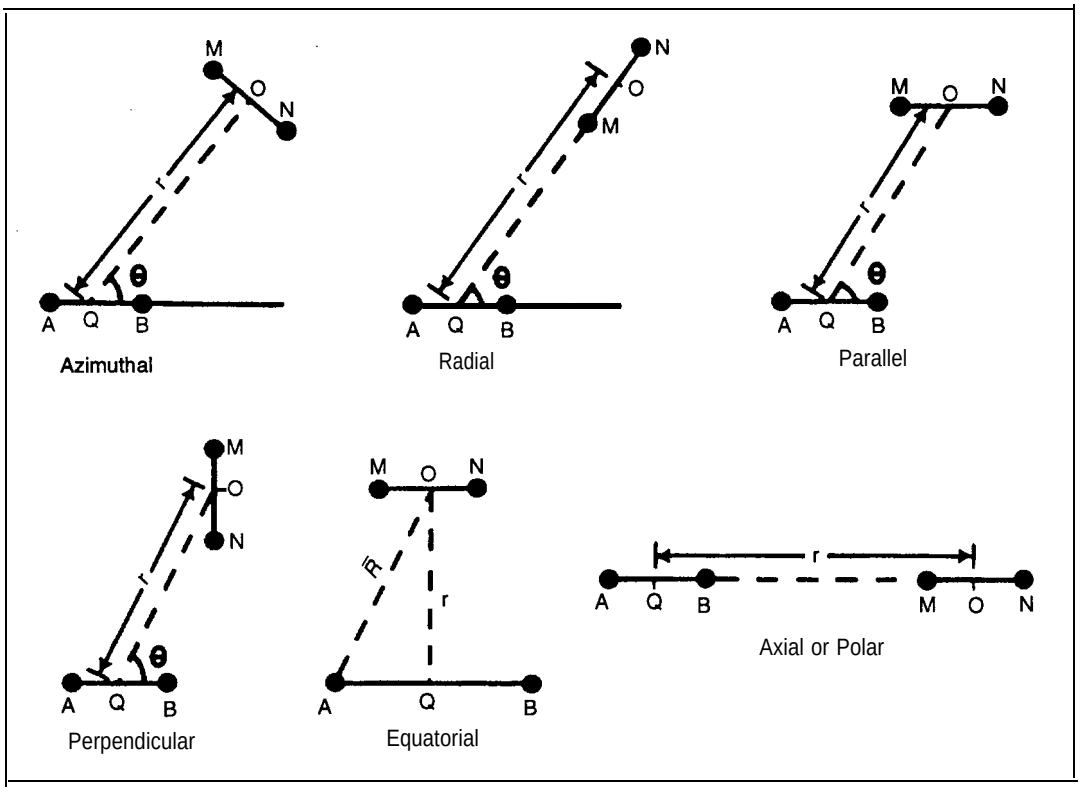


Figure 3-3 Dipole-dipole arrays. The equatorial array is bipole-dipole because AB is large (from Zohdy et al., 1974).

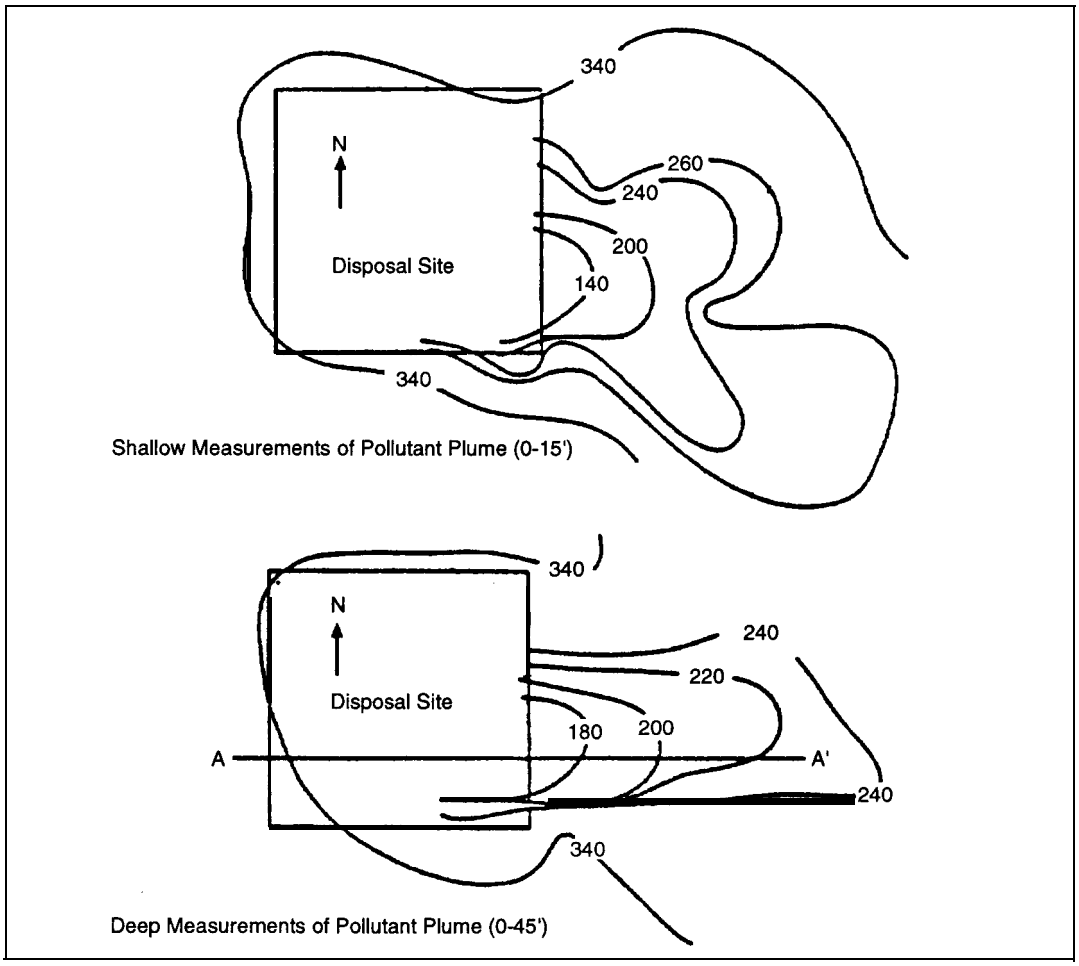


Figure 3-4a Resistivity soundings and profiles: isopleths of resistivity sounding data showing extent of a landfill plume (from Benson et al., 1984).

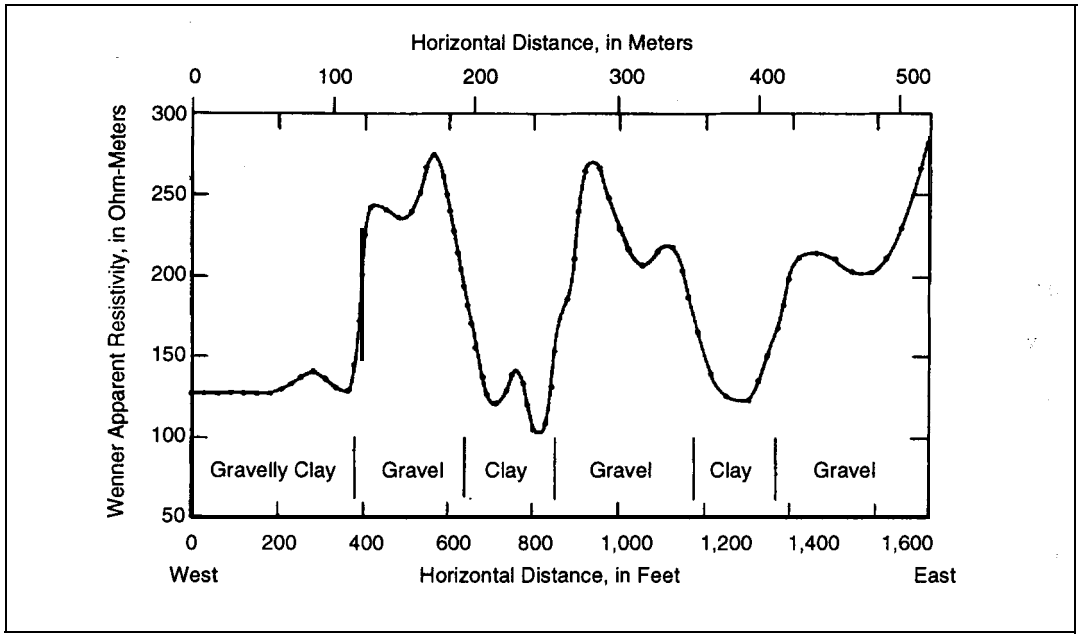


Figure 3-4b Resistivity soundings and profiles: resistivity profile across glacial clays and gravels (from Zohdy et al., 1974).

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

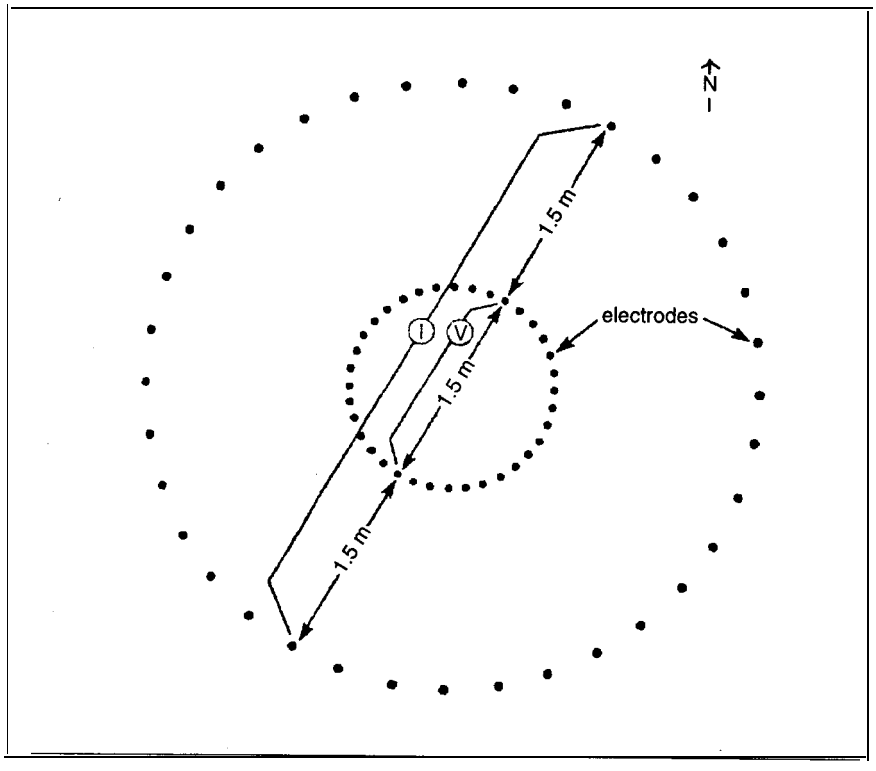


Figure 3-5a Specialized DC resistivity electrode configurations: layout of azimuthal resistivity array (Carpenter et al., 1991).

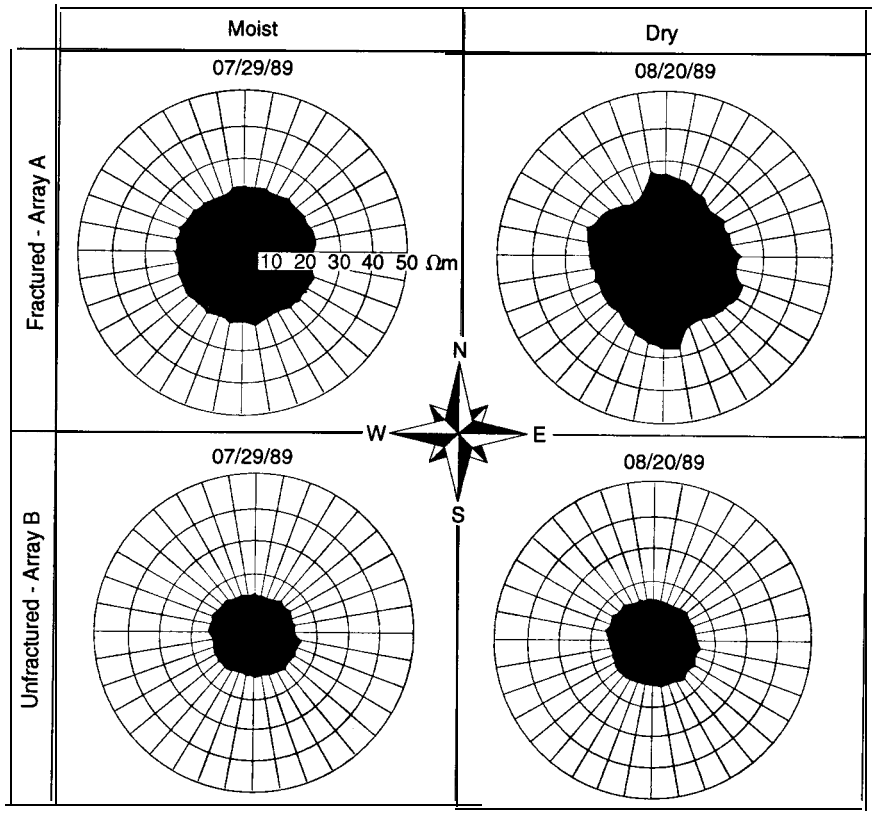


Figure 3-5b Specialized DC resistivity electrode configurations: azimuthal resistivity variations of fractured and unfractured landfill cover (Carpenter et al., l99l).

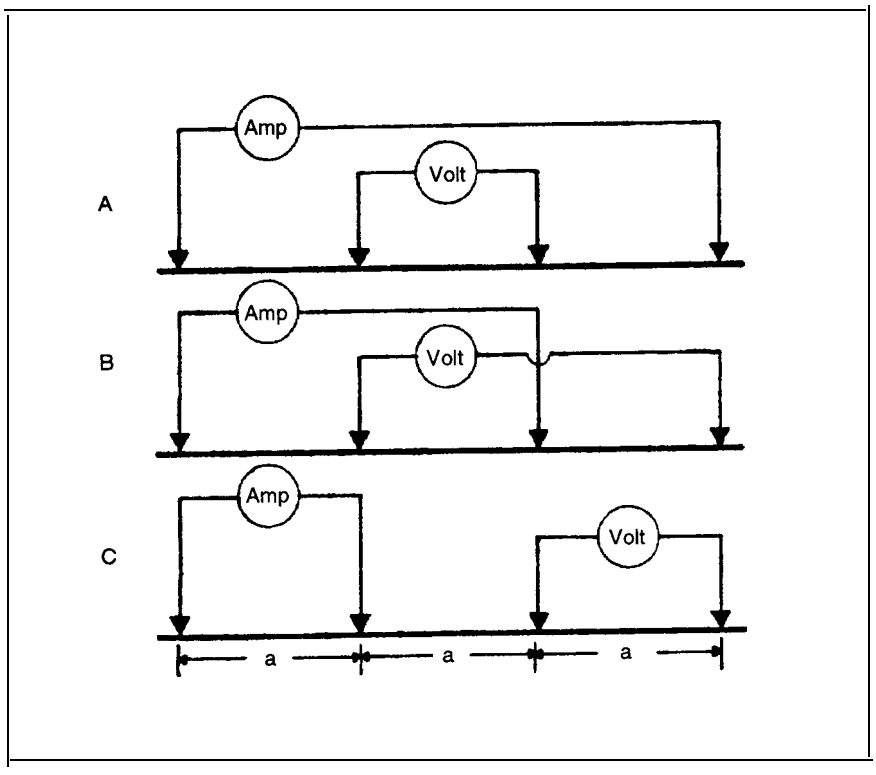


Figure 3-5c Specialized DC resistivity electrode configurations: tri-potential electrode array (Kirk and Rauch, 1977b).

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)$_s$

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

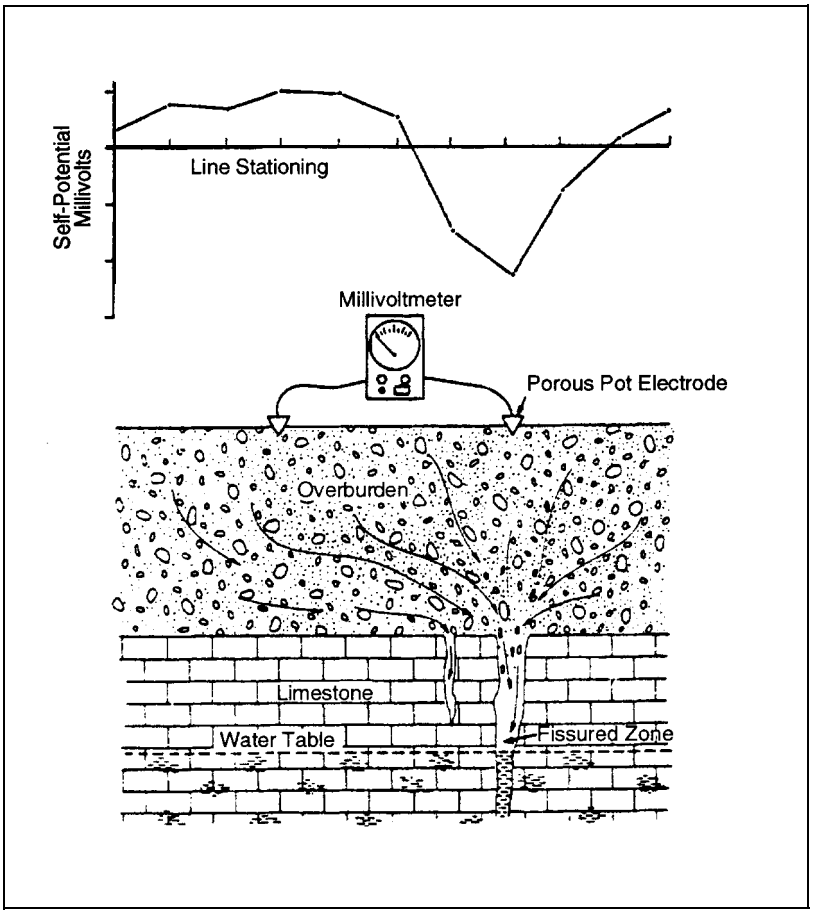


Figure 3-6a Self-potential measurements: apparatus and graph of measurement over a fissured zone of limestone illustrating negative streaming potential caused by ground-water seepage (Ogilvy and Bogoslovsky, 1979).

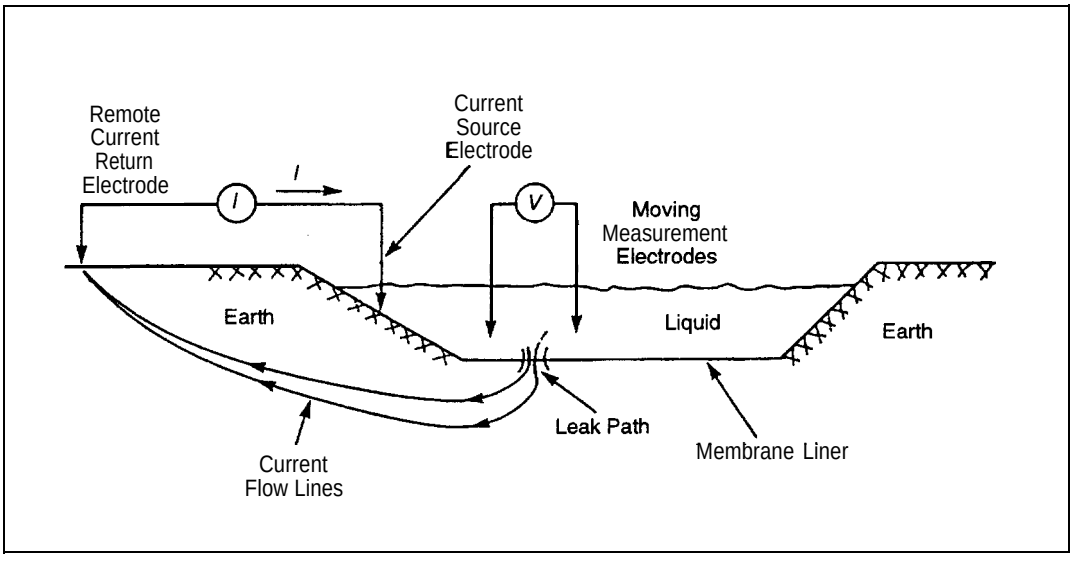


Figure 3-6b Self-potential measurements: electrical leak detection using modified self-potential method (Darilek and Parra, 1988 b).

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 |
|---|---|
| Ground-Water Applications | |
| 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 | Canada: Hobson et al. (1962), Lennox and Carlson (1970); Germany: Flathe (1955, 1964, 1970, 1976), Hallenbeck (1953); Other: 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 |
|---|---|
| Geologic Characterization Applications | |
| 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) |
| Contaminated Site Abdications | |
| 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.*


Ackermann, H.D. 1976. Geophysical Prospecting for Ground Water in Alaska. U.S. Geological Survey Earthquake Information Bull. 8(2) :18-20. [ER, SRR in permafrost areas]

Adams, J. M., W.J. Hinze, and L.A. Brown. 1975. Improved Application of Geophysics to Groundwater Resource Inventories in Glaciated Terrains. Water Resources Research Center Tech. Report No. 59 (NTIS PB244-879). Purdue University, West Lafayette, IN. [GR, IP]

Adams, M.L., M.S. Turner, and M.T. Morrow. 1988. The Use of Surface and Downhole Geophysical Techniques to Characterize Flow in a Fracture Bedrock Aquifer System. In: Proc. 2nd Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 825-847. [EMI, ER, SRR, BH]

Adams, W. M., F.L. Peterson, S.P. Mathur, L.K Lepley, C. Warren, and R.D. Huber. 1971. A Hydrogeophysical Survey Using Remote-Sensing Methods from Kawaihae to Kailua-Kona, Hawaii. Ground Water 9(1):42-50. [ER, AMT, aerial thermal infrared, aeromagnetic]

Ahmed, M.U. 1964. A Laboratory Study of Streaming Potentials. Geophysical Prospecting 12(1):49-64.

Ahmed S., G. de Marsily, and A. Talbot. 1988. Combined Use of Hydraulic and Electrical Properties of an Aquifer in a Geostatistical Estimation of Transmissivity. Ground Water 26(1):78-86.

Allen, R.P. 1984. Electrical Resistivity Surveys Used to Trace Leachate in Ground Water from Paper Mill Landfill. In: Proc. of the NWWA Tech. Division Eastern Regional Ground Water Conference (Newton, MA), National Water Well Association, Dublin, OH, pp. 167-174. [EMI, ER]

Allen, R.P. and B.A. Rogers. 1989. Geophysical Surveys in Support of a Remedial Investigation/Feasibility Study at the Municipal Landfill in Metamora, Michigan. In: Proc. 3rd Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 1007-1020. [ER, MAG, SRR]

Allen, J.P., R. Popma, and P. Doolen. 1985. Electrical Resistivity/Terrain Conductivity Surveys to Trace Process Wastewater Leachate in Ground Water from a Spray Irrigation System. In: Proc. of the AGWSE Eastern Regional Ground Water Conference (Portland, ME), National Water Well Association, Dublin, OH, pp. 243-251. [EMI, ER]

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, EM I, GPR, MD, MAG, combustible gas detectors]

Andres, K.G. and R. Canace. 1984. Use of the Electrical Resistivity Technique to Delineate a Hydrocarbon Spill in the Coastal Plains Deposits of New Jersey (of the New Jersey Coastal Plain): A Case Study. In: Proc. (lst) NWWA/API Conf. on Petroleum Hydrocarbons and Organic Chemicals in Ground Water—Prevention, Detection and Restoration, National Water Well Association, Dublin, OH, pp. 188-195.

Angoran, Y.E., D.V. Fitterman, and D.J. Marshall. 1974. Induced Polarization: A Geophysical Method for Locating Cultural Metallic Refuse. Science 1841287-1288.

Baizer, M.M. and H. Lund (eds.). 1983. Organic Electrochemistry, 2nd ed. Marcel Dekker, New York, 1166 pp. [IP]

Bardossy, A., L Borgardi, and W.E. Kelly. 1986. Geostatistical Analysis of Geoelectric Estimates for Specific Capacity. J. Hydrology 84:81-95.

Barker, R.D. 1974. The Interpretation of Induced Polarization Sounding Curves in the Frequency Domain. Geophysical Prospecting 22(4):610-626.

Barker, R.D. 1975. A Note on the Induced Polarization of the Bunter Sandstone. Geoexploration 13:227-234.

Barker, R.D. and P.F. Worthington. 1973. Some Hydrogeophysical Properties of the Bunter Sandstone of Northwest England. Geoexploration 11:151-170. [SRR, ER]

Barton, GJ. 1984. Land Use and Temporal Effects on Shallow Earth Resistivity. 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. 483-508. [ER]

Basokur, A.T. 1990. Microcomputer Program for the Direct Interpretation of Resistivity Sounding Data. Comp. and Geosci. 16(4):587-601.

Bays, C.A. 1946. Use of Electrical Geophysical Methods in Groundwater Supply. Illinois State Geological Survey Circular 122. [ER, BH]

Bays, C.A. 1950. Prospecting for Ground Water-Geophysical Methods. J. Am. Water Works Ass. 42:947-956. [ER]

Bays, C.A. and S.H. Folks. 1944. Developments in the Application of Geophysics to Ground Water Problems. Illinois State Geological Survey Circular 108. [ER, BH]

Beeson, S. and C.R.C. Jones. 1988. The Combined EMT/VES Geophysical Method for Siting Boreholes. Ground Water 26:54-63.

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

Benson, R. C., R.A. Glaccum, and M.R. Noel. 1984. 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., M.S. Turner, W.D. Volgelsong, and P.P. Turner. 1985. Correlation Between Field Geophysical Measurements and Laboratory Water Sample Analysis. In: Conference on Surface and Borehole Geophysical Methods and Ground Water Investigations (2nd, Fort Worth, TX), National Water Well Association, Dublin, OH, pp. 178-197. [EMI, ER]

Benson, R. C., M. Turner, P. Turner, and W. Vogelsang. 1988. In Situ, Time Series Measurements for Long-Term Ground-Water Monitoring. In: Ground-Water Contamination: Field Methods, A.G. Collins and A.I. Johnson (eds.), ASTM STP 963, American Society for Testing and Materials, Philadelphia, PA, pp. 58-72. [EMI, ER]

Berk, W.J. and B.S. Yare. 1977. An Integrated Approach to Delineating Contaminated Ground Water. Ground Water 15(2):138-145. [ER]

Bernard, J. and P. Valla. 1991. Groundwater Exploration in Fissured Media with Electrical and VLF Methods. Geoexploration 27:81-91.

Bertin, J. 1968. Some Aspects of Induced Polarization (Time Domain). Geophysical Prospecting 16:401-426.

Bertin, J. and J. Loeb. 1976. Experimental and Theoretical Aspects of Induced Polarization, 2 Volumes. Gebruder Borntraeger, Berlin.

Bhattacharya, P.K. and H.P. Patra. 1968. Direct Current Geoelectric Sounding—Principles and Interpretation. Elsevier, New York, 135 pp.

Biella, G., A. Lozei, and I. Tabacco. 1983. Experimental Study of Some Hydrogeophysical Properties of Unconsolidated Porous Media. Ground Water 21(6):741-751. [ER]

Bisdorf, R.J. 1990. Geoelectrical Studies on the Panoche Fan Area of the San Joaquin Valley, California. In: Proc. of a U.S. Geological Survey Workshop on Environmental Geochemistry, B.R. Doe (ed.), U.S. Geological Survey Circular 1033, pp. 133-137. [ER]

Bisdorf, R.J. and A.A.R. Zohdy. 1979. Geoelectrical Investigations with Schlumberger Soundings near Venice, Parrish and Homosassa, Florida. U.S. Geological Survey Open-File Report 79-841, 114 pp.

Bleil, D.F. 1953. Induced Polarization: A Method of Geophysical Prospecting. Geophysics 18(3):636-661.

Bodmer, R., S.H. Ward, and H.F. Morrison. 1968. On Induced Polarization and Groundwater. Geophysics 33(5):805-821.

Bogoslovsky, V.V. and A.A. Ogilvy. 1970a. Applications of Geophysical Methods for Studying the Technical Status of Earth Dams. Geophysical Prospecting 18:758-773. [ER, SP, 1P, SRR]

Bogoslovsky, V.A. and A.A. Ogilvy. 1970b. Natural Potential Anomalies as a Qualitative Index of the Rate of Seepage from Water Reservoirs. Geophysics 18(2):261-268. [SP]

Bogoslovsky, V.V. and A.A. Ogilvy. 1972. The Study of Streaming Potentials on Fissured Media Models. Geophysical Prospecting 20(4):109-117.

Bogoslovsky, V.V. and A.A. Ogilvy. 1973. Deformation of Natural Electric Fields near Drainage Structures. Geophysical Prospecting 21(4):716-723. [SP]

Bogoslovsky, V.V. and A.A. Ogilvy. 1977. Magnetometric and Electrometric Methods for the Investigation of the Dynamics of Landslide Processes. Geophysical Prospecting 25(3):280-291. [SP, MAG]

Borns, D.J. and S. Pickering. 1990. Enduser Quality Assurance Requirements for Geophysical Surveys: A Case Study Provided by a DC Grid at the Waste Isolation Pilot Plant. In: Proc. (3rd) Symp. on the Application of Geophysics to Engineering and Environmental Problems, Sot. Eng. and Mineral Exploration Geophysicists, Golden, CO, pp. 231-241.

Bottcher, C.F. 1952. Electric Polarization. Elsevier, NY.

Bradley, M.W. 1986. Surface Geophysical Investigations at the North Hollywood Dump, Memphis, Tennessee. In: Proc. Focus Conf. on Southeastern Ground Water Issues (Tampa, FL), National Water Well Association, Dublin, OH, pp. 324-343. [EMI, ER]

Breusse, J.J. 1963. Modern Geophysical Methods for Subsurface Water Exploration. Geophysics 28(4):633-657. [ER]

Brickell, M.E. 1984. Geophysical Techniques to Delineate a Contaminant Plume. In: Proc. of the NWWA Tech. Division Eastern Regional Ground Water Conference (Newton, MA), National Water Well Association, Dublin, OH, pp. 175-207. [EMI, ER, BH]

Bruehl, D.H. 1983. Use of Geophysical Techniques to Delineate Ground-Water Contamination. In: Proc. Third Nat. Symp. on Aquifer Restoration and Ground Water Monitoring, National Water Well Association, Dublin, OH, pp. 295-300. [ER, GR, SRR]

Bruehl, D.H. 1984a. Delineation of Ground Water Contamination by Electrical Resistivity Depth soundings. 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. 403-412. [ER]

Bruehl, D.H. 1984b. Use of Complementary Geophysical Techniques to Delineate Ground Water Contamination. In: Proc. of the NWWA Tech. Division Eastern Regional Ground Water Conference (Newton, MA), National Water Well Association, Dublin, OH, pp. 265-273. [ER, SRR, GR]

Buhle, M.B. 1953. Earth Resistivity in Ground-Water Studies in Illinois. Trans. Am. Inst. Mining Met. Eng., Petroleum Division 196(4):1-5.

Buhle, M.B. and J.E. Brueckmann. 1964. Electrical Earth Resistivity Surveying in Illinois. Illinois State Geological Survey Circular 376. [ground water resource evaluation]

Burdick, R.G. 1982. Application of the Electrical Resistivity Method to Mining Problems. In: Premining Investigations for Hardrock Mining, U.S. Bureau of Mines Information Circular 8891, pp. 29-35. [fault, abandoned mine, and leachate detection]

Butler, D.K. and J.L. Llopis. 1985. Military Requirements for Geophysical Ground Water Detection and Exploration. In: Conference on Surface and Borehole Geophysical Methods and Ground Water Investigations (2nd, Fort Worth, TX), National Water Well Association, Dublin, OH, pp. 228-248. [EMI, ER, SRR].

Carpenter, E.W. 1955. Some Notes Concerning the Wenner Configuration. Geophysical Prospecting 3:388-402. [tri-potential resistivity]

Carpenter, G.C. and D.R. Bassarab. 1964. Case Histories of Resistivity and Seismic Ground Water Studies. Ground Water 2(1):21-25.

Carpenter, P.J. 1900. Landfill Assessment Using Electrical Resistivity and Seismic Refraction Techniques. In: Proc. (3rd) Symp. on the Application of Geophysics to Engineering and Environmental Problems, Sot. Eng. and Mineral Exploration Geophysicists, Golden, CO, pp. 139-154.

Carpenter, P.J., R.S. Kaufman, and B. Price. 1990a. Use of Resistivity Soundings to Determine Landfill Structure. Ground Water 28:569-575.

Carpenter, P.J., M.C. Keeley, and R.S. Kaufman. 1990b. Azimuthal Resistivity, Soil Moisture, and Infiltration over a Fracture Glacial Till Landfill Cover (Abstract). Trans. Am. Geophys. Union 71:519.

Carpenter, P.J., S.F. Calkin, and R.S. Kaufman. 1991. Assessing a Fractured Landfill Cover Using Electrical Resistivity and Seismic Refraction Techniques. Geophysics 56(11):1896-1904. [Azimuthal resistivity]

Barrington, TJ. and D.A. Watson. 1981. " Preliminary Evaluation of an Alternate Electrode Array for Use in Shallow Subsurface Electrical Resistivity Studies. Ground Water 19(1):48-57.

Cartwright, K. and M.R. McComas. 1968. Geophysical Surveys in the Vicinity of Sanitry Landfills in Northeastern Illinois. Ground Water 6(5):23-30. [ER, thermal]

Chapman, MJ. and E.S. Bair. 1992. Mapping a Brine Plume Using Surface Geophysical Methods in Conjunctions with Ground Water Quality Data. Ground Water 12(3):203-209. [ER and EM1]

Cherkauer, D.S. and R.W. Taylor. 1988. Geophysically Determined Ground Water Flow into the Channels Connecting Lakes Huron and Erie. In: Proc. Second Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 779-799. [ER, CSP]

Cichowicz N.L., R.W. Pease, Jr., P.J. Stellar, and H.J. Jaffe. 1981. Use of Remote Sensing Techniques in a Systematic Investigation of an Uncontrolled Hazardous Waste Site. EPA/600/2-81/187 (NTIS PB82-103896). [ER, SRR, GPR, MD]

Cleff, R. (cd.). 1991. An Evaluation of Soil Gas and Geophysical Techniques for Detection of Hydrocarbons. API Publication No. 4509, American Petroleum Institute, Washington, DC. [GPR, EMI, ER, complex resistivity]

Coetsee, V.D.A., R. Meyer, C.D. Elphinstome, H. Bezuidenhout, and A. Watson. 1992. Hydraulic Aquifer Characteristics Determined from Resistivity Sounding Parameters Using Empirical Formulae and Geostatistical Techniques. In SAGEEP '92, Society of Engineering and Mineral Exploration Geophysicists, Golden, CO, pp. 291-308.

Collette, L.S. and TJ. Katsube. 1973. Electrical Parameters of Rocks in Developing Geophysical Techniques. Geophysics 38(l):76-91.

Cook, K.L. and R.G. Van Nostrand. 1954. Interpretations of Resistivity Data over Filled Sinks. Geophysics 19(4):761-790.

Cook, P. G., G.R. Walter, G. Buselli, I. Potts, and A.R. Dodds. 1992. The Application of Electromagnetic Techniques to Groundwater Recharge Investigations. J. Hydrology 130:201-229. [ER, EM I, TDEM]

Corwin, R.F. 1986. Electrical Resistivity and Self-Potential Monitoring for Ground Water Contamination. In: Proc. Surface and Borehole Geophysical Methods and Ground Water Instrumentation Conf. and Exp., National Water Well Association, Dublin, OH, pp. 203-214.

Corwin, R.F. 1990. Applications of the Self-Potential Method for Engineering and Environmental Investigations. In: Proc. (3rd) Symp. on the Application of Geophysics to Engineering and Environmental Problems, Soc. Eng. and Mineral Exploration Geophysicists, Golden, CO, pp. 107-122.

Darilek, G.T and J.O. Parra. 1988a. The Electrical Leak Location Methods for Geomembrane Liners. In: Proc. 14th Research Symp. (Land Disposal, Remedial Action, Incineration and Treatment of Hazardous Waste), EPA/600/9-88/021 (PB89-174403), pp. 167-176.

Darilek, G.T. and J.O. Parra. 1998b. The Electrical Leak Location Method for Geomembrane Liners. EPA/600/2-88/035 (NTIS PB88-220496).

Darilek, G.T. and D.L. Laine. 1989. Understanding Electrical Leak Location Surveys of Geomembrane Liners and Avoiding Specification Pitfalls. In: Superfund ’89, Proceedings of the 10th Annual Conference, Hazardous Material Control Research Institute, Silver Spring, MD, pp. 56-66.

Davis, P.A. 1979. Interpretation of Resistivity Sounding Data: Computer Programs for Solutions to the Forward and Inverse Problems. Minnesota Geological Survey Information Circular 17.

Denne, J.E., et al. 1984. Remote Sensing and Geophysical Investigations of G1acial Buried Valleys in Northeastern Kansas. Ground Water 22(1):56-65. [ER, GR, SRR, thermal]

Dudley, Jr., W.W. and L.D. McGinnis. 1962. Seismic Refraction and Earth Resistivity Investigation of Hydrogeologic Problems in the Humboldt River Basin, Nevada. Desert Research Institute Technical Report 1, University of Nevada, Las Vegas, NV, 29 pp.

Ehrlich, M, and L.G. Rosen. 1987. Application of Seismic, EM and Resistivity Techniques to Design and Ground Water Monitoring Programs at a Landfill in Northeastern Illinois. In: Proc. NWWA Focus Conf. on Midwestern Ground Water Issues (Indianapolis, IN), National Water Well Association, Dublin, OH, pp. 189-206.

Emilsson, G.R. and P.R. Morin. 1989. Using Vertical Electric Soundings to Accurately Map a Buried Channel in Coastal Plain Sediments. In Proc. Focus Conf. on Eastern Regional Ground Water Issues, National Water Well Association, Dublin, OH, pp. 41-54. [ER]

Erchul, R.A. and D.K. Butler. 1986. The Use of Spontaneous Potential in the Detection of Subterranean Flow Patterns in and Around Sinkholes. In: Proc. Environmental Problems in Karst Terranes and Their Solutions Conference (Bowling Green, KY), National Water Well Association, Dublin, OH, pp. 465-486. [ER, SP]

Evans, R.B. and G.E. Schweitzer. 1984. Assessing Hazardous Waste Problems. Environ. Sci. Technol. 18(11) :330A-339A. [EMI, ER, GPR, MAG, MD, SRR]

Filler, D.M. and S-S. Kuo. 1989. Subsurface Cavity Explorations Using Non-Destructive Geophysical Methods. In: Proc. Third Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 827-840. [ER, GPR, SRR]

Fink, J. B., et al. (eds.). 1990. Induced Polarization. Society of Exploration Geophysicists, Tulsa, OK, 424 pp.

Fink, Jr., W.B., and D.B. Aulenbach. 1974. Protracted Recharge of Treated Sewage into Sand Part II—Tracing the Flow of Contaminated Ground Water with a Resistivity Survey. Ground Water 12(4):219-222.

Flathe, H. 1955. Possibilities and Limitations in Applying Geoelectrical Methods to Hydrological Problems in the Coastal Areas of Northwestern Germany. Geophysical Prospecting 3:95-110.

Flathe, H. 1964. New Ways for Interpretation of Geological Resistivity Measurement in the Search for and Delimitation of Aquifers. Bull. IASH 9(1):52-61.

Flathe, H. 1970. Interpretation of Geoelectrical Resistivity Measurements for Solving Hydrogeolical Problems. In: Mining and Groundwater Geophysics/1967, L.W. Merely (cd), Geological Survey of Canada Economic Geology Report 26, pp. 580-597.

Flathe, H. 1976. The Role of a Geologic Concept in Geophysical Research Work for Solving Hydrogeological Problems. Geoexploration 14:195-206. [ER]

Foster, J.W. and M.B. Buhle. 1951. An Integrated Geophysical and Geological Investigation of Aquifers in Glacial Drift near Champaign-Urbana, Illinois. Economic Geology 46:367-397. [ER]

Fountain, L.S. 1976. Subsurface Cavity Detection: Field Evaluation of Radar, Gravity, and Earth Resistivity Methods. In: Subsidence over Mines and Caverns, Transportation Research Record 612, Transportation Research Board,National Academy of Sciences, Washington, DC, pp. 38-46.

Fountain, L.W. 1986. Detection and Location of Leaks in Geomembrane-Lined Liquid Waste Impoundments Using an Electrical Technique. In: Proc. Surface and Borehole Geophysical Methods and Ground Water Instrumentation Conf. and Exp., National Water Well Association, Dublin, OH, pp. 117-126.

Fournier, C. 1989. Spontaneous Potentials and Resistivity Surveys Applied to Hydrogeology in a Volcanic Area Case History of the Chaine Des Puys (Puy-de-Dome, France). Geophysical Prospecting 37:647-668.

Fowler, J.W. and A. Ayubcha. 1986. Selection of Appropriate Geophysical Techniques for the Characterization of Abandoned Waste Sites. In: Proc. Surface and Borehole Geophysical Methods and Ground Water Instrumentation Conf. and Exp., National Water Well Association, Dublin, OH, pp. 625-656. [ER, EMI, SRR, GPR, GR, MAG]

Fox, F.L. and D.A. Gould. 1984. Delineation of Subsurface Contamination Using Multiple Surficial Geophysical Methods. In: Proc. of the NWWA Tech. Division Eastern Regional Ground Water Conference (Newton, MA), National Water Well Association, Dublin, OH, pp. 254-264. [EMI, ER]

Frangos, W. 1990. Interpretation of Data from Electrical Resistivity Measurements. In: Proc. (3rd) Symp. on the Application of Geophysics to Engineering and Environmental Problems, Sot. Eng. and Mineral Exploration Geophysicists, Golden, CO, pp. 29-58.

Fretwell, J.D. and M.T. Stewart. 1981. Resistivity Study of a Coastal Karst Terrain, Florida. Ground Water 19(2):156-162.

Frische, R.H. and H. von Buttlar. 1957. A Theoretical Study of Induced Electrical Polarization. Geophysics 22(3):688-706.

Frohlich, R.K 1972. Methods of Determining Aquifer Storage Capacity and Fresh-Saline Water Interfaces by Geoelectrical Investigations. Missouri Water Resources Research Center Report OWRR-A-046-M0 (NTIS PB216-812), 39 pp.

Frohlich, R.K 1973. Detection of Fresh-Water Aquifers in the Glacial Deposits of North-Western Missouri by Geoelectrical Methods. Water Resources Bull. 9(4):723-34.

Frohlich, R.K 1974. Combining Geoelectric and Drill-Hole Investigations for Detecting Fresh Water Aquifers in Northwestern Missouri. Geophysics 39(3):340-352.

Frohlich, R.K and W.E. Kelly. 1983. The Relation Between Hydraulic Transmissivity and Transverse Resistance in a Complicated Aquifer of Glacial Outwash Deposits. J. Hydrology 79(3/4):215-229.

Frohlich, R.K and W.E. Kelly. 1988. Estimates of Specific Yield With the Geoelectric Resistivity Method in Glacial Aquifers. J. Hydrology 97(1/2):33-44.

Frohlich, R.K and C.D. Parke. 1989. The Electrical Resistivity of the Vadose Zone-Field Survey. Ground Water 27(4):524-530.

Frohlich, R.K and G.P. Smith. 1974. The Detection of Subsurface Stream Channels in Carbonate Rocks by Geoelectrical Methods. Water Resources Center Report OWRR A-065-MO(l). University of Missouri, Columbia, MO (NTIS PB229-847), 71 pp.

Gabanski, G., J. Julik, and O. Bassou. 1984. Assessment of Buried Aquifers in Minnesota Using Computer-Generated Werner Electric Sounding Curves. 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. 107-129.

Ghatge, S.L. and D.L. Pasicznyk. 1986. Integrated Geophysical Methods in the Determination of Bedrock Topography. In: Proc. Surface and Borehole Geophysical Methods and Ground Water Instrumentation Conf. and Exp., National Water Well Association, Dublin, OH, pp. 601-624, [ER, TDEM, IP, SRR, GR, MAG]

Gilkeson, R.H. and K. Cartwright. 1982. The Application of Surface Geophysical Methods in Monitoring Network Design. In: Proc. Second Nat. Symp. on Aquifer Restoration and Ground Water Monitoring, National Water Well Association, Dublin, OH, pp. 169-183. [EMI, ER, SP, thermal]

Gilkeson, R.H., T.H. Larson, and P.C. Heigold. 1984. Definition of Contaminant Pathways: An Integrated Geophysical and Geological Study. 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. 567-583. [ER, thermal]

Gilmer, T.H. and M.P. Helbling. 1984. Geophysical Investigations of a Hazardous Waste Site in Massachusetts. 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. 618-634. [EMI, ER, MAG, SRR]

Gilmer, T.H., E.J. Harmon, and D.S. Kronig. 1986. Estimation of Alluvial Aquifer Characteristics from Resistivity Soundings. In: Proc. Surface and Borehole Geophysical Methods and Ground Water Instrumentation Conf. and Exp., National Water Well Association, Dublin, OH, pp. 163-186.

Ginsberg, A. and A. Lavanon. 1976. Determination of a Salt-Water Interface by Electrical Resistivity Soundings. Hydrol. Sci. Bull. 21(4):561-568.

Goldman, M.M. 1990. Non-Conventional Methods in Geoelectrical Prospecting. Prentice-Hall, New York, 150 pp. [EM, TDEM, ER]

Gondwe, E. 1991. Saline Water Intrusion in Southeast Tanzania. Geoexploration 27:25-34. [ER]

Gorhan, H.L. 1976. The Determination of the Saline/Fresh Water Interface by Resistivity Soundings. Bull. Ass. Eng. Geol. 13:163-175.

Goyal, V. C., S. Niwas, and P.K Gupta. 1991. Theoretical Evaluations of Modified Wenner Array for Shallow Resistivity Exploration. Ground Water 29(4):582-586.

Greenhouse, J.P. and R.D. Harris. 1983. Migration of Contaminants in Groundwater at a Landfill: A Case Study 7. DC, VLF, and Inductive Resistivity Surveys. J. Hydrology 63:177-197.

Greenhouse, J.P., L. Faulkner, and J. Wong. 1985. Geophysical Monitoring of an Injected Contaminant Plume with a Disposable E-Log. In: NWWA Conference on Surface and Borehole Geophysical Methods and Ground Water Investigations (2nd Fort Worth, TX), National Water Well Association, Dublin, OH, pp. 64-84. [EMI, ER, BH]

Habberjam, G.B. 1969. The Location of Spherical Cavities Using a Tri-Potential Resistivity Technique. Geophysics 34(5):780-784.

Hackbarth, D.A. 1971. Field Study of Subsurface Spent Sulfite Liquor Movement Using Earth Resistivity Measurements. Ground Water 9(3):11-16.

Hackett, J.E. 1956. Relation Between Earth Resistivity and Glacial Deposits near Shelbyville, Illinois, Illinois State Geological Survey Circular 223, 19 pp.

Hallenback, F. 1953. Gee-Electrical Problems of the Hydrology of West German Area. Geophysical Prospecting 1:241-249.

Hallof, P.J. 1964. A Comparison of the Various Parameters Employed in the Variable-Frequency Induced-Polarization Method. Geophysics 29:425-433.

Harman, H.D. 1986. Detailed Stratigraphic and Structural Control: The Keys to Complete and Successful Geophysical Surveys of Hazardous Waste Sites. In: Proc. 6th Nat. Conf. on Hazardous Wastes and Hazardous Materials, Hazardous Materials Control Research Institute, Silver Spring, MD, pp. 19-21 [ER]

Harmon, E.J. and M.F. Hajicek. 1992. Schlumberger Soundings and Sand-Column Resistivity Testing for Determining Stream-Aquifer Connections, Great Sand Dunes National Monument, Colorado. In: SAGEEP '92, Society of Engineering and Mineral Exploration Geophysicists, Golden, CO, pp. 275-290.

Hawley, P.E. 1943. Fault Location by Electrical Constant Depth Prospecting-An Example. Geophysics 8:391-403.

Heigold P. C., R.H. Gilkeson, K Cartwright, and P.C. Reed. 1979. Aquifer Transmissivity from Surficial Resistivity Methods. Ground Water 17(4):338-345. [See also 1980 discussion by W.E. Kelly and reply by P.C. Heigold in Ground Water 18(2) :183-184.]

Henriet, J.P. 1976. Direct Applications of the Dar Zarrouk Parameters in Ground Water Surveys. Geophysical Prospecting 24:344-353. [ER]

Hitchcock, A.S. and H.D. Harman, Jr. 1983. Application of Geophysical Techniques as a Site Screening Procedure at Hazardous Waste Sites. In: Proc. Third Nat. Symp. on Aquifer Restoration and Ground Water Monitoring, National Water Well Association, Dublin, OH, pp. 307-313. [ER, MAG]

Hobson, G.D., J.E. Wyder, and C.V. Brandon. 1962. Aquifer Exploration in Canada by Geophysical Methods. Am. Water Works Ass. J. 54(9):1073-1081. [ER, SRR]

Hoekstra, P. P.V. Sellman, and A. Delaney. 1975. Ground and Airborne Resistivity Surveys of Permafrost near Fairbanks Alaska. Geophysics 40:641-656. [ER, airborne EM]

Horton, K.A., R.M. Morey, L. Isaacson, and R.H. Beers. 1981. The Complementary Nature of Geophysical Techniques for Mapping Chemical Waste Disposal Sites: Impulse Radar and Resistivity. In: Proc. (2nd) Nat. Conf. on Management of Uncontrolled Hazardous Waste Sites, Hazardous Materials Control Research Institute, Silver Spring, MD, pp. 158-164. [ER, GPR]

HRB-Singer, Inc. 1971. Detection of Abandoned Underground Coal Mines by Geophysical Methods. Project 14010, Report EHN. Prepared for U.S. EPA and PA Dept. of Env. Res. [VLF, IP, SP].

Hubbert, M.K. 1944. An Exploratory Study of Faults in the Cave in Rock and Rosiclare Districts by the Earth-Resistivity Method. In: Geological and Geophysical Survey of Fluorspar Areas in Hardin County, Illinois, Part 2. U.S. Geological Survey Bull. 942, pp. 73-147.

Hughes, L.J. et al. 1986. Applications of Two Electrical Geophysical Techniques in Mapping Ground Water Contamination. In: Proc. Surface and Borehole Geophysical Methods and Ground Water Instrumentation Conf. and Exp., National Water Well Association, Dublin, OH, pp. 65-86. [SP, IP for brine toxic waste plume]

Huntley, D. 1986. Relation Between Permeability and Electrical Resistivity in Granular Aquifers. Ground Water 24(4):466-474.

Huntley, D. and H.M. Mishler. 1984. Relationship Between Permeability and Electrical Resistivity in Granular and Fractured-Rock Aquifers. In: NWWA/EPA Conf. on Surface and Borehole Geophysical Methods in Ground Water Investigations (1st, San Antonio TX), National Water Well Association, Dublin, OH, pp. 18-36.

Jackson, P. D., S.D. Taylor, and P.N. Stamford. 1978. Resistivity Porosity Particle Shape Relationships for Marine Sands. Geophysics 43(6):1250-1268.

Jackson, P. G., P. Meldrum, and G.M. Williams. 1990. Principles of Computer-Controlled Multi-Electrode Resistivity System for Automatic Data Acquisition. Technical Report WE/89/21. The British Geological Survey, Keyworth, Nottingham, UK, 24 pp.

Jagammadha, V.V.S. and V.B. Rao. 1962. Variations of Electrical Resistivity of River Sands, Calcite and Quartz Powders with Water Content. Geophysics 17(4):450-479.

Jansen, J. 1990. Surficial Geophysical Techniques for the Detection of Bedrock Fracture Systems. In: Ground Water Management 3:239-253 (7th NWWA Eastern GW Conference). [EMI, azimuthal resistivity]

Jansen, J. and R. Taylor. 1989. Geophysical Methods for Groundwater Exploration or Groundwater Contamination Studies in Fracture Controlled Aquifers. In: Proc. Third Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 855-869. [azimuthal resistivity, EMI, VLF, thermal]

Johnson, G.A. and T.E. Saylor. 1987. Detailed Subsurface Mapping of Fracture Closure in a Crystalline Bedrock Formation. In: Proc. First Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 643-657. [ER]

Joiner, T.J. and W.L. Scarborough. 1969. Hydrology of Limestone Terranes: Geophysical Investigations. Geological Survey of Alabama Bull. 94D. [ER, GR, SRR]

Joiner, TJ., J.C. Warman, W.L Scarborough, and D.B. Moore. 1967. Geophysical Prospecting for Ground Water in the Piedmont Area, Alabama. Alabama Geological Survey Circular 42,48 pp. [ER, MAG, SRR]

Joiner, TJ., J.C. Warman, and W.L. Scarborough. 1968. An Evaluation of Some Geophysical Methods for Water Exploration in the Piedmont Area. Ground Water 6(1):19-25. [ER, SRR]

Jones, B.E. 1937. Results to Be Expected from Resistivity Measurements. Trans. Am. Geophysical Union 18:399-403.

Kalenov, E.N. 1957. Interpretation of Vertical Electrical Sounding Curves. Gostopekhizdat, Moscow, 472 pp.

Kean, W.F. and R.B. Rogers. 1981. Monitoring Leachate in Groundwater by Corrected Resistivity Methods. Bull. Ass. Eng. Geol. 18(1):101-107.

Kean, W.F., R.W. Taylor, and J.M. Byers. 1984. Electrical Conductivity, Clay Content and Porosity of Unconsolidated Sediments. 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. 1-17.

Kean, W. F., M.J. Wailer, and H.R. Layson. 1987. Monitoring Moisture Migration in the Vadose Zone with Resistivity. Ground Water 25(5):562-571.

Keck, W. G., G. Henry, Jr. and R.C. Minning. 1981. The Keck Method of Computing Apparent Resistivity. Ground Water Monitoring Review 1(4):64-68.

Keevil, Jr., N.B. and S.H. Ward. 1962. Electrolyte Activity Its Effect on Induced Polarization. Geophysics 27(5):677-690.

Keller, G.V. and F.C. Frischknecht. 1970. Electrical Methods in Geophysical Prospecting, 2nd ed. Pergamon Press, New York, 517 pp. [First edition 1966).

Kelly, S.F. 1961. Geophysical Exploration for Water by Electrical Resistivity. New England Water Works ASS. J. 65(2):118-189.

Kelly, W.E. 1976a. Estimating Aquifer Permeability by Surface Electrical Resistivity Measurements. University of Rhode Island Department of Civil Engineering Technical Report, NTIS PB261-584.

Kelly, W.E. 1976b. Geoelectric Sounding for Delineating Ground-Water Contamination. Ground Water 14:6-10.

Kelly, W.E. 1977. Geoelectric Sounding for Estimating Aquifer Hydraulic Conductivity. Ground Water 15(6):420-425. [See also 1978 discussion by M.A. Sabet and reply in Ground Water 16(3):206-207]

Kelly, W.E. and R.K Frohlich. 1985. Relation Between Aquifer Electrical and Hydraulic Properties. Ground Water 23(2):182-189.

Kelly, W.E. and P.F. Reiter. 1984. Influence of Anisotropy on Relations Between Aquifer Hydraulic and Electrical Properties. J. Hydrology 74:311-321.

Kelly, W.E., I. Bogardi, M. Nicklin, and A. Bardossy. 1988. Combining Surface Geoelectrics and Geostatistics for Estimating the Degree and Extent of Ground-Water Pollution. In: Ground-Water Contamination: Field Methods, A.G. Collins and A.I. Johnson (eds.), ASTM STP 963, American Society for Testing and Materials, Philadelphia, PA, pp. 73-85. [ER]

Kelly, W.E., I. Bogardi, O. Mazac, and I. Landa. 1989. Geoelectrics in Ground-Water Studies. In: Recent Advances in Ground-Water Hydrology. J.E. Moore, A.A. Zaporozec, S.C. Csallany, and T.C. Varuly (eds.), American Institute of Hydrology, Minneapolis, MN, pp. 422-436. [EMI, ER].

Kent, D.C. and L.V.A. Sendlein. 1972. Å Basin Study of Ground-Water Discharge from Bedrock into Glacial Drift: Part 1, Definition of Ground-Water Systems. Ground Water 10(4):24-34. [ER, SRR]

Kirk, K.G. and H.W. Rauch. 1977a. Location of Fracture Zones by Electrical Resistivity Surveying with the Tri-Potential Technique (Abstract). EOS (Tans. Am. Geophys. Union) 58(6):392.

Kirk, K.G. and H. Rauch. 1977b. The Application of the Tri-Potential Method of Resistivity Prospecting for Ground-Water Exploration and Land Use planning in Karst Terrains. In: Karst Hydrogeology: Proceedings of the Twelfth Meeting of the International Association of Hydrogeologists, J.S. Tolson and F.L. Doyle (eds.), University of Alabama-Huntsville Press, Huntsville, AL, pp. 285-299.

Kirk, K.G. and E. Werner. 1981. Handbook of Geophysical Cavity-Locating Techniques with Emphasis on Electrical Resistivity. U.S. Department of Transportation, 174 pp.

Klefstad, G., L.V.A. Sendlein, and R.C. Palmquist. 1975. Limitations of the Electrical Resistivity Measurements in Landfill Investigations. Ground Water 13(5):418-427.

Knuth, M. 1988. Complementary Use of EM-31 and Dipole-Dipole Resistivity to Locate the Source of Oil Brine Contamination. In: Proc. 2nd Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 583-595.

Kofoed O. 1979. Geosounding Principles I, Resistivity Sounding Measurements. Elsevier, New York, 276 pp.

Kosinski, W.K and W. E. Kelly. 1981. Geoelectric Sounding for Predicting Aquifer Properties. Ground Water 19(2): 163-171. [See also 1982 discussion by P.J. Leonard-Mayer and R.W. Taylor and reply in Ground Water 20(1) :111-112.]

Krumenacher, M.S. and R.W. Taylor. 1988. Innovative Application of Induced Polarization for Detecting Organic Ground Water Contamination. In: Proc. (5th) NWWA/API Conf. on Petroleum Hydrocarbons and Organic Chemicals in Ground Water: Prevention, Detection and Restoration, National Water Well Association, Dublin, OH, pp. 75-90.

Kunetz, G. 1966. Principles of Direct Current Resistivity Prospecting. Geoexploration Monograph Series No. 1. Gebrüder Borntraeger, Berlin, 103 pp.

Kwader, T. 1985. Estimating Aquifer Permeability from Formation Resistivity Factors. Ground Water 23(6):762-766.

Laine, D.L. and M.P. Miklas, Jr. 1989. Detection and Location of Leaks in Geomembrane Liners Using an Electrical Method: Case Histories. In: Superfund ’89, Proceedings of the 10th Annual Conference, Hazardous Material Control Research Institute, Silver Spring, MD, pp. 35-40.

Laine, D.L., J.O. Parra, and T.E. Owen. 1985. Application of an Automatic Earth Resistivity System for Detecting Ground Water Migration under a Municipal Landfill. In: Conference on Surface and Borehole Geophysical Methods and Ground Water Investigations (2nd, Fort Worth, TX), National Water Well Association, Dublin, OH, pp. 34-51.

Lange, A.L. and J.F. Quinlan. 1988. Mapping Caves from the Surface of Karst Terranes by the Natural Potential Method. In: Proc. Second Conf. on Environmental Problems in Karst Terranes and Their Solutions (Nashville, TN), National Water Well Association, Dublin, OH, pp. 369-390. [SP]

Lange, A.L., R.B. McEuen, and E.P. Gustafson. 1986. The Application of Active and Passive Electrical Methods in Ground Water Monitoring. In: Proc. Surface and Borehole Geophysical Methods and Ground Water Instrumentation Conf. and Exp., National Water Well Association, Dublin, OH, pp. 87-116. [ER, SP]

LeBrecque, DJ., D.D. Weber, and R.B. Evans. 1984a. Comparison of the Resistivity and Electromagnetic Methods over a Contaminant Plume Using Numerical Modeling. In: NWWA/EPA Conf. on Surface and Borehole Geophysical Methods in Ground Water Investigations (1st, San Antonio, TX), National Water Well Association, Dublin, OH, pp. 316-323.

LeBrecque, D.J., D.D. Weber, and R.B. Evans. 1984b. Numerical Modeling of Electrical Geophysical Data over Contaminated Plumes. In: Proc. (lst) Nat. Conf. on Hazardous Wastes and

Environmental Emergencies, Hazardous Materials Control Research Institute, Silver Spring, MD, pp. 117-122.

Lee, F.W. 1936. Geophysical Prospecting for Underground Waters in Desert Areas. US. Bureau of Mines Information Circular 6899,27 pp. [ER]

Lennox, D.H. and V. Carlson. 1970. Integration of Geophysical Methods for Ground Water Exploration in the Prairie Provinces, Canada. In: Mining and Groundwater Geophysics/1967, L.W. Merely (cd.), Geological Survey of Canada Economic Geology Report 26, pp. pp. 517-535. [ER, GR, SRR]

Leonard-Mayer, P.J. 1984a. A Surface Resistivity Method for Measuring Hydrologic Characteristics of Jointed Formations. U.S. Bureau of Mines Report of Investigations 8901, 45 pp. [azimuthal resistivity]

Leonard-Mayer, P.J. 1984b. Development and Use of Azimuthal Resistivity Surveys for Jointed Formations. 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. 52-91.

Lord, Jr., A. E., S. Tyagi, and R.M. Koerner. 1980. Nondestructive Testing (NDT) Methods Applied to Environmental Problems Involving Hazardous Material Spills. In: Proc. Nat. Conf. on Control of Hazardous Materials Spills (Louisville, KY), Vanderbilt University, Nashville, TN, pp. 174-179. [Review of 17 methods including SP and IP; both had low ratings for applications evaluated.]

Lord, Jr., A.E, and R.M. Koerner. 1987. Nondestructive Testing (NDT) Techniques to Detect Contained Subsurface Hazardous Waste. EPA/600/2-87/078 (NTIS PB88-102405). [17 methods, including ER, SP and IP; EM I, GPR, MAG, MD best]

Madden, T.R. and T. Cantwell. 1967. Induced Polarization: A Review. In: Mining Geophysics, Vol. II, Theory, D.A. Hansen et al. (eds.), Society of Exploration Geophysicists, Tulsa, OK pp. 373-400.

Maillet, R. 1947. The Fundamental Equations of Electrical Prospecting. Geophysics 12(4):529-556.

Mark, D.L., D.S. Williams, and D. Huntley. 1986. Application of Dipole-Dipole Resistivity to a Hydrogeologic Investigation. In: Proc. Surface and Borehole Geophysical Methods and Ground Water Instrumentation Conf. and Exp., National Water Well Association, Dublin, OH, pp. 151-152.

Marshall, D.J. and T.R. Madden. 1959. Induced Polarization, A Study of Its Causes. Geophysics 24(4):790-816.

Martinelli, E. 1978. Ground Water Exploration by Geoelectrical Methods in Southern Africa. Bull. Ass. Eng. Geol. 15(1):113-124.

Mattick, R.E., F.H. Olmsted, and A.A.R. Zohdy. 1973. Geophysical Studies in the Yuma Area, Arizona and California. U.S. Geological Survey Professional Paper 726-D, 36 pp. [SRR, ER, GR, SRL, AEM]

Mazac, O., W.E. Kelly, and I. Landa. 1985. A Hydrogeophysical Model for Relations Between Electrical and Hydraulic Properties of Aquifer. J. Hydrology 791-19.

Mazac, O., W.E. Kelly, and Il Landa. 1987. Surface Geoelectrics for Groundwater Pollution and Protection Studies. J. Hydrology 93:277-294.

Mazac, O., I. Landa, and W.E. Kelly. 1989. Surface Geoelectrics for the Study of Ground-Water Pollution. J. Hydrology 111:163-176.

Mazac, O., W.E. Kelly, and I. Landa. 1992. Geoelectrics on Comprehensive Ground Water Contamination Studies. In: Current Practices in Ground Water and Vadose Zone Investigations, ASTM STP 1118, D.M. Nielsen and M.N. Sara (eds.), American Society for Testing and Materials, Philadelphia, PA, pp. 79-89.

Mbonu, P.D.C., J.O. Ebeniro, C.O. Ofoegbu, and A.S. Ekine. 1991. Geoelectric Sounding for the Determination of Aquifer Characteristics in Parts of the Umuahla Area of Nigeria. Geophysics 56(2):284-291.

McGinnis, L.D. and J.P. Kempton. 1961. Integrated Seismic, Resistivity, and Geological Studies of Glacial Deposits. Illinois State Geological Survey Circular 323, 23 pp.

Medeiros, W.E. and O.A. L. de Lima. 1990. A Geoelectrical Investigation for Ground Water in Crystalline Terrains of Central Bahia, Brazil. Ground Water 28(4):518-523.

Meidav, T. 1960. An Electrical-Resistivity Survey for Ground Water. Geophysics 25(5):1077-1093.

Merkel, R.H. 1972. The Use of Resistivity Techniques to Delineate Acid Mine Drainage in Ground Water. Ground Water 10(5):38-42.

Merkel, R.H. and J.T. Kaminski. 1972. Mapping Ground Water by Using Electrical Resistivity with a Buried Current Source. Ground Water 10(2):18-25.

Mohamed, S.S. 1970. Induced Polarization: A Method to Study the Water Collecting Properties of Rocks. Geophysical Prospecting 18:654-665.

Mooney, H.M. 19W. Handbook of Engineering Geophysics, Vol 2: Electrical Resistivity. Bison Instruments, Minneapolis, MN, 83 pp.

Mooney, R.M. and W.W. Wetzel. 1956. The Potentials about a Point Electrode and Apparent Resistivity Curves for a Two-, Three- and Four-Layered Earth. University of Minnesota Press, Minneapolis, MN, 145 pp.

Niwas, S. and D.C. Singhal. 1985. Aquifer Transmissivity of Porous Media from Resistivity Data. J. Hydrology 82:143-153.

Noel, M.R., R.C. Benson, and R.A. Glaccum. 1982. The Use of Contemporary Geophysical Techniques to Aid Design of Cost-Effective Monitoring Well Networks and Data Analysis. In: Proc. Second Nat. Symp. on Aquifer Restoration and Ground Water Monitoring, National Water Well Association, Dublin, OH, pp. 163-168. [EMI, ER]

Ogden, A.E. and P.S. Eddy, Jr. 1984. The Use of Tri-Potential Resistivity to Locate Fractures and Caves for Siting High Yield Water Wells. 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. 130-149.

Ogden, A.E., J.T. Taylor, and M.O. Smith. 1991. Tri-Potential Resistivity Applications at a Leaky Underground Storage Tank Site. In: Proc. (4th) Symp. on the Application of Geophysics to Engineering and Environmental Problems, Sot. Eng. and Mineral Exploration Geophysicists, Golden, CO, pp. 247-260.

Ogilvy, A.A. and V. Bogoslovsky. 1979. The Possibilities of Geophysical Methods Applied for Investigating the Impact of Man on the Geologic Medium. Geophysical Prospecting 27(4):775-789. [SP]

Ogilvy, A.A. and E.N. Kuzima. 1972. Hydrogeologic and Engineering Geologic Possibilities for Employing the Methods of Induced Potentials. Geophysics 37(5):839-861.

Ogilvy, A.A., M.A. Ayed and V. Bogoslovsky. 1969. Geophysical Studies of Water Leakages from Reservoirs. Geophysical Prospecting 17:36-62. [SP]

Olhoeft, G.R. 1984. Clay-Organic Reactions Measured with Complex Resistivity. In: Expanded Abstracts, 54th Annual International Meeting and Exposition of the Society of Exploration Geophysicists, SEG, Tulsa, OK, pp. 147-148.

Olhoeft, G.R. 1985. Low-Frequency Electrical Properties. Geophysics 50(12):2492-2503.

Olhoeft, G.R. 1986. Direct Detection of Hydrocarbons and Organic Chemicals with Ground Penetrating Radar and Complex Resistivity. In: Proc. (3rd) NWWA/API Conf. on Petroleum Hydrocarbons and Organic Chemicals in Ground Water, National Water Well Association, Dublin, OH, pp. 284-305.

Olhoeft, G.R. 1990. Monitoring Geochemical Processes with Geophysics. In: In: Proc. of a U.S. Geological Survey Workshop on Environmental Geochemistry, B.R. Doe (cd.), U.S. Geological Survey Circular 1033, pp. 57-60. [complex resistivity]

Olhoeft, G.R. 1992. Geophysical Detection of Hydrocarbon and Organic Chemical Contamination. In: SAGEEP ’92, Society of Engineering and Mineral Exploration Geophysicists, Golden, CO, pp. 587-595. [complex resistivity, GPR]

Olhoeft, G.R. and T.V.V. King. 1991. Mapping Subsurface Organic Compounds Noninvasively by Their Reactions with Clays. In: U.S. Geological Survey Toxic Substance Hydrology Program, Proceedings of the Technical Meeting, Monterey, CA, March 11-15, 1991, U.S. Geological Survey Water Resources Investigations Report 91-4043, pp. 552-557. [complex resistivity]

Orellana, E. and H.M. Mooney. 1966. Master Tables and Curves for Vertical Electrical Sounding over Layered Structures. Intersciencis, Madrid, Spain, 150 pp. (Available from. Technical Information Center, U.S. Army Corps of Engineers Waterways Experiment Station, PO Box 631, Vicksburg, MS, 39180).

Orellana, E. and H.M. Mooney. 1972. Two- and Three-Layer Master Curves and Auxiliary Point Diagrams for Vertical Electrical Sounding Using Wenner Arrangement. Intersciencia, Madrid, Spain, 41 pp.

Page, L.M. 1968. Use of the Electrical Resistivity Method for Investigation Geologic and Hydrologic Conditions in Santa Clara County, California. Ground Water 6(5):31-40.

Park, S.K. and S.K Dickey. 1989. Accurate Estimation of Conductivity of Water From Geoelectrical Measurements-A New Way to Correct for Clay. Ground Water 27:786-792.

Parkhomenko, E.I. 1967. Electrical Properties of Rocks. Plenum Press, New York, 314 pp.

Parra, J.O. 1988a. Electrical Response of a Leak in a Geomembrane Liner. Geophysics 53(11):1445. 1452.

Parra, J.O. 1988b. Model Studies of Electrical Leak Detection Surveys in Geomembrane-Lined Impoundments. Geophysics 53(11):1453-1458.

Patella, D. and D. Schiavone. 1977. Comparative Analysis of Time-Domain and Frequency-Domain in the Induced-Polarization Prospecting Method. Geophysical Prospecting 25(3):496-511.

Patra, H.P. and K. Mallick. 1980. Geosounding Principles, Vol. 2, Time Varying Geoelectric Soundings. Elsevier, New York.

Pease, Jr., R.W. and S.C. James. 1981. Integration of Remote Sensing Techniques with Direct Environmental Sampling for Investigating Abandoned Hazardous Waste Sites. In: Proc. (2nd) Nat. Conf. on Management of Uncontrolled Hazardous Waste Sites, Hazardous Materials Control Research Institute, Silver Spring, MD, pp. 171-176. [ER, GPR, MD, SRR]

Pennington, D. 1985. Selection of Proper Surface Resistivity Techniques and Equipment for Evaluation of Groundwater Contamination. In: Conference on Surface and Borehole Geophysical Methods and Ground Water Investigations (2nd, Fort Worth, TX), National Water Well Association, Dublin, OH, pp. 23-33.

Peters, W. R., D.W. Shultz, and B.M. Duff. 1982a. Electrical Resistivity Techniques for Locating Liner Leaks. In: Proc. (3rd) Nat. Conf. on Management of Uncontrolled Hazardous Waste Sites, Hazardous Materials Control Research Institute, Silver Spring, MD, pp. 31-35.

Peters, W. R., D.W. Shultz, and B.M. Duff. 1982b. Electrical Resistivity Techniques for Locating Liner Leaks. In: Proc. 8th Research Symp. (Land Disposal of Hazardous Waste), EPA/600/9-82/002 (PB82-173022), pp. 250-260.

Petersen, R. C., J.R. Wagner, M.A. Hemphill-Haley, L.N. Weller, R. Kilbury, and J.B.F. Champlin. 1986. Resistivity Mapping of a Complex Aquifer System at a Hazardous Waste Site in the Salinas Valley, California. In: Proc. Surface and Borehole Geophysical Methods and Ground Water Instrumentation Conf. and Exp., National Water Well Association, Dublin, OH, pp. 197-202. [ER, EM I]

Pfeifer, M.C., H.T. Andersen, and C.K. Skokan. 1990. Permanent DC-Resistivity Arrays to Monitor the Development of a Disturbed Rock Zone Around Underground Excavations. In: Proc. (3rd) Symp. on the Application of Geophysics to Engineering and Environmental Problems, Sot. Eng. and Mineral Exploration Geophysicists, Golden, CO, pp. 243-254.

Pitchford, A.M., A.T. Mazzella, and K.R. Scarborough. 1988. Soil-Gas and Geophysical Techniques for Detection of Subsurface Organic Contamination. EPA/600/4-88/019 (NTIS PB88-208194). [GPR, EMI, ER, complex resistivity, SRR, MD, MAG]

Plivas, G. and J. Wong. 1975. Resistivity Investigations of the Salt-Water a Contamination of a Sandy Aquifer in the Township of Ancaster. In: Case Histories in the Application of Geophysics to

Ground Water Problems, Water Resource Paper 5, Ontario Ministry of Environment, Toronto Ont.

Poole, V.L. and P.C. Heigold. 1981. Geophysical Assessment of Aquifers Supplying Ground Water to Eight Small Communities in Illinois. Illinois State Geological Survey Environmental Geology Notes 91. [ER]

Priddy, R.R. 1955. Fresh-Water Strata of Mississippi as Revealed by Electric Studies. Miss. Geol. Surv. Bull. 83.

Radstake, F, W. Geirnaert, T.W. Kleinendorst, and J.C. Terhell. 1991. Applications of Forward Modeling Resistivity Profiles. Ground Water 29(1):13-17.

Reed, P.C. 1985. Comparative Analysis of Surface Resistivity Surveys and Natural-Gamma Radiation Borehole Logs in Illinois. In: NWWA Conference on Surface and Borehole Geophysical Methods and Ground Water Investigations (2nd, Fort Worth, TX), National Water Well Association, Dublin, OH, pp. 215-227.

Reed, P. C., K. Cartwright, and D. Osby. 1981. Electrical Earth Resistivity Surveys near Brine Holding Ponds in Illinois. Illinois State Geological Survey Environmental Geology Notes 95.

Reed, P.E., P.D. DuMontelle, M.L. Sargent and M.M. Killey. 1983. Nuclear Logging and Electrical Earth Resistivity Techniques in the Vadose Zone in Glaciated Earth Materials. In: Proc. NWWA/EPA Conf. on Characterization and Monitoring in the Vadose (Unsaturated) Zone (lst, Las Vegas, NV), National Water Well Association, Dublin, OH, pp. 580-601.

Rehm, B.W., T.R. Stolzenburg, and D.G. Nichols. 1985. Field Measurement Methods for Hydrogeologic Investigations: A Critical Review of the Literature. EPRI EA-4301 Electric Power Research Institute, Palo Alto, CA. [Major methods: ER, EMI, SRR, BH, Other: IR, SP, IP/CR, SRR, GPR, MAG, GR]

Rijo, L., W.H. Pelton, E.C. Feitosa, and S.H. Wood. 1977. Apparent Resistivity Data from Apachi Valley, Rio Grande Do Norte, Brazil. Geophysics 42(4):811-822. [ground water resource evaluation]

Ringstad, C.A. and D.C. Bugenig. 1984. Electrical Resistivity Studies to Delimit Zones of Acceptable Ground Water Quality. Ground Water Monitoring Review 4(4):66-69.

Ritzi, Jr., R.W. and R.H. Andolsek. 1992. Relation Between Anisotropic Transmissivity and Azimuthal Resistivity Surveys in Shallow, Fractured Carbonate Flow Systems. Ground Water 30(5):774-780.

Roberts, R. G., W.J. Hinze, and D.I. Leap. 1989. A Multi-Technique Geophysical Approach to Landfill Investigations. In: Proc. 3rd Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 797-811. [EMI, ER, GPR, GR, MAG, SRR]

Rodriguez, E.B. 1984. A Critical Evaluation of the Use of Geophysics in Ground Water Contamination Studies in Ontario. 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. 603-617. [EMI, ER, VLFl

Rodriguez R. and J.P. Wellner, Jr. 1988. Mapping Subsurface Leakage Systems in Karst Areas Using the Method of Electrical Resistivity, Russellville, Kentucky. In: Proc. Second Conf. on Environmental Problems in Karst Terranes and Their Solutions (Nashville, TN), National Water Well Association, Dublin, OH, pp. 391-418.

Rogers, R.B. and W.F. Kean. 1980. Monitoring Groundwater Contamination at a Fly-Ash Disposal Site Using Surface Electrical Resistivity Methods. Ground Water 18:472-478.

Roman, I. 1952. Resistivity Reconnaissance. In: Symposium on Surface and Subsurface Reconnaissance, ASTM STP 122, American Society for Testing and Materials, Philadelphia, PA, pp. 171-220.

Roux, P.H. 1978. Electrical Resistivity Evaluations of Solid Waste Disposal Facilities. EPA/SW-729, 94 pp.

Roy, A. and A. Apparao. 1971. Depth of Investigation in Direct Current Methods. Geophysics 36:943-959.

Roy, A. and C. Shikhar. 1973. Comparative Field Performance of Electrode Arrays in Time Domain Induced Polarization Profiling. Geophysical Prospecting 21:626-634.

Roy, K.K. and H.M. Elliot. 1980. Resistivity and IP Surveys for Delineating Saline Water and Fresh Water Zones. Geoexploration 18:145-162.

Rudy, R.J. and J.A. Caoile. 1984. Utilization of Shallow Geophysical Sensing at Two Abandoned Municipal/Industrial Waste Landfills on the Missouri River Floodplain. Ground Water Monitoring Review 4(4):57-65. [ER, EMI]

Rumbaugh, III, J. O., J.A. Caldwell, and S.T. Shaw. 1987. A Geophysical Ground Water Monitoring Program for a Sanitary Landfill: Implementation and Preliminary Analysis. In: Proc. First Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 623-641. [EMI, ER]

Russell, G.M. 1990. Application of Geophysical Techniques for Assessing Ground-Water Contamination near a Landfill at Stuart Florida. In: Ground Water Management 3:211-225 (7th NWWA Eastern GW Conference). [ER, EMI, VLF, GPR]

Russell, G.M. and A.L. Higer. 1988. Assessment of Ground-Water Contamination near Lantana Landfill, Southeast Florida. Ground Water 26(2):156-164. [ER]

Samuelson, A.C. 1987. Electrical Resistivity Applications to Glacial Groundwater Site Evaluations in East-Central Indiana. In: Proc. NWWA Focus Conf. on Midwestern Ground Water Issues (Indianapolis, IN), National Water Well Association, Dublin, OH, pp. 207-229.

Sauck, W.A. and S.M. Zabik. 1992. Azimuthal Resistivity Techniques and the Directional Variations of Hydraulic Conductivity in Glacial Sediments. In: SAGEEP '92, Society of Engineering and Mineral Exploration Geophysicists, Golden, CO, pp. 197-222.

Saunders, W.R. and J.A. Stanford. 1984. Integration of Individual Geophysical Techniques as a Means to Characterize an Abandoned Hazardous Waste Site. 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. 584-602. [EMI, ER, SRR]

Sayed, M.A. 1984. Use of Electrical Resistivity Method to Study Vertical Hydrologic Boundaries in Wadi Sudr, Sinai Peninsula, Egypt. In: Proc. 2n Int. Conf. on Ground Water Quality Research, N.N. Durham, and A.E. Redelfs (eds.), Oklahoma State University, Stillwater, OKj pp. 203-207.

Sayre, A.N. and E.L. Stephenson. 1937. The Use of Resistivity Methods in the Location of Saltwater Bodies in the El Paso, Texas Area. Trans. Am. Geophys. Union 18:393-398.

Schimschal, U. 1981. The Relationship of Geophysical to Hydraulic Conductivity at the Brantley Dam Site, New Mexico. Geoexploration 19:115-125. [DC resistivity, neutron probe]

Schneider, G.W. and J.P. Greenhouse. 1992. Geophysical Detection of Perchloroethylene in a Sandy Aquifer Using Resistivity and Nuclear Logging Techniques. In: SAGEEP '92, Society of Engineering and Mineral Exploration Geophysicists, Golden, CO, pp. 619-628.

Schoepke, R.A. and K.O. Thomsen. 1991. Use of Resistivity Soundings to Define the Subsurface Hydrogeology in Glacial Sediments. In: Ground Water Management 5:917-929 (5th NOAC). [Michigan TCE contamination]

Schroeder, N. 1970. Interpretation of Depth to Salt Water by Application of Electrical Soundings. Geoexploration 8:l13-116.

Schultz, D.W.R. and B.M. Duff. 1985. An Electrical Technique for Detecting Leaks in Membrane Liners. In: Proc. llth Research Symp. (Land Disposal of Hazardous Waste), EPA 600/9-85/013 (PB85-196376), pp. 371.

Schultz, D.W., B.M. Duff, and W.R. Peters. 1984a. Technique to Assess the Integrity of Geomembrane Liners. EPA/600/2-84/180 (NTIS PB85-122414), 78 pp.

Schultz, D.W., B.M. Duff, and W.R. Peters. 1984a. Performance of an Electrical Resistivity Technique for Detecting and Locating Geomembrane Failures. EPA/600/D-84/123 (NTIS PB84-190594), 16 pp.

Seigel, H.O. 1959. Mathematical Formulation and Type Curves for Induced Polarization. Geophysics 24(3):547-565.

Seitz, H., A.T. Wallace, and R.E. Williams. 1972. Investigation of a Landfill in Granite Loess Terrain. Ground Water 10(4):35-41. [ER]

Sheriff, S.D. 1992. Spreadsheet Modeling of Electrical Sounding Experiments. Ground Water 30(6):971-974.

Shields, R.R. and W.E. Sopper. 1969. An Application of Surface Geophysical Techniques to the Study of Watershed Hydrology. Water Resources Bull. 5(3):37-49. [ER, SRR]

Sjostrom, K-J. and W.R. Sill. 1991. An Electrical Technique for Determination of Groundwater Flow Parameters. In: Proc. (4th) Symp. on the Application of Geophysics to Engineering and Environmental Problems, Sot. Eng. and Mineral Exploration Geophysicists, Golden, CO, pp. 119-128.

Smith, E.M. 1974. Exploration for a Buried Valley by Resistivity and Thermal Probe Surveys. Ground Water 12(2):78-83.

Smith, B.P. 1991. Application of Electrokinetic Spontaneous Potentials to Hydrogeologic Investigations in Northern New England. In: Ground Water Management 7:711-725 (8th NWWA Eastern GW Conference). [landfill, dam seepage]

Smith, D.L. and A.F. Randazzo. 1986. Assessment by Electrical Resistivity Methods of Potential Geological Hazards in Karstic Terranes. In: Proc. Environmental Problems in Karst Terranes and Their Solutions Conference (Bowling Green, KY), National Water Well Association, Dublin, OH, pp. 487-501.

Smith, D.L. and A. F. Randazzo. 1989. Application of Electrical Resistivity Measurements in the Identification of Preferred Zones of Groundwater Transmissivity. In: Proc. Third Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 979-992.

Soiltest, Inc. 1968. Earth Resistivity Manual. Soiltest, Inc., Evanston, IL, 46 pp. [Now Soiltest Products, Division, ELE International, Lake Bluff, IL]

Spicer, H.C. 1952. Electrical Resistivity Studies of Subsurface Conditions near Antigo, Wisconsin. U.S. Geological Survey Circular 181.

Stearns, B.G. and L.M.J. Dialmann, III. 1986. Geophysical Techniques and Monitoring Network Design at the Sike Disposal Pit Hazardous Waste Site, Crosby, TX. In: Proc. Surface and Borehole Geophysical Methods and Ground Water Instrumentation Conf. and Exp., National Water Well Association, Dublin, OH, pp. 657-673. [ER, GPR]

Stewart, M. and J. Wood 1986. Geologic and Geophysical Character of Fracture Zones in a Carbonate Aquifer. In: Proc. Focus Conf. on Southeastern Ground Water Issues (Tampa, FL), National Water Well Association, Dublin, OH, pp. 289-294. [ER, GR]

Stewart, M., M. Layton, and T. Lizanec. 1983. Applications of Resistivity Surveys to Regional Hydrogeologic Reconnaissance. Ground Water 21(1):42-48.

Stewart, M., A. Stodghill, and P. Putzier. 1985. Geoelectric Delineation of a Coastal Ridge Aquifer. In: NWWA Conference on Surface and Borehole Geophysical Methods and Ground Water Investigations (2nd, Fort Worth, TX), National Water Well Association, Dublin, OH, pp. 1-11.

Stickel, Jr., J.F., L.E. Blakely, and B.B. Gordon. 1952. Geophysics and Water. J. Am. Water Works Ass. 44:23-35. [ER, SRR]

Stierman, D.J. and L.C. Ruedisili. 1988. Integrating Geophysical and Hydrogeological Data: An Efficient Approach to Remedial Investigations of Contaminated Ground Water. In: Ground-Water Contamination: Field Methods, A.G. Collins and A.I. Johnson (eds.), ASTM STP 963, American Society for Testing and Materials, Philadelphia, PA, pp. 43-56. [ER, EM I]

Stierman, D.J., L.C. Ruedisili, and J.M. Stangl. 1986. The Application of Surface Geophysics to Mapping Hydrogeologic Conditions of a Glaciated Area in Northwest Ohio. In: Proc. Surface and Borehole Geophysical Methods and Ground Water Instrumentation Conf. and Exp., National Water Well Association, Dublin, OH, pp. 591-600. [ER, SRR, MAG]

Stellar, R.L. and P. Roux. 1975. Earth Resistivity Surveys-A Method for Defining Ground-Water Contamination. Ground Water 13:145-150. Association, Dublin, OH, pp. 327-333.

Sumner, J.S. 1976. Principles of Induced Polarization for Geophysical Interpretation. Elsevier, New York, 277 pp.

Sumner, J.S. 1979. The Induced Polarization Exploration Method. In: Geophysics and Geochemistry in the Search of Metallic Ores, P.J. Hood (cd.), Economical Geology Report 31, Geological Survey of Canada, pp. 123-133.

Swartz, J.H. 1937. Resistivity Studies of Some Salt-Water Boundaries in the Hawaiian Islands. Trans. Am. Geophys. Union 18387-393.

Swartz, J.H. 1939. Geophysical Investigations in the Hawaiian Islands., Trans. Am. Geophys. Union 20:292-298.

Sweeney, J.J. 1984. Comparison of Electrical Resistivity Methods for Investigation of Ground Water Conditions at a Landfill Site. Ground Water Monitoring Review 4(1):52-59. [ER, EMI]

Tamburi, A., R. Allard, and U. Roeper. 1985. Tomographic Imaging of Ground Water Pollution Plumes. In: Hazardous Wastes in Ground Water: A Soluble Dilemma (Proc. 2nd Canadian/American Conference on Hydrogeology, Banff, Alberta), B. Hitchon, and M.R. Turdell (eds.), National Water Well Association. [ER]

Tamburi, A., U. Roelper, and A. Wexler. 1988. An Application of Impedance-Computed Tomography to Subsurface Imaging of Pollution Plumes. In: Ground-Water Contamination: Field Methods, A.G. Collins and A.I. Johnson (eds.), ASTM STP 963, American Society for Testing and Materials, Philadelphia, PA, pp. 86-100. [ER]

Taylor, R.W. 1984. The Determination of Joint Orientation and Porosity from Azimuthal Resistivity Measurements. 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. 37-49.

Taylor, R.W. 1985. An Automated D.C. Resistivity System. In: NWWA Conference on Surface and Borehole Geophysical Methods and Ground Water Investigations (2nd, Fort Worth, TX), National Water Well Association, Dublin, OH, pp. 12-22. [ER, IP, SP]

Taylor, R.W. 1992. Continuous Electrical Resistivity Surveys Along the Lake Michigan and Green Bay Coastlines of Wisconsin. In: SAGEEP ’92, Society of Engineering and Mineral Exploration Geophysicists, Golden, CO, pp. 129-144.

Taylor, R.W. and D.S. Cherkauer. 1984. The Application of Combined Seismic and Electrical Measurement to the Determination of the Hydraulic Conductivity of a Lake Bed. Ground Water Monitoring Review 4(4):78-85.

Taylor, R. and J. Jansen. 1988. Azimuthal Resistivity Techniques to Delineate Zones of High Secondary Porosity in Fracture Controlled Aquifers. In: Proc. Second Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 153-170.

Taylor, R.W. and A. Fleming. 1988. Characterization of Jointed Systems by Azimuthal Resistivity Survey. Ground Water 26:468-474.

Topper, K.D. and C.A. Legg. 1974. Geophysical Exploration for Ground Water in the Lusaka District, Republic of Zambia. J. of Geophysics (Berlin) 40(1):97-112. [ER, SRR]

Tucci, P. 1984. Surface Resistivity Studies for Water Resources Investigations, near Tucson, Arizona. 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. 92-106.

Tucci, P. 1986. Surface-Geophysical Investigations in Melton Valley, Oak Ridge Reservation, Tennessee. In: Proc. Focus Conf. on Southeastern Ground Water Issues (Tampa, FL), National Water Well Association, Dublin, OH, pp. 344-374. [EMI, ER]

Underwood, J.E., K. J. Laudon, and T.S. Laudon. 1984. Seismic and Resistivity Investigations near Norway, Michigan. Ground Water Monitoring Review 4(4):86-91.

Urish, D.W. 1981. Electrical Resistivity-Hydraulic Conductivity Relationships in Glacial Outwash Aquifers. Water Resources Research 17(5):1401-1408.

Urish, D.W. 1983. The Practical Application of Surface Electrical Resistivity to Detection of Groundwater Pollution. Ground Water 21(2):144-152.

Urish, D.W. 1984. Detection of a Radioactive Plume by Surface Resistivity Methods. 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. 413-428.

Urish, D.W. and R.K Frohlich. 1990. Surface Electrical Resistivity in Coastal Groundwater Exploration. Geoexploration 26:267-289.

U.S. Environmental Protection Agency (EPA). 1993. Subsurface Field Characterization and Monitoring Techniques: A Desk Reference Guide, Volume I: Solids and Ground Water. EPA/625/R-93/O03a. Available from EPA Center for Environmental Research Information, Cincinnati, OH. [Section 1.2 covers surface electrical methods]

U.S. Geological Survey (USGS). 1980. Geophysical Measurements. In: National Handbook of Recommended Methods for Water Data Acquisition, Chapter 2 (Ground Water, rev. 1980), Office of Water Data Coordination, Reston, VA pp. 2-24 to 2-76. [TC, MT, AMT, EMI, ER, IP, SRR, SRL, GR, BH]

Vacquier, V., C.R. Holmes, P.R. Kintzinger, and M. Lavergne. 1957. Prospecting for Groundwater by Induced Electrical Polarization. Geophysics 22660-687.

Van, G.P., S.K. Park, and P. Hamilton. 1991. Monitoring Leaks from Storage Ponds Using Resistivity Methods. Geophysics 56(8):1267-1270.

Van, G.P., S.K. Park, and P. Hamilton. 1992. Use of Resistivity Monitoring Systems to Detect Leaks from Storage Ponds. In: SAGEEP '92, Society of Engineering and Mineral Exploration Geophysicists, Golden, CO, pp. 629-648.

Van Dam, J.C. 1976. Possibilities and Limitations of the Resistivity Method of Geoelectrical Prospecting in the Solution of Geohydrogeological Problems. Geoexploration 14:179-193.

Van Dam, J.C. and J.J. Meulenkamp. 1967. Some Results of the Gee-Electrical Resistivity Method in Ground Water Investigations in the Netherlands. Geophysical Prospecting 15(1):92-115.

Van Nostrand R.G. and K.L. Cook, 1966, Interpretation of Resistivity Data. U.S. Geological Survey Professional Paper 499,310 pp.

Van Overmeeren, R.A. 1981. Combination of Electrical Resistivity, Seismic Refraction, and Gravity Measurements for Groundwater Exploration in Sudan. Geophysics 46:1304-1313.

Van Overmeeren, R.A. 1989. Aquifer Boundaries Explored by Geoelectrical Measurements in the Coastal Plains of Yemen A Case of Equivalence. Geophysics 54:38-48.

Verma, R.K 1980. Master Tables for Electromagnetic Depth Sounding Interpretation. Plenum, New York.

Verma, R.K, M.K. Rao, and C.V. Rao. 1980. Resistivity Investigations of Ground Water in Metamorphic Areas near Dhanbord, India. Ground Water 18(1):46-55.

Vogelsang, D. 1974. Compatibility of EM Soundings and IP Surveys. Geophysical Prospecting 22(4):781-790. Comments in Geophysical Prospecting 25(1):182-185.

Wachs, D., A. Arad, and A. Olshina. 1979. Locating Ground Water in the Santa Catherina Area Using Geophysical Methods. Ground Water 17(3):258-263. [ER, SRR]

Wait, J.R. (cd.). 1959. Overvoltage Research and Geophysical Applications. Pergamon Press, New York. [IP]

Wait, J.R. 1982. Gee-Electromagnetism. Academic Press, New York, 268 pp. [IP, EMI]

Wailer, M.J. and J.L. Davis. 1984. Assessment of Innovative Techniques to Detect Waste Impoundment Liner Failure. EPA/600/2-84/041 (NTIS PB84-157858), 148 pp. [28 methods assessed including ER, SRR, acoustic emission monitoring]

Walther, E. G., D. LeBrecque, D.D. Weber, R.B. Evans and J.J. Van Ee. 1983. Study of Subsurface Contamination with Geophysical Monitoring Methods at Henderson, Nevada. In: Proc. (4th) Nat. Conf. on Management of Uncontrolled Hazardous Waste Sites, Hazardous Materials Control Research Institute, Silver Spring, MD, pp. 28-36. [EMI, ER, complex resistivity]

Walther, E. G., A.M. Pitchford, and G.R. Olhoeft. 1986. A Strategy for Detecting Subsurface Organic Contaminants. In: Proc. (3rd) NWWA/API Conf. on Petroleum Hydrocarbons and Organic Chemicals in Ground Water, National Water Well Association, Dublin, OH, pp. 357-380. [complex resistivity]

Wantland, D. 1952. Geophysical Measurements of the Depth of Weathered Mantel Rock. In: Symp. on Surface and Subsurface Reconnaissance, ASTM STP 122, American Society for Testing and Materials, Philadelphia, PA, pp. 115-135. [ER]

Wantland, D. 1953. Second Phase of Geophysical Investigations in Connection with the United State Geological Survey Ground Water Studies in the Gallatin River Valley, Montana. Bureau of Reclamation Geology Report No. C-121. [ER]

Ward, S.H. 1980. Electrical, Electromagnetic and Magnetotelluric Methods. Geophysics 45(11): 1659-1660.

Ward, S.H. 1988. The Resistivity and Induced Polarization Methods. In: Proc. (lst) Symp. on the Application of Geophysics to Engineering and Environmental Problems, Sot. Eng. and Mineral Exploration Geophysicists, Golden, CO, pp. 109-251.

Ward, S. H., and D.C. Fraser. 1967. Conduction of Electricity in Rocks. In: Mining Geophysics, Vol. H, Theory, D.A. Hansen et al. (eds.), Society of Exploration Geophysicists, Tulsa, OK, pp. 197-223.

Warner, D.L. 1969. Preliminary Field Studies Using Earth Resistivity Measurements for Delineating Zones of Contaminated Ground Water. Ground Water 7(1):9-16.

Watson, J., D. Stedje, M. Barcelo, and M. Stewart. 1990. Hydrogeologic Investigation of Cypress Dome Wetlands in Well Field Areas North of Tampa Florida. In: Ground Water Management 3:163-176 (7th NWWA Eastern GW Conference). [TDEM, VLF, ER, GPR]

Wexler, A. and C.J. Mandel. 1985. An Impedance Computed Tomography Algorithm and System for Ground Water and Hazardous Waste Imaging. In: Hazardous Wastes in Ground Water: A Soluble Dilemma (Proc. 2nd Canadian/American Conference on Hydrogeology, Banff, Alberta), B. Hitchon, and M.R. Turdell (eds.), National Water Well Association, pp. 156-161. [ER]

Wheatcraft, S.W., K.C. Taylor, and J.G. Haggard. 1984. Investigation of Electrical Properties of Porous Media. EPA/600/4-84/089 (NTIS PB85-137156), 117 pp. [DC and complex resistivity.]

White, P.A. 1988. Measurement of Ground-Water Parameters Using Salt-Water Injection and Surface Resistivity. Ground Water 26(2):179-186.

White, R.M. and S.S. Brandwein. 1982. Application of Geophysics to Hazardous Waste Investigations. In: Proc. (3rd) Nat. Conf. on Management of Uncontrolled Hazardous Waste Sites, Hazardous Materials Control Research Institute, Silver Spring, MD, pp. 91-93. [EMI, ER, GPR, MAG]

White, R. M., D.G. Miller, Jr., S.S. Brandwein, and A.F. Benson. 1984. Pitfalls of Electrical Surveys for Ground Water Contamination Investigations. 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. 472-482. [EMI, ER]

Wilcox, S.W. 1944. Sand and Gravel Prospecting by the Earth Resistivity Method. Geophysics 9(1):36-46.

Williams, J. S., A.L. Tolman, and C.W. Fontaine. 1984. Geophysical Techniques in Contamination Site Investigations Usefulness and Problems. In: Proc. of the NWWA Tech. Division Eastern Regional Ground Water Conference (Newton, MA), National Water Well Association, Dublin, OH, pp. 208-233. [EMI, ER, SRR]

Williams, E.M., C.K. Skokan, and H.T. Andersen. 1990. Detection of Conductive Fracture Zones bv Underground Multicomponent DC-Resistivity Surveying. In: Proc. (3rd) Symp. on the Application of Geophysics to Engineering and Environmental Problems, Sot. Eng. and Mineral Exploration Geophysicists, Golden, CO, pp. 255-256.

Wilson, G,V., T.J. Joiner, and J.L. Warner. 1970. Evaluation, by Test Drilling, of Geophysical Methods Used for Ground-Water Development in the Piedmont Area, Alabama. Alabama Geological Survey Circular 65, 15 pp. [ER, MAG, SRR]

Windschauer, R.I. 1986. A Surface Geophysical Study of a Borrow Pit Lake. In: Proc. Surface and Borehole Geophysical Methods and Ground Water Instrumentation Conf. and Exp., National Water Well Association, Dublin, OH, pp. 283-292. [ER, EMI]

Woessner, W.W., R. Lazuk, and S. Payne. 1989. Characterization of Aquifer Heterogeneities Using EM and Surface Electrical Resistivity Surveys at the Lubrecht Experimental Forests, Western Montana. In: Proc. Third Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 951-963.

Wong, P.-Z., J. Koplik, and J.P. Tomanic. 1984. Conductivity and Permeability of Rocks. Physical Review B 30(11):6606-6614.

Workman, L.E. and M.M. Leighton. 1937. Search for Ground Water by the Electrical Resistivity Method. Trans. Am. Geophys. Union 18:403-409.

Worthington, P.F. 1975a. Procedures for the Optimum Use of Geophysical Methods in Ground-Water Development Programs. Ass. Eng. Geol. Bull. 12(1):23-38. [ER, IP, SRR, GR]

Worthington, P.F. 1975b. Quantitative Geophysical Investigations of Granular Aquifers. Geophysical Surveys 2(3):313-366. [ER, SRR]

Worthington, P.F. 1976. Hydrogeophysical Equivalence of Water Salinity, Porosity, and Matrix Conduction in Arenaceous Aquifers. Ground Water 14(4):224-232.

Worthington, P.F. 1977a. Geophysical Investigations of Ground Water Resources in the Kalahari Basin. Geophysics 42(1):87-92. [ER]

Worthington, P.F. 1977b. Influence of Matrix Conduction upon Hydrogeophysical Relationships in Arenaceous Aquifers. Water Resources Research 13(1):87-92. [See also 1977 comment by W.E. Kelly and reply in Water Resources Research 13(6) :1023-1024.]

Worthington, P. and D. Griffiths. 1975. Application of Geophysical Methods in Exploration and Development of Sandstone Aquifers. Quart. J. Eng. Geol. 8:73-102. [ER, SRR]

Yazicigil, H. and L.V.A. Sendlein. 1982. Surface Geophysical Techniques in Ground Water Monitoring, Part II. Ground Water Monitoring Review 2(1):56-62. [ER, Thermal]

Yong, R.N. and E.J. Hoppe. 1989. Application of Electric Polarization to Contaminant Detection in Soils. Canadian Geotechnical Journal 26:536-550.

Yule, D.E., J.L. Llopis, and M.K. Sharp. 1985. Geophysical Studies at Center Hill Dam, Tennessee. Misc. Paper GL-85-29. U.S. Army Corps of Engineers Waterways Experiment Station, Vicksburg, MS, 20 pp. [SP]

Zohdy, A.A.R. 1964. The Auxiliary Point Method of Electrical Sounding Interpretation, and Its Relationship to the Dar Zarrouk Parameters. Geophysics 24(3):425-433.

Zohdy, A.A.R. 1965. Geoelectrical and Seismic Refraction Investigations near San Jose, California. Ground Water 3(3):41-48.

Zohdy, A.A.R. 1969. The Use of Schlumberger and Equatorial Sounding in Groundwater Investigations near El Paso. Geophysics 34(5):713-728.

Zohdy, A.A.R. 1970a. Variable Azimuth Schlumberger Resistivity Sounding and Profiling near a Vertical Contact. U.S. Geological Survey Bull. 1313-A, 22 pp.

Zohdy, A.A.R. 1970b. Geometrical Factors of Bipole-Dipole Arrays. U.S. Geological Survey Bull. 1313-B, 27 pp.

Zohdy, A.A.R. 1970c. Electrical Resistivity Sounding with an L-Shaped Array. U.S. Geological Survey Bull. 1313-C, 20 pp.

Zohdy, A.A.R. 1974a. A Computer Program for the Automatic Interpretation of Schlumberger Sounding Curves over Horizontally Stratified Media. NTIS PB-232703/AS, 25 pp.

Zohdy, A.A.R. 1974b. A Computer Program for the Calculation of Schlumberger Sounding Curves by Convolution. NTIS PB-232056, 13 pp.

Zohdy, A.A.R. 1974c. Use of Dar Zarrouk Curves in the Interpretation of Vertical Electrical Sounding Data. U.S. Geological Survey Bull. 1313-D, 41 pp.

Zohdy, A.A.R. 1975. Automatic Interpretation of Schlumberger Sounding Curves, Using Modified Dar Zarrouk Functions. U.S. Geological Survey Bull. 1313-E, 39 pp.

Zohdy, A.A.R. 1988. Groundwater Exploration with Schlumberger Soundings near Jean, Nevada. U.S. Geological Survey Open-File Report 88-291, 66 pp.

Zohdy, A.A.R. 1989. A New Method for the Automatic Interpretation of Schlumberger and Wenner Sounding Curves. Geophysics 54(2):245-253.

Zohdy, A.A.R. and R.J. Bisdorf. 1975. Computer Programs for the Forward Calculation and Automatic Inversion of Werner Sounding Curves. NTIS PB-247265/AS.

Zohdy, A.A.R. and D.B. Jackson. 1969. Application of Deep Electrical Soundings for Ground-Water Exploration in Hawaii. Geophysics 34(4):584-600.

Zohdy, A.A., G.P. Eaton, and D.R. Mabey. 1974. Application of Surface Geophysics to Ground-Water Investigations. U.S. Geological Survey Techniques of Water-Resource Investigations TWRI 2-D1, 116 pp. [ER, GR, MAG, SRR]

Zonge, K.E. et al. 1972. Comparison of Time Frequency and Phase Measurements in Induced Polarization. Geophysical Prospecting 20:626-648.

# 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

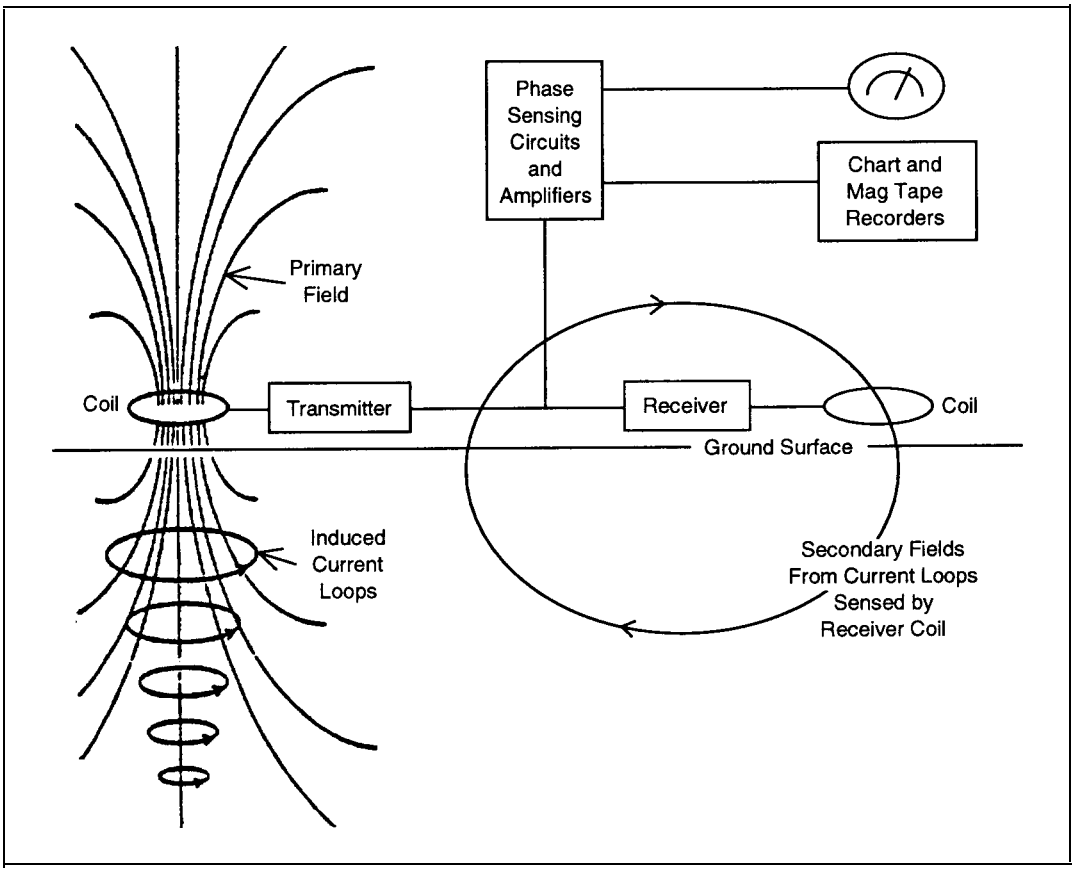


Figure 4-1a Electromagnetic induction: block diagram showing EMI principle of operations (adapted from Benson et al., 1984).

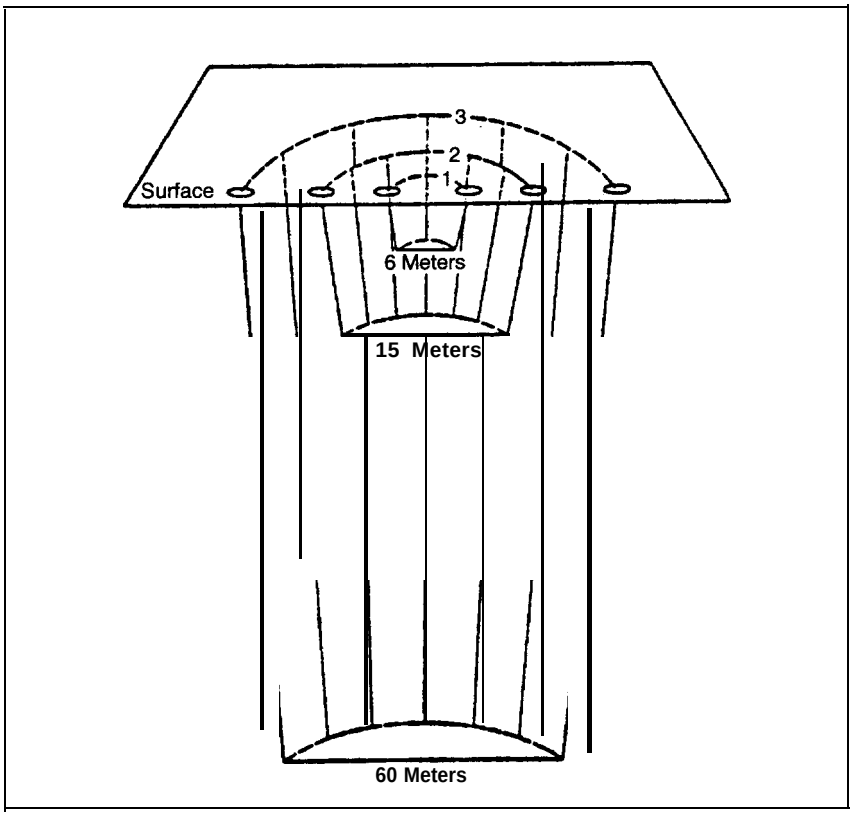


Figure 4-lb Electromagnetic induction: the depth of EMI soundings is dependent upon coil spacing and orientation selected ( from Benson et al., 1984).

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

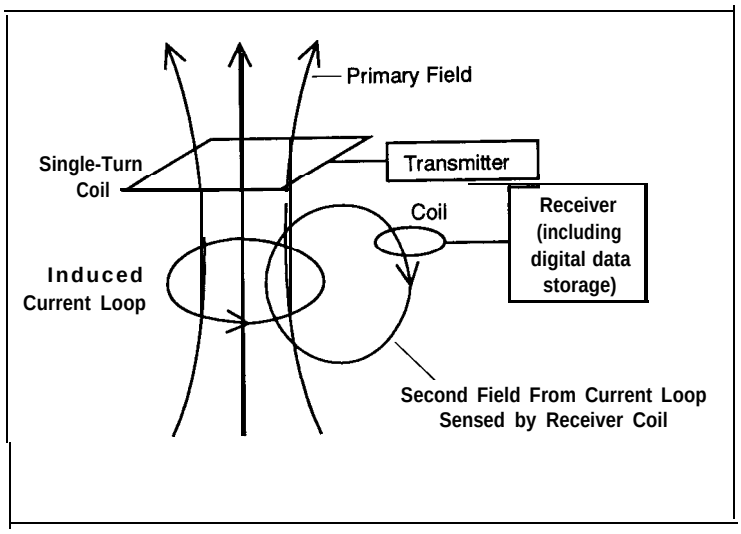


Figure 4-2a Time domain electromagnetic: block diagram showing TDEM principles of operation.

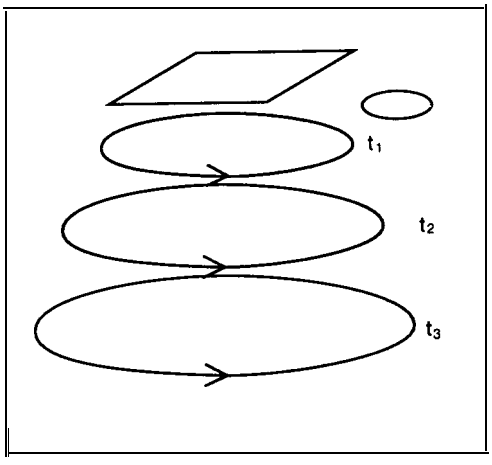


Figure 4-2b Time domain electromagnetics: the depth of TDEM soundings depends on transmitter current, loop size, and time of measurement.

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 |
|---|---|
| TDEM | |
| 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) |
| VLF Resistivity | |
| 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.*


Adams, M.L., M.S. Turner, and M.T. Morrow. 1988. The Use of Surface and Downhole Geophysical Techniques to Characterize Flow in a Fracture Bedrock Aquifer System. In: Proc. 2nd Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 825-847. [EMI, ER, SRR, BH]

Adams, W.M., F.L. Peterson, S.P. Mathur, L.K Lepley, C. Warren, and R.D. Huber. 1971. A Hydrogeophysical Survey Using Remote-Sensing Methods from Kawaihae to Kailua-Kona, Hawaii. Ground Water 9(1):42-50. [ER, AMT, aerial thermal infrared, aeromagnetic]

Allen, R.P. 1984. Electrical Resistivity Surveys Used to Trace Leachate in Ground Water from Paper Mill Landfill. In: Proc. of the NWWA Tech. Division Eastern Regional Ground Water Conference (Newton, MA), National Water Well Association, Dublin, OH, pp. 167-174. [EMI, ER]

Allen, R.P. and M.A. Seelen. 1992. The Use of Geophysics in the Detection of Buried Toxic Agents at a U.S. Military Installation. In: Current Practices in Ground Water and Vadose Zone Investigations, ASTM STP 1118, D.M. Nielsen and M.N. Sara (eds.), American Society for Testing and Materials, Philadelphia, PA, pp. 59-68. [MAG, EMI, GPR]

Allen, R. P., R. Popma, and P. Doolen. 1985. Electrical Resistivity/Terrain Conductivity Surveys to Trace Process Wastewater Leachate in Ground Water from a Spray Irrigation System. In: Proc. of the AGWSE Eastern Regional Ground Water Conference (Portland, ME), National Water Well Association, Dublin, OH, pp. 243-251. [EMI, ER]

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]

Arcone, S.A. 1979. Detection of Arctic Water Supplies with Geophysical Techniques. U.S. Army Cold Regions Research and Engineering Lab Report 79-15, Hanover NH. [EMI]

Barlow, P.M. and B.J. Ryan. 1985. An Electromagnetic Method for Delineating Ground-Water Contamination, Wood River Junction, Rhode Island. U.S. Geological Survey Water-Supply Paper 2270, pp. 35-49.

Bartel, L.C. 1989. Delineation of Brine Drilling-Fluid Loss in an Unsaturated Zone-Application to Contamination Monitoring. In: Proc. Third Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 841-854. [CSAMT]

Barton, G.J. and T. Ivanhenko. 1991. Electromagnetic Terrain Conductivity and Ground Penetrating Radar Investigations at and near the CIBA-GEIGY Superfund Site, Ocean County, New Jersey: Quality Control Assurance Plan and Results. In: Proc. (4th) Symp. on the Application of

Geophysics to Engineering and Environmental Problems, Soc. Eng. and Mineral Exploration Geophysicists, Golden, CO, pp. 357-360.

Bazinet, R. and J.M. Legault. 1986. Prospecting to Ground Water with Scalar Audio Magnetotellurics. In: Proc. Surface and Borehole Geophysical Methods and Ground Water Instrumentation Conf. and Exp., National Water Well Association, Dublin, OH, pp. 295-314. [AMT]

Beeson, S. and C.R.C. Jones. 1988. The Combined EMT/VES Geophysical Method for Siting Boreholes. Ground Water 26:54-63.

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

Benson, R., R. Glaccum, and P. Beam. 1981. Minimizing Cost and Risk in Hazardous Waste Site Investigations Using Geophysics. In: Proc. (2nd) Nat. Conf. on Management of Uncontrolled Hazardous Waste Sites, Hazardous Materials Control Research Institute, Silver Spring, MD, pp. 84-88. [EMI]

Benson, R.C., R.A. Glaccum, and M.R. Noel. 1984. 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., M.S. Turner, W.D. Volgelsong, and P.P. Turner. 1985. Correlation Between Field Geophysical Measurements and Laboratory Water Sample Analysis. In: Conference ***on*** Surface and Borehole Geophysical Methods and Ground Water Investigations (2nd, Fort Worth, TX), National Water Well Association, Dublin, OH, pp. 178-197. [EMI, ER]

Benson, R. C., M. Turner, P. Turner, and W. Vogelsong. 1988. In Situ, Time Series Measurements for Long-Term Ground-Water Monitoring. In: Ground-Water Contamination: Field Methods, A.G. Collins and A.I. Johnson (eds.), ASTM STP 963, American Society for Testing and Materials, Philadelphia, PA, pp. 58-72. [EMI, ER]

Bernard, J. and P. Valla. 1991. Groundwater Exploration in Fissured Media with Electrical and VLF Methods. Geoexploration 27:81-91.

Bosschart, R.A. 1970. Ground Electromagnetic Methods. In: Mining and Groundwater Geophysics/1967, L.W. Merely (cd), Geological Survey of Canada Economic Geology Report 26, pp. 67-80.

Boutwell, G.P. and T.A. Lawrence. 1988. Electromagnetic Data Interpretation Using Multivariate Least-Square Regression. In: Proc. of the Focus Conf. on Eastern Regional Ground Water Issues (Stanford, CT), National Water Well Association, Dublin, OH, pp. 3-20. [EMI]

Bradley, M.W. 1986. Surface Geophysical Investigations at the North Hollywood Dump, Memphis, Tennessee. In: Proc. Focus Conf. on southeastern Ground Water Issues (Tampa, FL), National Water Well Association, Dublin, OH, pp. 324-343. [EMI, ER]

Brickell, M.E. 1984. Geophysical Techniques to Delineate a Contaminant Plume. In: Proc. of the NWWA Tech. Division Eastern Regional Ground Water Conference (Newton, MA), National Water Well Association, Dublin, OH, pp. 175-207. [EMI, ER, BH]

Butler, D.K. and J.L. Llopis. 1985. Military Requirements for Geophysical Ground Water Detection and Exploration. In: Conference on Surface and Borehole Geophysical Methods and Ground Water Investigations (2nd, Fort Worth, TX), National Water Well Association, Dublin, OH, pp. 228-248. [EMI, ER, SRR].

Cagniard, L. 1953. Basic Theory of the Magnetotelluric Method of Geophysical Prospecting. Geophysics 18(3):605-635.

Cameron, D.R., E. DeJong, D.W.L. Read, and M. Oosterveld. 1981. Mapping Salinity Using Resistivity and Electromagnetic Inductive Techniques. Canadian J. Soil Science 61:67-78.

Carr, III, J. L., C.S. Ulmer, C.K. Eger, and P. Mann. 1990. Delineation of a Suspected Drum and Hazardous Waste Disposal Site Utilizing Multiple Geophysical Methods: Shaver's Farm, Chickmauga, Walker County, Georgia. In: Proc. Fourth Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods. Ground Water Management 2:1097-1111. [EMI, VLF, MAG]

Chapman, M.J. and E.S. Bair. 1992. Mapping a Brine Plume Using Surface Geophysical Methods in Conjunctions with Ground Water Quality Data. Ground Water 12(3):203-209. [ER and EM I]

Chew, W.C. 1990. Waves and Fields in Inhomogeneous Media. Van Nostrand Reinhold, New York, 611 pp.

Cook, P. G., G.R. Walter, G. Buselli, I. Potts, and A.R. Dodds. 1992. The Application of Electromagnetic Techniques to Groundwater Recharge Investigations. J. Hydrology 130:201-229. [ER, EMI, TDEM]

Corwin, D.L. and J.D. Rhoades. 1982. An Improved Technique for Determining Soil Electrical Conductivity-Depth Relations from Above-Ground Electromagnetic Measurements. Soil Sci. Soc. Am. J. 46(3):517-520.

Corwin, D.L. and J.D. Rhoades. 1984. Measurement of Inverted Electrical Conductivity Profiles Using Electromagnetic Induction. Soil Sci. Soc. Am. J. 48:288-291.

Cox, S.A. and W.R. Saunders. 1990. Application of Electromagnetic and Ground Penetrating Radar Geophysical Techniques for Identifying Zones of Potential Subsurface Contamination. Ground Water Management 2:1035-1047 (4th NOAC).

Davis, J.O. 1991. Depth Zoning and Specialized Processing Methods for Electromagnetic Geophysical Surveys to Remote Sense Hydrocarbon Type Ground Water Contaminants. In: Ground Water Management 5:905-913 (5th NOAC).

de Jong, E., A.K. Ballantine, D.R. Cameron, and D.W.L. Read. 1979. Measurement of Apparent Electrical Conductivity in Soils by an Electromagnetic Induction Probe to Aid Salinity Surveys. Soil Sci. Soc. Am. J. 43:810-812.

Drew, T.A., A. Thomas, and R. Wyatt. 1985. Application of Surface Geophysics to Ground Water Management Planning. In: Proc. of the AGWSE Eastern Regional Ground Water Conference (Portland, ME), National Water Well Association, Dublin, OH, pp. 232-242. [EMI]

Duran, P.B. 1984. The Effects of Cultural and Natural Interference on Electromagnetic Conductivity Data. 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. 509-530.

Duran, P.B. 1987. The Use of Marine Electromagnetic Conductivity as a Tool in Hydrogeologic Investigations. Ground Water 25(2):160-166.

Duran, P.B. and F.P. Haeni. 1982. The Use of Electromagnetic-Conductivity Techniques in the Delineation of Groundwater Leachate Plumes. In: The Impact of Waste Storage and Disposal on Ground Water Resources, Proc. of the Northeast Conference, Novitiski and Levine (eds.), Center for Environmental Research, Cornell University, Ithaca, NY, pp. 8.4.1-8.4.33.

Ehrlich, M, and L.G. Rosen. 1987. Application of Seismic, EM and Resistivity Techniques to Design and Ground Water Monitoring Programs at a Landfill in Northeastern Illinois. In: Proc. NWWA Focus Conf. on Midwestern Ground Water Issues (Indianapolis, IN), National Water Well Association, Dublin, OH, pp. 189-206.

Emilsson, G.R. and R.T. Wroblewski. 1988. Resolving Conductive Contaminant Plumes in the Presence of Irregular Topography. In: Proc. 2nd Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 617-635. [ER, EMI]

Environmental Consulting & Technology (EC&T), Inc., Technos, Inc., and UXB International, Inc. 1990). Construction Site Environmental Survey and Clearance Procedures Manual. U.S. Army Toxic and Hazardous Materials Agency, Aberdeen Proving Ground MD. [GPR, EMI, MAG, MD, soil gas]

Evans, R.B. and G.E. Schweitzer. 1984. Assessing Hazardous Waste Problems. Environ. Sci. Technol. 18(11):330A-339A. [EMI, ER, GPR, MAG, MD, SRR]

Feld, R.H., M. Stammler, G.A. Sandness, and C.S. Kimball. 1983. Geophysical Investigations of Abandoned Waste Sites and Contaminated Industrial Areas in West Germany. In: Proc. (4th) Nat. Conf. on Management of Uncontrolled Hazardous Waste Sites, Hazardous Materials Control Research Institute, Silver Spring, MD, pp. 68-70. [EMI, GPR, MAG]

Felsen, L.B. (ed.). 1976. Transient Electromagnetic Fields. Springer-Verlag, New York, 274 pp.

Fitterman, D.V. 1986. Transient Electromagnetic Sounding in the Michigan Basin for Ground Water Evaluation. In: Proc. Surface and Borehole Geophysical Methods and Ground Water Instrumentation Conf. and Exp., National Water Well Association, Dublin, OH, pp. 334-353.

Fitterman, D.V. 1987. Examples of Transient Sounding for Ground-Water Exploration in Sedimentary Aquifers. Ground Water 25:685-692.

Fitterman, D.V. and P. Hoekstra. 1984. Mapping Salt-Water Intrusion with Transient Electromagnetic Soundings. In: NWWA/EPA Conf. on Surface and Borehole Geophysical Methods in Ground Water Investigations (1st, San Antonio TX), National Water Well Association, Dublin, OH, pp. 429-454.

Fitterman, D.V. and M.T. Stewart. 1986. Transient Electromagnetic Sounding for Groundwater. Geophysics 51:995-1005.

Fitterman, D.V., C.M. Menges, A.M. Al Kamali, and F.E. Jama. 1991. Electromagnetic Mapping of Buried Paleochannels in Eastern Abu Dhabi Emirate, U.A.E. Geoexploration 27:111-133. [EMI, TDEM]

Fitzgerald, L.J., A.K. Angers, and M.E. Radville. 1986. The Application of VLF Geophysical Equipment to Hazardous Waste Site Investigations in New England. In: Proc. of the Third Annual Regional Ground Water Conference (Springfield, MA), National Water Well Association, Dublin, OH, pp. 527-540.

Fowler, J.W. and A. Ayubcha. 1986. Selection of Appropriate Geophysical Techniques for the characterization of Abandoned Waste Sites. In: Proc. Surface and Borehole Geophysical Methods and Ground Water Instrumentation Conf. and Exp., National Water Well Association, Dublin, OH, pp. 625-656. [ER, EMI, SRR, GPR, GR, MAG]

Fowler, J.W. and D.L. Pasicznyk. 1985. Magnetic Survey Methods Used in the Initial Assessment of a Waste Disposal Site. In: Conference on Surface and Borehole Geophysical Methods and Ground Water Investigations (2nd, Fort Worth, TX), National Water Well Association, Dublin, OH, pp. 267-281. [EMI, MAG]

Fox, F.L. and D.A. Gould. 1984. Delineation of Subsurface Contamination Using Multiple Surficial Geophysical Methods. In: Proc. of the NWWA Tech. Division Eastern Regional Ground Water Conference (Newton, MA), National Water Well Association, Dublin, OH, pp. 254-264. [EMI, ER]

Friedel, M.J., J.A. Jessop, R.E. Thill, and D.L. Veith. 1990. Electromagnetic Investigation of Abandoned Mines in the Galena, KS, Area. U.S. Bureau of Mine Report of Investigations 9303,20 pp. [EMI, GPR]

Frischknecht, F.C. 1900.). Application of Geophysical Methods to the Study of Pollution Associated with Abandoned and Injection Wells. In: Proc. of a U.S. Geological Survey Workshop on Environmental Geochemistry, B.R. Doe (cd), U.S. Geological Survey Circular 1033, pp. 73-77. [aeromagnetic, TDEM]

Garland, G.D. 1960. Earth Currents. In: Methods and Techniques in Geophysics, Vol. 1, S.K. Runcom (ed.), Interscience Publishers, New York, pp. 278-307.

Ghatge, S.L. and D.L. Pasicznyk. 1986. Integrated Geophysical Methods in the Determination of Bedrock Topography. In: Proc. Surface and Borehole Geophysical Methods and Ground Water Instrumentation Conf. and Exp., National Water Well Association, Dublin, OH, pp. 601-624. [ER, TDEM, IP, SRR, GR, MAG]

Gilkeson, R.H. and K. Cartwright. 1982. The Application of Surface Geophysical Methods in Monitoring Network Design. In: Proc. Second Nat. Symp. on Aquifer Restoration and Ground Water Monitoring, National Water Well Association, Dublin, OH, pp. 169-183. [EMI, ER, SP, thermal]

Gilkeson, R.H., S.R. Gorin, and D.E. Laymon. 1992. Application of Magnetic and Electromagnetic Methods to Metal Detection. In: SAGEEP ’92, Society of Engineering and Mineral Exploration Geophysicists, Golden, CO, pp. 309-328.

Gilmer, T.H. and M.P. Helbling. 1984. Geophysical Investigations of a Hazardous Waste Site in Massachusetts. 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. 618-634. [EMI, ER, MAG, SRR]

Glaccum, R.A., R.C. Benson, and M.R. Noel. 1982. Improving Accuracy and Cost-Effectiveness of Hazardous Waste Site Investigations. Ground Water Monitoring Review 2(3):36-40. [EMI, GPR]

Goldman, M.M. 1990. Non-Conventional Methods in Geoelectrical Prospecting. Prentice-Hall, New York, 150 pp. [EM, TDEM, ER]

Goldman, M., D. Gilad A. Ronen, and A. Melloul. 1991. Mapping of Seawater Intrusion into the Coastal Aquifer of Israel by the Time Domain Electromagnetic Method. Geoexploration 28:153-174.

Grady, SJ. and F.P. Haeni. 1984. Application of Electromagnetic Techniques in Determining Distribution and Extent of Ground Water Contamination at a Sanitary Landfill, Farmington, Connecticut. 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. 338367. [EMI, VLF, SRR]

Greenhouse, J.P. and R.D. Harris. 1983. Migration of Contaminants in Groundwater at a Landfill: A Case Study 7. DC, VLF, and Inductive Resistivity Surveys. J. Hydrology 63:177-197.

Greenhouse, J.P. and D.D. Slaine. 1982. Case Studies of Geophysical Contaminant Mapping at Several Waste Disposal Sites. In: Proc. 2nd Nat. Symp. on Aquifer Restoration and Ground Water Monitoring, National Water Well Association, Columbus, OH, pp. 299-315. [EMI]

Greenhouse, J.P. and D.D. Slaine. 1983. The Use of Reconnaissance Electromagnetic Methods to Map Contaminant Migration. Ground Water Monitoring Review 3(2):47-59.

Greenhouse, J.P. and D.D. Slaine. 1986. Geophysical Modeling and Mapping of Contamination Around Three Waste Disposal Sites in southern Ontario. Canadian Geotechnical J. 23:372-384. [EMI]

Greenhouse, J.P., L. Faulkner, and J. Wong. 1985. Geophysical Monitoring of an Injected Contaminant Plume with a Disposable E-Log. In: NWWA Conference on Surface and Borehole Geophysical Methods and Ground Water Investigations (2nd, Fort Worth, TX), National Water Well Association, Dublin, OH, pp. 64-84. [EMI, ER, BH]

Haeni, F.P. 1986. The Use of Electromagnetic Methods to Delineate Vertical and Lateral Lithologic Changes in Glacial Aquifers. In: Proc. Conf. on Surface and Borehole Geophysical Methods and Ground Water Instrumentation, National Water Well Association, Worthington, OH, pp. 259-282.

Hall, D.W. and D.L. Pasicznyk. 1987. Application of Seismic Refraction and Terrain Conductivity Methods at a Ground Water Pollution Site in North-Central New Jersey. In: Proc. 1st Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 505-524.

Hankins, J.B., R.M. Danielson, and P.A. Gregson. 1991. Delineation of Metal Hydroxide Sludge Disposal Areas Using Electromagnetic and Ground-Penetrating Radar. In: Ground Water Management 7675-691 (8th NWWA Eastern GW Conference).

Hoekstra, P. 1978. Electromagnetic Methods for Mapping Shallow Permafrost. Geophysics 43(4):782-787.

Hoekstra, P. 1990. Surface Geophysical Surveys for Mapping Boundaries Between Fresh and Salty Water. In: Ground Water Management 3:227-237 (7th NWWA Eastern GW Conference). [TDEM]

Hoekstra, P., and M.W. Blohm. 1990. Case Histories of Time Domain Electromagnetic Soundings in Environmental Geophysics. In: Geotechnical and Environmental Geophysics, Vol II., S.H. Ward (ed), Society of Exploration Geophysicists, Tuksa, OK pp. 1-15.

Hoekstra, P. and H. Cline. 1986. Time Domain Electromagnetic Soundings (TDEM) for Deep Ground Water Investigations. In: Proc. Surface and Borehole Geophysical Methods and Ground Water Instrumentation Conf. and Exp., National Water Well Association, Dublin, OH, pp. 241-258. [TDEM, CSAMT]

Hoekstra, P. and L. Evans. 1986. Time Domain Electromagnetic (TDEM) Exploration for Characterization of Injection Zones and Salt Water Intrusion Mapping. In: Proc. Focus Conf. on southeastern Ground Water Issues (Tampa, FL), National Water Well Association, Dublin, OH, pp. 389-404.

Hoekstra, P. and R.P. Standish. 1984. Applications of Fixed Frequency Conductivity Profiling and Transient Soundings to Ground Water Exploration. In: NWWA/EPA Conf. on Surface and Borehole Geophysical Methods in Ground Water Investigations (1st, San Antonio TX), National Water Well Association, Dublin, OH, pp. 150-173. [EMI, TDEM]

Hoekstra, P., J. Hild, and D. Toth. 1992. Time Domain Electromagentic Measurements to Determine Water Quality in the Floridan Aquifer. In: SAGEEP ’92, Society of Engineering and Mineral Exploration Geophysicists, Golden, CO, pp. 111-128.

Hoekstra, P., R. Lahti, J. Hild, C.R. Bates, and D. Phillips. 1992. Case Histories of Shallow Time Domain Electromagnetic in Environmental Site Assessment. Ground Water Monitoring Review 12(4):110-117.

Hoyt, Jr., W.H. 1974. Engineering Electromagnetic, 3rd ed. McGraw-Hill New York.

HRB-Singer, Inc. 1971. Detection of Abandoned Underground Coal Mines by Geophysical Methods. Project 14010, Report EHN. Prepared for U.S. EPA and PA Dept. of Env. Res. [VLF, IP, SP]

Jackson, J.D. 1975. Classical Electromagnetic. John Wiley & Sons, New York.

James, B., V. Price, and J. Hild. 1990. Transient Electromagnetic Imaging of a Basin Margin Underneath the Savannah River Site, Aiken, South Carolina. In: Proc. (3rd) Symp. on the Application of Geophysics to Engineering and Environmental Problems, Sot. Eng. and Mineral Exploration Geophysicists, Golden, CO, pp. 261-274.

Jansen, J. 1990. Surficial Geophysical Techniques for the Detection of Bedrock Fracture Systems. In: Ground Water Management 3:239-253 (7th NWWA Eastern GW Conference). [EMI, azimuthal resistivity]

Jansen, J. 1991. Synthetic Resistivity Sounding for Groundwater Inveatigations. In: Ground Water Management 5:877-888 (5th NOAC). [vertical EMI sounding]

Jansen, J. and R. Taylor. 1988. Surface Geophysical Techniques for Fracture Detection. In: Proc. Second Conf. on Environmental Problems in Karst Terranes and Their Solutions (Nashville, TN), National Water Well Association, Dublin, OH, pp. 419-441. [EMI, VLF, thermal fracture trace]

Jansen, J. and R. Taylor. 1989. Geophysical Methods for Groundwater Exploration or Groundwater Contamination Studies in Fracture Controlled Aquifers. In: Proc. Third Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 855-869. [EMI, ER, VLF, thermal]

Jansen, J., B. Haddad, W. Fassbender, and P. Jurcek. 1992. Frequency Domain Electromagnetic Induction Sounding Survey for Landfill Site Characterization Studies. Ground Water Monitoring Review 12(4):103-109.

Johnson, I. and Z. Doborzynski. 1988. A Novel Fixed-Source Electromagnetic System. Geophysical Prospecting 36167-193.

Jordon, E.D. (ed). 1963. Electromagnetic Wave Theory. Pergamon, New York.

Jordan, T.E., D.G. Leask, D.D. Slaine, T.M. Dobush, and I.N. MacLeod. 1991. The Use of High Resolution Electromagnetic Methods for Reconnaissance Mapping of Buried Wastes. In: Ground Water Management 5:849-861 (5th NOAC).

Kachonoski, R.G., E.G. Gregorich, and I.J. Van Wesenbeeck. 1988. Estimating Spatial Variations of Soil Water Content Using NonContacting Electromagnetic Inductive Methods. Can. J. Soil Science 68715-722.

Kaufman, A.A. and G.V. Keller. 1981. The Magnetotelluric Sounding Method. Elsevier, New York, 686 pp.

Kaufman, A.A. and G.V. Keller. 1983. Frequency and Transient Soundings. Elsevier, New York.

Kelly, W.E., I. Bogardi, O. Mazac, and I. Landa. 1989. Geoelectrics in Ground-Water Studies. In: Recent Advances in Ground-Water Hydrology. J.E. Moore, A.A. Zaporozec, S.C. Csallany, and T.C. Varuly (eds.), American Institute of Hydrology, Minneapolis, MN, pp. 422-436. [EMI, ER]

Kerfoot, W.B. and S.W. Rumba 1985. Combined EM Resistivity and Fluorometry with Direct Ground Water Flow Measurements for Local Characterization of Landfill Plumes. In: Proc. Fifth Nat. Symp. on Aquifer Restoration and Ground Water Monitoring, National Water Well Association, Dublin, OH, pp. 372-387. [EMI]

Knuth, M. 1988. Complementary Use of EM-31 and Dipole-Dipole Resistivity to Locate the Source of Oil Brine Contamination. In: Proc. 2nd Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 583-595.

Koefoed, O. and D.T. Biewinga. 1976. The Application of Electromagnetic Frequency Sounding to Groundwater Problems. Geoexploration 14229-241.

Koerner, R.M., A.E. Lord, Jr., S. Tyagi, and J.E. Brugger. 1982. Use of NDT Methods to Detect Buried Containers in Saturated Silty Clay Soil. In: Proc. (3rd) Nat. Conf. on Management of Uncontrolled Hazardous Waste Sites, Hazardous Materials Control Research Institute, Silver Spring, MD, pp. 12-16. [GPR, MAG, MD, VLFl

Kong, J.A. 1975. Theory of Electromagnetic Waves. John Wiley& Sons, New York, 339 pp.

Kraus, J.D. 1984. Electromagnetic, 3rd ed. McGraw-Hill, NY, 775 pp.

Kufs, C.T., D.J. Messinger, and S. Del Re. 1986. Statistical Modeling of Geophysical Data. In: Proc. 7th Nat. Conf. on Management of Uncontrolled Hazardous Waste Sites, Hazardous Materials Control Research Institute, Silver Spring, MD, pp. 110-114. [EMI, MAG, MD]

Kuo, J.T. and D.-H. Cho. 1980. Transient Time-Domain Electromagnetic. Geophysics 45(2):271-291.

Ladwig, KJ. 1983. Electromagnetic Induction Methods for Monitoring Acid Mine Drainage. Ground Water Monitoring Review 446-57.

Ladwig, KJ. 1984. Use of Surface Geophysics to Determine Flow Patterns and Acid-Source Areas in Surface Mine Spoil. 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. 455-471. [EMI]

Lankston, R.W. and B.W. Hecker. 1988. Enhancing VLF-EM Data Through Application of Frequency Domain Operators. In: Proc. Second Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 655-673.

Lawrence, L.T. 1984. Subsurface Geophysical Investigations and Site Mitigation. In: Proc. 5th Nat. Conf. on Management of Uncontrolled Hazardous Waste Sites, Hazardous Materials Control Research Institute, Silver Spring, MD, pp. 481-485. [EMI, GPR]

LeBrecque, DJ., D.D. Weber, and R.B. Evans. 1984. Comparison of the Resistivity and Electromagnetic Methods over a Contaminant Plume Using Numerical Modeling. 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. 316323.

Lluria, M.R. 1990. Controlled Source Audio-Frequency Magnetotelhn-its: An Effective Surface Geophysical Tool in the Exploration for Groundwater Hosted in Fractured Bedrock Aquifers. In: Proc. Fourth Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods. Ground Water Management 2:1143-1157.

Lord, Jr. A.E., and R.M. Koerner. 1982. Electromagnetic Methods in Subsurface Investigations. In: Proc. Conf. on Updating Subsurface Sampling of Soils and Rocks and Their In-Situ Testing (Santa Barbara, CA), S.K. Saxena (ed), Engineering Foundation, New York, NY, pp. 113-133.

Lord, Jr., A.E. and R.M. Koerner. 1986. Nondestructive Testing (NDT) Location of Containers Buried in Soil. In: Proc. 12th Research Symp. (Land Disposal, Remedial Action, Incineration and Treatment of Hazardous Waste), EPA/600/9-86/022 (PB87-119491), pp. 161-169. [EMI, GPR, MAG, MD]

Lord, Jr., A.E. and R.M. Koerner. 1987a. Nondestructive Testing (NDT) Techniques to Detect Contained Subsurface Hazardous Waste. EPA/600/2-87/078 (NTIS PB88-102405). [EMI, GPR, MAG, MD, brief review of 13 other methods]

Lord, Jr., A.E., and R.M. Koerner. 1987b. Nondestructive Testing (NDT) for Location of Containers Buried in Soil. In: Proc. 13th Research Symp. (Land Disposal, Remedial Action, Incineration and

Treatment of Hazardous Waste), EPA/600/S9-87/015 (PB87-233151), pp. 224-234. [EMI, GPR, MAG, MD]

Lord, Jr., A.E., R.M. Koerner, and J.E. Brugger. 1982. Use of Electromagnetic Wave Methods to Locate Subsurface Anomalies. In: Proc. 3rd Nat. Conf. on Management of Uncontrolled Hazardous Waste Sites, Hazardous Materials Control Research Institute, Silver Spring, MD, pp. 119-124. [EMI]

Lorraine, P. and D.R. Carson. 1970. Electromagnetic Fields and Waves, 2nd ed. W.H. Freeman, San Francisco.

Lowrie, W. and G.F. West. 1965. The Effect of Conducting Overburden on Electromagnetic Prospecting Measurements. Geophysics 30(4):624-632.

Lyverse, M.A. 1989. Surface Geophysical Techniques and Test Drilling Used to Assess Ground-Water Contamination by Chloride in an Alluvial Aquifer. In: Proc. 3rd Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 993-1006. [EMI]

Mack, TJ. and P.E. Maus. 1986. Detection of Contaminant Plumes in Ground Water of Long Island New York by Electromagnetic Terrain Conductivity Surveys. U.S. Geological Survey Water-Resources Investigations Report 86-4045, 39 pp.

Maimone, M., D. Keil, R. Lahti, and P. Hoekstra. 1989. Geophysical Surveys for Mapping *Boundaries* of Fresh Water and Salty Waters in southern Nassau County, Long Island, NY. In: Proc. Third Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 965-977. [TDEM]

McBride, R.A., A.M. Gordon, and S.C. Shrive. 1990. Estimating Forest Soil Quality from Terrain Measurements of Apparent Electrical Conductivity. Soil Sci. Sot. Am. J. 54290-293. [EMI]

McNeill, J.D. 1980a. Electrical Conductivity of Soils and Rock. Technical Note TN-5. Geonics Limited, Mississaugua, Ontario.

McNeill, J.D. 1980b. Electromagnetic Terrain Conductivity Measurement at Low Induction Numbers. Technical Note TN-6. Geonics Limited, Mississaugua, Ontario.

McNeill, J.D. 1982. Electromagnetic Resistivity Mapping of Contaminant Plumes. In: Proc. (3rd) Nat. Conf. on Management of Uncontrolled Hazardous Waste Sites, Hazardous Materials Control Research Institute, Silver Spring, MD, pp. 1-6.

McNeill, J.D. 1988. Advances in Electromagnetic Methods for Groundwater Studies. In: Proc. (lst) Symp. on the Application of Geophysics to Engineering and Environmental Problems, Soc. Eng. and Mineral Exploration Geophysicists, Golden, CO, pp. 252-348.

McNeill, J.D. 1990. Influence of Galvanic Currents on Electromagnetic Surveys. In: Proc. (3rd) Symp. on the Application of Geophysics to Engineering and Environmental Problems, Soc. Eng. and Mineral Exploration Geophysicists, Golden, CO, pp. 223-228.

McNeill, J.D. 1991. Advances in Electromagnetic Methods for Groundwater Studies. Geoexploration 2765-80.

McNeill, J.D. and V. Labson. 1991. Geological Mapping Using VLF Radio Fields. In: Electromagnetic Methods in Applied Geophysics, Vol. 2, Applications, M.N. Nabighian (ed.), Society of Exploration Geophysicists, Tulsa, OK, Part B, pp. 521-640.

McQuown, M.S., S.R. Becker, and P.T. Miller. 1991. Subsurface Characterization of a Landfill Using Integrated Geophysical Techniques. In: Ground Water Management 5:933-946 (5th NOAC). [EMI, SRR]

Medlin, E, and M. Knuth. 1986. Monitoring the Effects of a Ground Water Recovery System with EM. In: Proc. Surface and Borehole Geophysical Methods and Ground Water Instrumentation Conf. and Exp., National Water Well Association, Dublin, OH, pp. 368-270.

Merin, I.S. 1989. A Successful Example of Locating Previously Undocumented Underground Storage Tanks Using Terrain Conductivity. In: Proc. 6th Nat. Conf. on Hazardous Wastes and Hazardous Materials, Hazardous Material Control Research Institute, Silver Spring, MD, pp. 445-450.

Meyer, B.K, C.K Eger, and W.T. Blasingame. 1990. Applications of a Geophysical Tool (WADI) Which Monitors Very Low Frequency (VLF) Radio Waves at the Tower Chemical NPL Site. In: Proc. Fourth Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods. Ground Water Management 2:1113-1127.

Mills, T., L. Evans, and M. Blohm. 1987. The Use of Time Domain Electromagnetic Soundings for Mapping Sea Water Intrusion in Monterey County, California: A Case Study. In: Proc. First Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 601-621.

Mills, T., P. Hoekstra, M.W. Blohm, and L. Evans. 1988. Time Domain Electromagnetic Soundings for Mapping Sea-Water Intrusion in Monterey, California. Ground Water 26:771-782.

Morgenstern, K.A. and T.L. Syverson. 1988a. Determination of Contaminant Migration in Vertical Faults and Basalt Flows with Electromagnetic Conductivity Techniques. In: Proc. 2nd Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 597-615

Morgenstern, K.A. and T.L. Syverson. 1988b. Utilization of Vertical and Horizontal Dipole Configurations of the EM 34-3 for Contaminant Mapping in Faulted Terrain. In: Superfund ’88, Proceedings of the 9th Annual Conference, Hazardous Material Control Research Institute, Silver spring MD, pp. 84-92.

Nabighian, M.N. (ed.). 1988. Electromagnetic Methods in Applied Geophysics, Vol. 1, Theory. Society of Exploration Geophysicists, Tulsa, OK, 528 pp.

Nabighian, M.N. (ed). 1991. Electromagnetic Methods in Applied Geophysics, Vol. 2, Parts A and B, Applications. Society of Exploration Geophysicists, Tulsa, OK, Part A, pp. 1-520, Part B, pp. 521-992.

Nabighian, M.N. and J.C. Macnae. 1991. Time Domain Electromagnetic Prospecting Methods. In: Electromagnetic Methods in Applied Geophysics, Vol. 2, Applications, M.N. Nabighian (ed), Society of Exploration Geophysicists, Tulsa, OK, Part A pp. 427-520.

Noel, M.R., R.C. Benson, and R.A. Glaccum. 1982. The Use of Contemporary Geophysical Techniques to Aid Design of Cost-Effective Monitoring Well Networks and Data Analysis. In: Proc. Second

Nat. Symp. on Aquifer Restoration and Ground Water Monitoring, National Water Well Association, Dublin, OH, pp. 163-168. [EMI, ER]

Palacky, G.J., I.L. Ritsema and S.J. DeJong. 1981. Electromagnetic Prospecting for Groundwater in Precambrian Terrains in the Republic of Upper Volta. Geophysical Prospecting 29(6):932-955.

Paterson, N.R. and V. Ronka. 1971. Five Years of Surveying with the Very Low Frequency-Electromagnetics Method. Geoexploration 9(1):7-26.

Patra, H.P. 1970. Central Frequency Sounding in Shallow Engineering and Hydrological Problems. Geophysical Prospecting 182%254. [EMI]

Payne, M.I. 1991. The Electromagnetic Traversing Method of Ground Water Exploration in Crystalline Rock Terrain. In: Ground Water Management 5:863-875 (5th NOAC).

Pease, Jr., R.W. and S.C. James. 1981. Integration of Remote Sensing Techniques with Direct Environmental Sampling for Investigating Abandoned Hazardous Waste Sites. In: Proc. (2nd) Nat. Conf. on Management of Uncontrolled Hazardous Waste Sites, Hazardous Materials Control Research Institute, Silver Spring, MD, pp. 171-176. [ER, GPR, MD, SRR]

Petersen, R.C., J.R. Wagner, MA. Hemphill-Haley, L.N. Weller, R. Kilbury, and J.B.F. Champlin. 1986. Resistivity Mapping of a Complex Aquifer System at a Hazardous Waste Site in the Salinas Valley, California. In: Proc. Surface and Borehole Geophysical Methods and Ground Water Instrumentation Conf. and Exp., National Water Well Association, Dublin, OH, pp. 197-202. [ER, EMI]

Pfannkuch, H.O. 1969. On the Correlation of Electrical Conductivity Properties of Porous Systems with Viscous Flow Transport Coefficients. In: Fundamentals of Transport Phenomena in Porous Media, Elsevier, New York, pp. 42-54.

Pierce, H.A. and D.B. Hoover. 1986. Results of Natural-Source Electromagnetic Methods for Ground Water Studies near Las Vegas, NV. In: Proc. Surface and Borehole Geophysical Methods and Ground Water Instrumentation Conf. and Exp., National Water Well Association, Dublin, OH, pp. 354-367. [natural source telluric, AMT]

Pitchford, A.M., A.T. Mazzella, and K.R. Scarborough. 1988. Soil-Gas and Geophysical Techniques for Detection of Subsurface Organic Contamination. EPA/600/4-88/019 (NTIS PB88-208194). [GPR, EMI, ER, complex resistivity, SRR, MD, MAG]

Poddar, M. and B.S. Rather. 1983. VLF Survey of the Weathered Layer in southern India. Geophysical Prospecting 31:524-537.

Porstendorfer, G. 1975. Principles of Magneto-Telluric Prospecting. Gebrüder Borntaeger, Stuttgart.

Primeaux, D. 1984. Case History Terrain Geophysical Survey to Investigate Contaminant Migration from a Waste Site. In: NWWA/EPA Conf. on Surface and Borehole Geophysical Methods in Ground Water Investigations (1st, San Antonio TX), National Water Well Association, Dublin, OH, pp. 334-337. [EMI]

Primeaux, A.D. 1985. Geophysical Survey to Investigate Contaminant Migration from a Waste Site. In: Hazardous Wastes in Ground Water: A Soluble Dilemma (Proc. 2nd Canadian/American

Conference on Hydrogeology, Banff, Alberta), B. Hitchon, and M.R. Turdell (eds.), National Water Well Association, pp. 151-155. [EMI]

Raab, P.V. and F.C. Frischknecht. 1985. Investigation of Brine Contamination Using Time-Domain Electromagnetic Soundings. U.S. Geological Survey Open-File Report 85-528, 54 pp.

Rehm, B.W., T.R. Stolzenburg, and D.G. Nichols. 1985. Field Measurement Methods for Hydrogeologic Investigations A Critical Review of the Literature. EPRI EA-401. Electric Power Research Institute, Palo Alto, CA. [Major methods: ER, EMI, SRR, BH; Other: IR, SP, IP/CR, SRR, GPR, MAG, GR, thermal]

Rhoades, J.D. and D.L. Corwin. 1981. Determining Soil Electrical Conductivity-Depth Relations Using an Inductive Electromagnetic Soil Conductivity Meter. Soil Sci. Soc. Am. J. 45:255-260.

Rhoades, J.D. and J.D. Oster. 1986. Solute Content. In: Methods of Soil Analysis, Part 1, 2nd ed, A. Klute (ed), Agronomy Monograph No. 9. American Society of Agronomy, Madison, WI, pp. 985-1006.

Rinaldo-Lee, M.B. and R. Wagner. 1985. Monitoring Plume Migration Using Ground Surface Conductivity. In: Proc. of the AGWSE Eastern Regional Ground Water Conference (Portland, ME), National Water Well Association, Dublin, OH, pp. 252-276. [EMI]

Roberts,R.G., W.J. Hinze, and D.I. Leap. 1989. A Multi-Technique Geophysical Approach to Landfill Investigations. In: Proc. 3rd Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 797-811. [EMI, ER, GPR, GR, MAG, SRR]

Rodriguez, E.B. 1984. A Critical Evaluation of the Use of Geophysics in Ground Water Contamination Studies in Ontario. In: NWWA/EPA (Conf. on Surface and Borehole Geophysical Methods in Ground Water Investigations (1st San Antonio TX), National Water Well Association, Dublin, OH, pp. 603-617. [EMI, ER, VLF]

Rokityanksi, 1.1. 1982. Geoelectromagnetic Investigation of the Earth's Crest and Mantle. Springer-Verlag, New York.

Rudy, R.J. and J.A. Caoile. 1984. Utilization of Shallow Geophysical Sensing at Two Abandoned Municipal/Industrial Waste Landfills on the Missouri River Floodplain. Ground Water Monitoring Review 4(4):57-65. [ER, EMI]

Rudy, R.J. and J.B. Warner. 1986. Detection of Abandoned Underground Storage Tanks in Marion County, Florida. In: Proc. Surface and Borehole Geophysical Methods and Ground Water Instrumentation Conf. and Exp., National Water Well Association, Dublin, OH, pp. 674-688. [EMI, GPR, MAG]

Rumbaugh, III, J.O., J.A. Caldwell, and S.T. Shaw. 1987. A Geophysical Ground Water Monitoring Program for a Sanitary Landfill: Implementation and Preliminary Analysis. In: Proc. First Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 623-641. [EMI, ER]

Russell, G.M. 1990. Application of Geophysical Techniques for Assessing Ground-Water Contamination near a Landfill at Stuart Florida. In: Ground Water Management 3:211-225 (7th NWWA Eastern GW Conference). [ER, EMI, VLF, GPR]

Saunders, W.R. and S.A. Cox. 1987. Use of an Electromagnetic Induction Technique in Subsurface Hydrocarbon Investigations. In: Proc. 1st Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 585-600.

Saunders, W.R. and S.A. Cox. 1988. Technical and Logistical Problems Associated with the Implementation and Integration of Surface Geophysical Methods in Inactive Hazardous Waste Site Investigations. In: Proc. Second Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 637-653. [EMI]

Saunders, W.R. and R.M. Germeroth. 1985. Electromagnetic Measurements for Subsurface Hydrocarbon Investigations. In: Proc. (2nd) NWWA/API Conf. Petroleum Hydrocarbons and Organic Chemicals in Ground Water—Prevention, Detection and Restoration, 1985, National Water Well Association, Dublin, OH, pp. 310-321.

Saunders, W.R. and J.A. Stanford. 1984. Integration of Individual Geophysical Techniques as a Means to Characterize an Abandoned Hazardous Waste Site. In: NWWA/EPA Conf. on Surface and Borehole Geophysical Methods in Ground Water Investigations (1st, San Antonio TX), National Water Well Association, Dublin, OH, pp. 584-602. [EMI, ER, SRR]

Saunders, W.R., S. Smith, P. Gilmore, and S. Cox. 1991. The Innovative Application of Surface Geophysical Techniques for Remedial Investigations. In: Ground Water Management 5:947-961 (5th NOAC). [EMI, TDEM, GPR, soil gas]

Schelkunoff,S.A. 1943. Electromagnetic Waves. Van Nostrand, New York.

Schutts, L.D. and D.G. Nichols. 1991. Surface Geophysical Definition of Ground Water Contamination and Buried Waste Case Studies of Electrical Conductivity and Magnetic Applications. In: Ground Water Management 5:889-903 (5th NOAC).

Shope, S.B. 1987. Interpretation of EM Data Through Geoelectric Modeling with Application to a Landfill in southeastern New Hampshire. In: Proc. of the Fourth Annual Eastern Regional Ground Water Conference (Burlington, VT), National Water Well Association, Dublin, OH, pp. 593-626.

Sinha, A.K. 1989. Magnetic Wavetilt Measurements for Geological Fracture Mapping. Geophysical Prospecting 37427-445. [VLFJ

Slaine, D.D. and J.P. Greenhouse. 1982. Case Studies of Geophysical Contaminant Mapping at Several Waste Disposal Sites. In: Proc. 2nd Nat. Symp. on Aquifer Restoration and Ground Water Monitoring National Water Well Association, Dublin, OH, pp. 229-315. [EMI, VLF]

Slaine, D.D., P.K. Lee, and J.P. Phimister. 1984. A Comparison of a Geophysically and Geochemically Mapped Contaminant Plume. In: NWWA/EPA Conf. on Surface and Borehole Geophysical Methods in Ground Water Investigations (1st, San Antonio TX), National Water Well Association, Dublin, OH, pp. 383-402. [VLF]

Snow, G., T. Mills, M. Zidar, and I. Priestaf. 1990. Identification of Sources of Saline Intrusion in a Confined Aquifer System, Salinas Valley, California. Ground Water Management 1:595-607 (NWWA Cluster Conferences). [TDEM]

Spies, B.R. and D.E. Eggers. 1986. The Use and Misuse of Apparent Resistivity in Electromagnetic Methods. Geophysics 51:1462-1471.

Stenson, R.W. 1988. Electromagnetic Data Acquisition Techniques for Landfill Investigations. In: Proc. (lst) Symp. on the Application of Geophysics to Engineering and Environmental Problems, Soc. Eng. and Mineral Exploration Geophysicists, Golden, CO, pp. 735-746.

Steinberg, B.K. 1991. High-Resolution Electromagnetic (EM) Imaging of Subsurface Contaminant Plumes. In: Proc. Environ. Res. Conf. on Groundwater Quality and Waste Disposal, I.P. Muraka and S. Cordle (eds.), EPRI EN-6749, Electric Power Research Institute, Palo Alto, CA pp. 18-1 to 18-25.

Steinberg, B.K., S.J. Thomas, N.H. Bak, and M.M. Poulton. 1991. High- Resolution Electromagnetic Imaging of Subsurface Contaminant Plumes-Interim Report. EPRI EN-7515. Electric Power Research Institute, Palo Alto, CA.

Stewart, M.T. 1982. Evaluation of Electromagnetic Methods for Rapid Mapping of Salt-Water Interfaces in Coastal Aquifers. Ground Water 20:538-545.

Stewart, M. and R. Bretnall. 1984. Interpretation of VLF Resistivity Data for Ground Water Contamination Surveys. In: NWWA/EPA Conf. on Surface and Borehole Geophysical Methods in Ground Water Investigations (1st, San Antonio TX), National Water Well Association, Dublin, OH, pp. 368-382.

Stewart, M. and R. Bretnall. 1986. Interpretation of VLF Resistivity Data for Ground Water Contamination Surveys. Ground Water Monitoring Review 6(1):71-75.

Stewart, M.T. and M.C. Gay. 1986. Evaluation of Transient Electromagnetic Soundings for Deep Detection of Conductive Fluids. Ground Water 24351-356.

Stierman, D.J. and L.C. Ruedisili. 1988. Integrating Geophysical and Hydrogeological Data An Efficient Approach to Remedial Investigations of Contaminated Ground Water. In: Ground-Water Contamination: Field Methods, A.G. Collins and A.I. Johnson (eds.), ASTM STP 963, American Society for Testing and Materials, Philadelphia, PA, pp. 43-56. [ER, EMI]

Strangway, D.W. 1960. Electromagnetic Scale Modeling. In: Methods and Techniques in Geophysics, Vol. 2, S.K. Runcom (ed), Interscience Publishers, New York, pp. 1-31. [MT, TDEM]

Strangway, D.W. 1983. Audiofrequency Magnetotelluric (AMT) Sounding. Developments in Geophysical Exploration Methods 6107-160.

Strangway, D.W. and K Vozoff. 1970. Mining Exploration with Natural Electromagnetic Fields. In: Mining and Groundwater Geophysics/1967, L.W. Merely (cd), Geological Survey of Canada Economic Geology Report 26, pp. 109-122.

Strangway, D.W., C.M. Swift, Jr. and R.C. Homer. 1973. The Application of Audio-Frequency Magnetotellurics (AMT) to Mineral Exploration. Geophysics 38(6):1159-1175.

Strangway, D.W., J.D. Redman, and D. Macklin. 1980. Shallow Electrical Sounding in the Precambrian Crust of Canada and the United States. In: The Continental Crust and Its Mineral Deposits, Geological Association of Canada Special Paper 20, pp. 273-301. Also reprinted in Vozoff (1986). [magnetotelluric]

Stratton, J.A. 1941. Electromagnetic Theory. McGraw-Hill, New York.

Struttmann, T. and T. Anderson. 1989. Comparison of Shallow Electromagnetic and the Proton Precession Magnetometer Surface Geophysical Techniques to Effectively Delineate Buried Wastes. In: Superfund '89, Proceedings of the 10th Annual Conference, Hazardous Material Control Research Institute, Silver Spring, MD, pp. 27-34.

Sweeney, J.J. 1984. Comparison of Electrical Resistivity Methods for Investigation of Ground Water Conditions at a Landfill Site. Ground Water Monitoring Review 4(1):52-59. [ER, EMI]

Swift, Jr., C.M. 1988. Fundamentals of the Electromagnetic Method. In:Electromagnetic Methods in Applied Geophysics, Vol 1, M.N. Nabighian (ed), SEG Investigations in Geophysics No. 3, Society of Exploration Geophysicists, Tulsa, OK, pp. 5-10.

Syed, T., K.L. Zonge, S. Figgins, and A.R. Anzzolin. 1985. Application of the Controlled Source Audio Magnetotellurics (CSAMT) Survey to Delineate Zones of Ground Water Contamination-A Case History. In: NWWA Conference on Surface and Borehole Geophysical Methods and Ground Water Investigations (2nd, Fort Worth, TX), National Water Well Association, Dublin, OH, pp. 282-311.

Taylor, K, R. Bochicchio, and M. Widmer. 1991. A Transient Electromagnetic Survey to Define Hydrogeology A Case History. Geoexploration 27:43-54.

Taylor, K, M. Widmer, and M. Chesley. 1992. Use of Transient Electromagnetic to Define Local Hydrogeology in an Arid Alluvial Environment. Geophysics 57(2):343-352.

Telford, W.M., W.F. King, and A. Becker. 1977. VLF Mapping of Geologic Structure. Geological Survey of Canada Paper 76-25.

Tinlin, R.M., L.J. Hughes, and A.R. Anzzolin. 1988. The Use of Controlled Source Audio Magnetotellurics (CSAMT) to Delineate Zones of Ground-Water Contamination. In: Ground-Water Contamination Field Methods, A.G. Collins and A.I. Johnson (eds.), ASTM STP 963, American Society for Testing and Materials, Philadelphia, PA, pp. 101-118.

Tucci, P. 1986. Surface-Geophysical Investigations in Melton Valley, Oak Ridge Reservation, Tennessee. In: Proc. Focus Conf. on Southeastern Ground Water Issues (Tampa, FL), National Water Well Association, Dublin, OH, pp. 344-374. [EMI, ER]

Tweeton, D.R., C.L. Cumerlato, J.C. Hanson, and H.L. Kuhhnan. 1991. Field Tests of Geophysical Techniques for Predicting and Monitoring Leach Solution Flow During In Situ Mining. Geoexploration 28251-268. [seismic tomography, CSAMT]

U.S. Environmental Protection Agency (EPA). 1987. A Compendium of Superfund Field Operations Methods, Part 2. EPA/540/P-87/001 (OSWER Directive 9355.0-14) (NTIS PB88-181557). [EMI, ER, SRR, SRL, MAG, GPR, BH]

U.S. Environmental Protection Agency (EPA). 1993. Subsurface Field Characterization and Monitoring Technique A Desk Reference Guide, Volume I Solids and Ground Water. EPA/625/R-93/003a. Available from EPA Center for Environmental Research Information, Cincinnati, OH. [Section 13 covers surface electromagnetic methods.]

U.S. Geological Survey. 1980. Geophysical Measurements. In: National Handbook of Recommended Methods for Water Data Acquisition, Chapter 2 (Ground Water), Office of Water Data Coordination, Reston, VA, pp. 2-24 to 2-76. [TC, MT, AMT, EMI, ER, IP, SRR, SRL, GR, BH]

Valentine, R.M. and T. Kwader. 1985. Terrain Conductivity as a Tool for Delineating Hydrocarbon Plumes in a Shallow Aquifer-A Case Study. In: NWWA Conference on Surface and Borehole Geophysical Methods and Ground Water Investigations (2nd, Fort Worth, TX), National Water Well Association, Dublin, OH, pp. 52-63. [EMI]

Valentine, R.M. and T. Kwader. 1986. Terrain Conductivity as a Tool for Delineating Hydrocarbon Plumes in a Shallow Aquifer-A Case Study. In: Proc. Focus Conf. on southeastern Ground Water Issues (Tampa, FL), National Water Well Association, Dublin, OH, pp. 405-416. [EMI]

Verma, R.K 1982. Electromagnetic Sounding Interpretation Data over Three-Layer Earth, Vols. 1 and 2. IFI/Plenum, New York, Vol. 1:338 pp., Vol. 2:546 pp.

Vogelsang, D. 1974. Compatibility of EM Soundings and IP Surveys. Geophysical Prospecting 22(4):781-790. Comments in Geophysical Prospecting 25(1):182-185.

Vozoff, K (ed). 1986. Magnetotelluric Methods. Geophysics Reprint Series No. 5, Society of Exploration Geophysicists, Tulsa, OK, 800 pp.

Vozoff, K 1991. The Magnetotelluric Method. In: Electromagnetic Methods in Applied Geophysics, Vol. 2, Applications, M.N. Nabighian (ed), Society of Exploration Geophysicists, Tulsa, OK, Part B, pp. 641-712.

Wait, J.R. 1962. A Note on the Electromagnetic Response of a Stratified Earth. Geophysics 27(3):382-385.

Wait, J.R. 1970. Electromagnetic Waves in Stratified Media, 2nd ed. Pergamon Press, New York, 372 pp. [First edition 1962]

Wait, J.R. (cd). 1971. Electromagnetic Probing in Geophysics. The Golem Press, Boulder, CO, 391 pp.

Wait, J.R. 1981. Wave Propagation Theory. Pergamon Press, New York, 349 pp.

Wait, J.R. 1982. Gee-Electromagnetism. Academic Press, New York, 268 pp. [IP, EMI]

Wait, J.R. 1985. Electromagnetic Wave Theory. Harper and Row, New York, 308 pp.

Walsh, D.C. 1989. Surface Geophysical Exploration for Buried Drums in Urban Environments: Applications in New York City. In: Proc. Third Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 935-949. [EMI, MAG]

Walther, E.G., D. LeBrecque, D.D. Weber, R.B. Evans, and J.J. Van Ee. 1983. Study of Subsurface Contamination with Geophysical Monitoring Methods at Henderson, Nevada. In: Proc. (4th) Nat. Conf. on Management of Uncontrolled Hazardous Waste Sites, Hazardous Materials Control Research Institute, Silver Spring, MD, pp. 28-36. [EMI, ER, complex resistivity]

Ward, S.H. 1967a. Electromagnetic Theory for Geophysical Applications. In: Mining Geophysics, Vol. II, Theory, D.A. Hansen et al. (eds.), Society of Exploration Geophysicists, Tulsa, OK, pp. 10-196.

Ward, S.H. 1967b. The Electromagnetic Method. In: Mining Geophysics, Vol. II, Theory, D.A. Hansen et al. (eds.), Society of Exploration Geophysicists, Tulsa, OK, pp. 224-373.

Ward, S.H. 1980. Electrical Electromagnetic and Magnetotelluric Methods. Geophysics 45(11):1659-1660.

Ward, S.H. and H.F. Morrison (eds.). 1971. Special Issue on Electromagnetic Scattering. Geophysics 36(1):1-183.

Watson, J., D. Stedje, M. Barcelo, and M. Stewart. 1990. Hydrogeologic Investigation of Cypress Dome Wetlands in Well Field Areas North of Tampa Florida. In: Ground Water Management 3:163-176 (7th NWWA Eastern GW Conference). [TDEM, VLF, ER, GPR]

Weber, D.D. and G.T. Flatman. 1986. Statistical Approach to Groundwater Contamination Mapping with Electromagnetic Induction: A Case Study. In: Proc. Surface and Borehole Geophysical Methods and Ground Water Instrumentation Conf. and Exp., National Water Well Association, Dublin, OH, pp. 315-333.

Weber, D.D. and G.T. Flatman. 1986. Statistical Approach to Groundwater Contamination Mapping with Electromagnetic Induction Data Acquisition and Analysis. In: Proc. 7th Nat. Conf. on Management of Uncontrolled Hazardous Waste Sites, Hazardous Materials Control Research Institute, Silver Spring, MD, pp. 132-137.

Weber, D.D., J.F. Scholl, DJ. LeBrecque, E.G. Walther, and R.B. Evans. 1984. Spatial Mapping of Conductive Ground Water Contamination with Electromagnetic Induction. Ground Water Monitoring Review 4(4):70-77.

West, R.C. and S.H. Ward. 1988. The Borehole Controlled-Source Audiomagnetotelluric Response of a Three-Dimensional Fracture Zone. Geophysics 53(2):215-230.

Westphalen, O. and J. Rice. 1992. Drum Detection: EM vs. MAG, Some Revealing Tests. In: Ground Water Management 11:665-668 (Proc. of the 6th NOAC).

White, R.B. and R.B. Gainer. 1985. Control of Ground Water Contamination at an Active Uranium Mill. Ground Water Monitoring Review 5(2):75-82. [EMI]

White, R.M. and S.S. Brandwein. 1982. Application of Geophysics to Hazardous Waste Investigations. In: Proc. (3rd) Nat. Conf. on Management of Uncontrolled Hazardous Waste Sites, Hazardous Materials Control Research Institute, Silver Spring, MD, pp. 91-93. [EMI, ER, GPR, MAG]

White, R.M., D.G. Miller, Jr., S.S. Brandwein, and A.F. Benson. 1984. Pitfalls of Electrical Surveys for Ground Water Contamination Investigations. In: NWWA/EPA (Conf. on Surface and Borehole Geophysical Methods in Ground Water Investigations (1st, San Antonio TX), National Water Well Association, Dublin, OH, pp. 472-482. [EMI, ER]

Wightman, W.E., B.C. Martinek and D. Hammermeister. 1992. Geophysical Methods Used to Guide Hydrogeological Investigations at an UMTRA Site near Grand Junction, Colorado. In: Current Practices in Ground Water and Vadose Zone Investigations, ASTM STP 1118, D.M. Nielsen and M.N. Sara (eds.), American Society for Testing and Materials, Philadelphia, PA, pp. 69-78. [EMI]

Williams, B.G. and B.C. Baker. 1982. An Electromagnetic Induction Technique for Reconnaissance Surveys of Soil Salinity. Aust. J. Soil Res. 20:107-118.

Williams, J.S., A.L. Tolman, and C.W. Fontaine. 1984. Geophysical Techniques in Contamination Site Investigations Usefulness and Problems. In: Proc. of the NWWA Tech. Division Eastern Regional Ground Water Conference (Newton, MA), National Water Well Association, Dublin, OH, pp. 208-233. [EMI, ER, SRR]

Windschauer, R.J. 1986. A Surface Geophysical Study of a Borrow Pit Lake. In: Proc. Surface and Borehole Geophysical Methods and Ground Water Instrumentation Conf. and Exp., National Water Well Association, Dublin, OH, pp. 283-292. [ER, EMI]

Woessner, W.W., R. Lazuk and S. Payne. 1989. Characterization of Aquifer Heterogeneities Using EM and Surface Electrical Resistivity Surveys at the Lubrecht Experimental Forests, Western Montana. In: Proc. Third Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 951-963.

Wynn, J.C. 1979. An Experimental Ground-Magnetic and VLF-EM Traverse over a Buried Paleochannel near Salisbury, Maryland. U.S. Geological Survey Open-File Report 79-105, 8 pp.

Zonge, K. 1990. Application of Controlled Source Audio Frequency Magnetotelluric Measurements to Engineering and Environmental Problems. In: Proc. (3rd) Symp. on the Application of Geophysics to Engineering and Environmental Problems, Soc. Eng. and Mineral Exploration Geophysicists, Golden, CO, pp. 123-136.

Zonge, K.L. and L.J. Hughes. 1991. Controlled Source Audio-Frequency Magnetotellurics. In: Electromagnetic Methods in Applied Geophysics, Vol. 2, Applications, M.N. Nabighian (ed), Society of Exploration Geophysicists, Tulsa, OK, Part B, pp. 713-810.

# 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

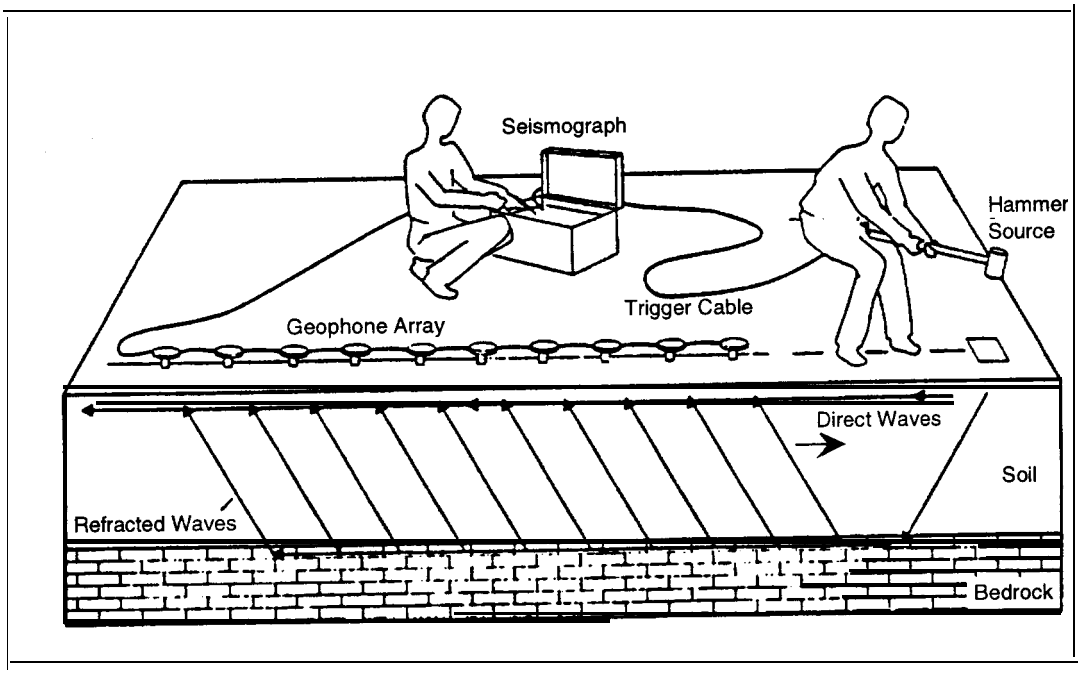


Figure 5-1 Field layout of a 12-channel seismograph showing the path of direct and refracted seismic waves in a two-layer soil/rock system (from Benson et al., 1984).

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.

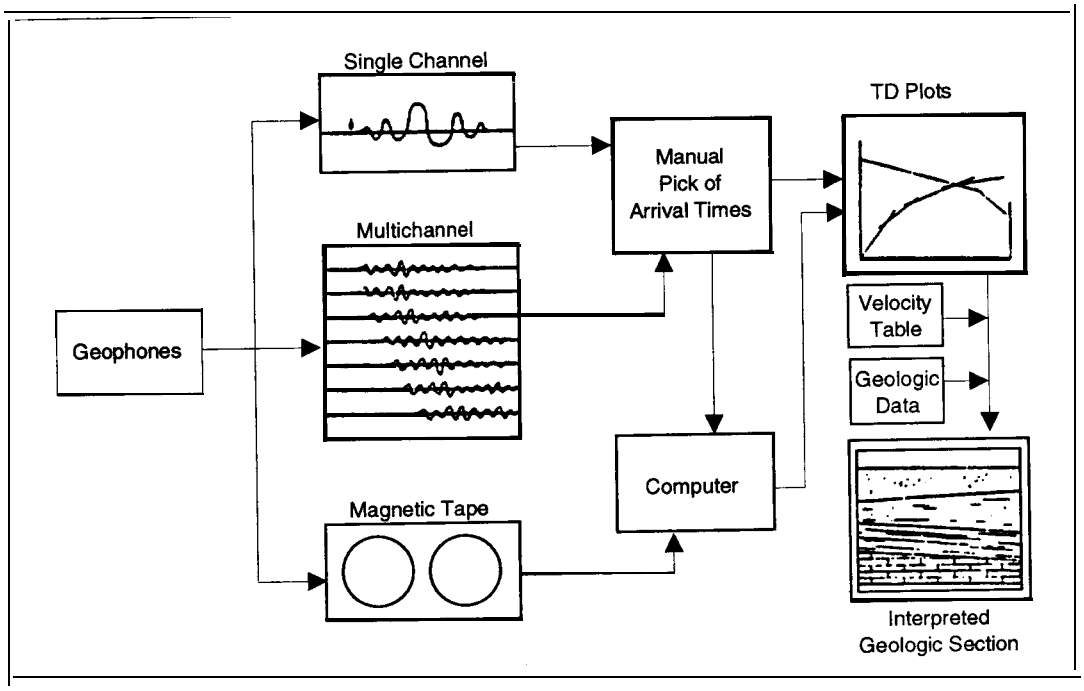


Figure 5-2 Flow diagram showing steps in the processing and interpretation of seismic refraction data (from Benson et al., 1984).

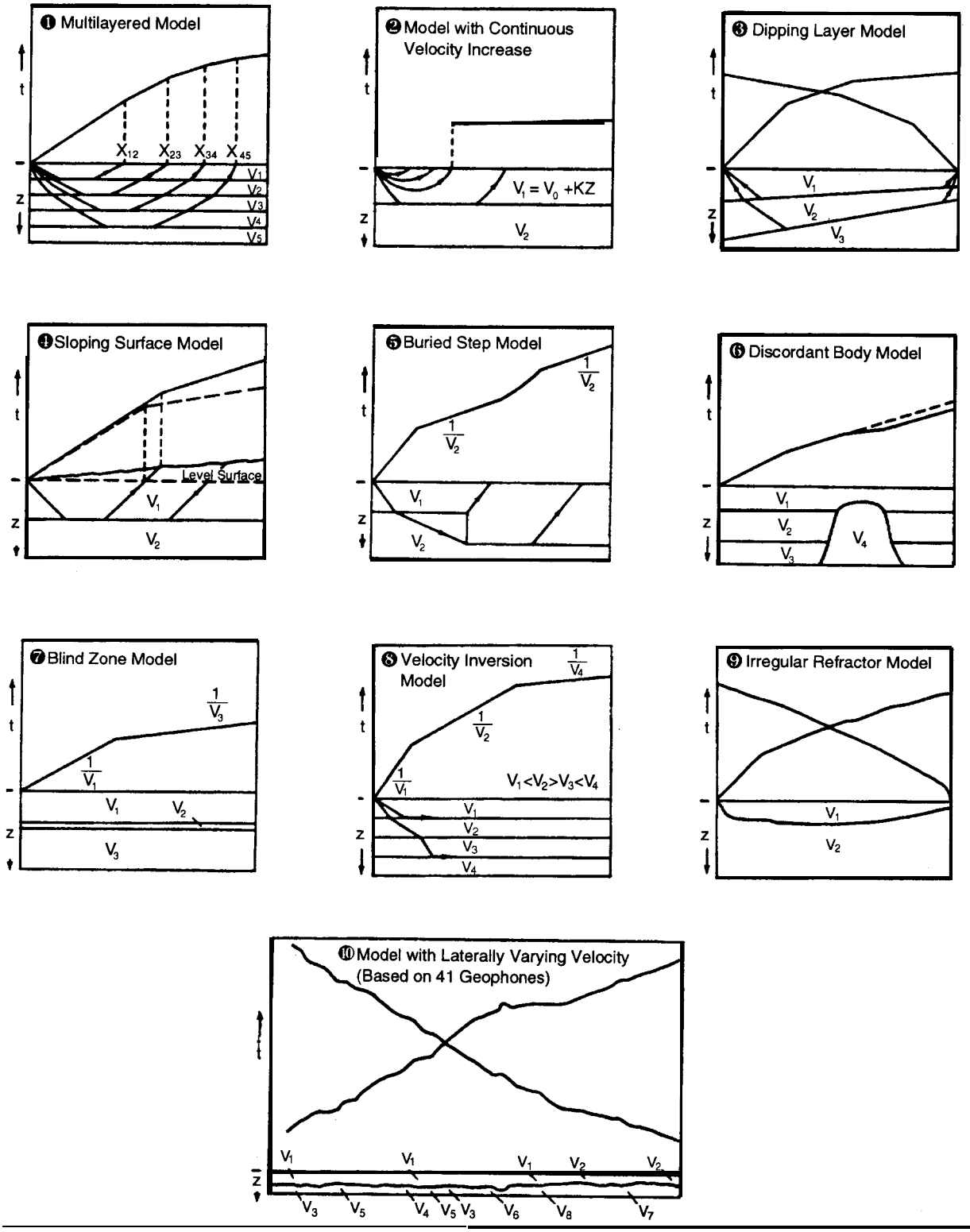


Figure 5-3 Schematic traveltime curves for idealized nonhomogenous geologic models (from Zohdy et al., 1974).

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.*


Ackermann, H.D. 1976. Geophysical Prospecting for Ground Water in Alaska. U.S. Geological Survey Earthquake Information Bulletin 8(2):18-20. [ER, SRR in permafrost areas]*

Ackermann, H.D., L.W. Pandratz, and D.A. Dansereau. 1983. A Comprehensive System for Interpreting Seismic Refraction Arrival-Time Data Using Interactive Computer Methods. U.S. Geological Survey Open-File Report 82-1065, 265 pp.

Adams, M.L. 1992. Seismic Reflection/Refraction Survey to Characterize the Subsurface at an NPL Site in the Mojave Desert. In: SAGEEP '92, Society of Engineering and Mineral Exploration Geophysicists, Golden, CO, pp. 565-585

Adams, M.L., M.S. Turner, and M.T. Morrow. 1988. The Use of Surface and Downhole Geophysical Techniques to Characterize Flow in a Fracture Bedrock Aquifer System. In: Proc. 2nd Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 825-847. [EMI, ER, SRR, VSP, borehole television]

Ali, H.O. 1985. Gravity and Seismic Refraction Measurements for Deep Ground Water Search in Southern Darfur Region, Sudan. In: NWWA Conference on Surface and Borehole Geophysical Methods and Ground Water Investigations (2nd, Fort Worth, TX), National Water Well Association, Dublin, OH, pp. 106-120.

Allen, C.F., L.V. Lombardi, and W.M. Wells. 1952. The Application of the Reflection Seismograph to Near-Surface Exploration. Geophysics 17:859-866.

Allen, R.P. and B.A. Rogers. 1989. Geophysical Surveys in Support of a Remedial Investigation/Feasibility Study at the Municipal Landfill in Metamora, Michigan. In: Proc. 3rd Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 1007-1020. [ER, MAG, SRR]

Allen, S.J. 1980. Seismic Method. Geophysics 45(11):1619-1633.

Arnow, T. and R.E. Mattick. 1968. Thickness of Valley Fill in the Jordan Valley East of the Great Salt Lake, Utah. U.S. Geological Survey Professional Paper 600-B, pp. B79-B82. [SRR]*

Auld, B.A. (cd.). 1990. Acoustic Fields and Waves in Solids, Vol. I and II, 2nd rev. Robert E. Krieger Publishing, Malabar, FL, (I) 435 pp, (II) 421 pp.

Ayers, J.F. 1988. Application of Geophysical Techniques in the Study of an Alluvial Aquifer. In: Proc. Second Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 801-824. [ER, SRR, SRL]

Ayers, J.F. 1989. Application and Comparison of Shallow Seismic Methods in the Study of an Alluvial Aquifer. Ground Water 27(4):550-563. [SRR, SRL] [See also 1990 discussion by R.W. Lankston and reply in Ground Water 28(l): 116-118.]

Badley, M.E. 1985. Practical Seismic Interpretation. International Human Resources Development Corporation, Boston, MA, 266 pp. [SRL, CSP]

Barker, R.D. and P.F. Worthington. 1973. Some Hydrogeophysical Properties of the Bunter Sandstone of Northwest England Geoexploration 11:151-170. [SRR, ER]*

Barr, Jr., F.J. 1973. Feasibility Study of a Seismic Reflection Monitoring System for Underground Waste-Material Injection Sites. In: Symposium on Underground Waste Management and Artificial Recharge, J. Braunstein (ed.), IASH Pub. No. 110, Int. Ass. of Hydrological Sciences, pp. 207-218.

Bates, C.R., D. Phillips, and B. Hoekstra. 1991. Geophysical Surveys for Fracture Mapping and Solution Cavity Delineation. In: Ground Water Management 7:659-673 (8th NWWA Eastern GW Conference). [shear-wave refraction, cross-borehole tomography]

Bates, C.R., D. Phillips, and J. Hild. 1992. Studies in P-Wave and S-Wave Seismics. In SAGEEP '92, Society of Engineering and Mineral Exploration Geophysicists, Golden, CO, pp. 261-274.

Baxter, P.A. and R.J. Mills. 1992. The Model SE880 Sonar Image and Record Enhancement System. In: SAGEEP '92, Society of Engineering and Mineral Exploration Geophysicists, Golden, CO, pp. 185-196.

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

Benson, R. C., R.A. Glaccum, and M.R. Noel. 1984. 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]

Berkhout, A.J. 1985. Seismic Migration: Imaging of Acoustic Energy by Wave Field Extrapolation. A. Theoretical Aspects (2nd ed.), 446 pp; B. Practical Aspects. Elsevier, New York.

Berkhout, A.J. 1987. Applied Seismic Wave Theory. Elsevier, New York, 377 pp.

Berkhout, A.J. 1988. Seismic Resolution: A Quantitative Analysis of the Resolving Power of Acoustical Echo Techniques. Pergamon, New York, 228 pp.

Bianchi, W.C. and H.I. Nightingale. 1975. Hammer Seismic Timing as a Tools for Artificial Recharge Site Selection. Soil Sci. Soc. Am. Proc 39(4):747-751.

Bikis, E.A. and B.R. Lewis. 1992. Integration of Shallow, High-Resolution Seismic Reflection Data and Subsurface Geological Information to Characterize the Hydrogeology at the Rocky Flats Nuclear Weapons Plant, Golden, Colorado. In: Ground Water Management 11:629-643 (Proc. of the 6th NOAC).

Birch, F.S. 1976. A Seismic Ground-Water Survey in New Hampshire. Ground Water 14:94-100. [SRR]

Birkelo, B.A., D.W. Steeples, R.D. Miller, and M. Sophocleous. 1987. Seismic Reflection Study of a Shallow Aquifer During a Pumping Test. Ground Water 25(6):703-709.

Blackey, M. and D.A. Stoner. 1988. Application of Seismic Refraction Analysis to Siting a Waste Disposal Facility over Carbonate Bedrock. In: Proc. 2nd Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 697-706.

Bland, D.R. 1988. Wave Theory and Applications. Oxford University Press, New York, 322 pp.

Bonini, W.E. 1959. Seismic-Refraction Method in Ground Water Exploration. Trans. Am. Inst. Mining Metall. Eng. 211:485-488.

Boyce, G. M., W.M. McCabe, and R.M. Koerner. 1981. Acoustic Emission Signatures of Various Rock Types in Unconfined Compression. In: Acoustic Emissions in Geotechnical Engineering Practice, V.P. Drnevich and R.E. Gray (eds.), ASTM STP 750, American Society for Testing and Materials, Philadelphia, PA pp. 142-154.

Broadbent, M. 1978. Seismic-Refraction Surveys for Canterbury Ground-Water Research. New Zealand Dept. of Scientific and Industrial Research, Geophysics Division, Report 131, 63 pp.*

Bruehl, D.H. 1983. Use of Geophysical Techniques to Delineate Ground-Water Contamination. In: Proc. Third Nat. Symp. on Aquifer Restoration and Ground Water Monitoring, National Water Well Association, Dublin, OH, pp. 295-300. [ER, GR, SRR]

Bruehl, D.H. 1984. Use of Complementary Geophysical Techniques to Delineate Ground Water Contamination. In: Proc. of the NWWA Tech. Division Eastern Regional Ground Water Conference (Newton, MA), National Water Well Association, Dublin, OH, pp. 265-273. [ER, SRR, GR]

Burdic, W.S. 1991. Underwater Acoustic System Analysis, 2nd ed. Prentice Hall, Englewood Cliffs, NJ, 445 pp. [lst ed. 1984]

Burgdorf, G.J. and B.H. Richard. 1984. Geophysical Exploration of Buried Valley Systems in Southwestern Ohio for Ground Water Resources. In: NWWA/EPA Conf. on Surface and Borehole Geophysical Methods in Ground Water Investigations (San Antonio TX), National Water Well Association, Dublin, OH, pp. 176-205. [GR, SRR]

Burke, K.B.S. 1970, A Review of Some Problems of Seismic Prospecting for Ground Water in Surficial Deposits. In: Mining and Groundwater Geophysics/1967, L.W. Merely (cd.), Geological Survey of Canada Economic Geology Report 26, pp. 569-579.

Burwell, Jr., E.B. 1940. Determination of Ground-Water Levels by the Seismic Method. Trans. Am. Geophys. Union 21:439-440.

Butler, D.K. and J.L. Llopis. 1985. Military Requirements for Geophysical Ground Water Detection and Exploration. In: NWWA Conference on Surface and Borehole Geophysical Methods and Ground Water Investigations (2nd,Fort Worth, TX), National Water Well Association, Dublin, OH, pp. 228-248. [EMI, ER, SRR].

Cardinell, A.P. and S.A. Berg. 1992. Marine Seismic Reflection Profiling to Define the Hydrogeologic Continuity at Camp Lejuene, North Carolina. In: SAGEEP ’92, Society of Engineering and Mineral Exploration Geophysicists, Golden, CO, pp. 1-20.

Carmichael, R.S. 1982. Handbook of Physical Properties of Rocks, Vol. 2. CRC Press, Boca Raton, FL. Seismic

Carpenter, P.J. 1990. Landfill Assessment Using Electrical Resistivity and Seismic Refraction Techniques. In: Proc. (3rd) Symp. on the Application of Geophysics to Engineering and Environmental Problems, Soc. Eng. and Mineral Exploration Geophysicists, Golden, CO, pp. 139-154.

Carpenter, G.C. and D.R. Bassarab. 1964. Case Histories of Resistivity and Seismic Ground Water Studies. Ground Water 2(1):21-25. [SRR]

Carpenter, P.J., S.F. Calkin, and R.S. Kaufman. 1991. Assessing a Fractured Landfill Cover Using Electrical Resistivity and Seismic Refraction Techniques. Geophysics 56(11):1896-1904.

CH2M Hill. 1991. Proceedings: NSF/EPRI Workshop on Dynamic Soil Properties and Site Characterization, Vol 1. EPRI NP-7337. Electric Power Research Institute, Palo Alto, CA. [seismic shear, SASW]

Cherkauer, D.S. and R.W. Taylor. 1988. Geophysically Determined Ground Water Flow into the Channels Connecting Lakes Huron and Erie. In: Proc. Second Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 779-799. [ER, CSP]

Cichowicz, N.L., R. W. Pease, Jr., P.J. Stollar, and H.J. Jaffe. 1981. Use of Remote Sensing Techniques in a Systematic Investigation of an Uncontrolled Hazardous Waste Site. EPA/600/2-81/187 (NTIS PB82-103896). [ER, SRR, GPR, MD]

Coates, R.F.W. 1989. Underwater Acoustic Systems. John Wiley& Sons, Hew York, 188 pp.

Colon-Dieppa, E. and F. Quinones-Marques. 1985. A Reconnaissance of the Water Resources of the Central Guanajibo Valley, Puerto Rico. U.S. Geological Survey Water Resources Investigations Report 82-4050, 47 pp. [SRR]*

Criner, J.H. 1966. Seismic Surveying with Firecrackers -A Modification of the Sledgehammer Method. U.S. Geological Survey Professional Paper 550-B, pp. 104-107.

Crosby, G.W. 1976. Geophysical Study of the Water-Bearing Strata in Bitteroot Valley, Montana. OWRI A-063-MONT(l). Montana University Joint Water-Resources Research Center Report 80, Bozeman, MT, 68 pp. [SRR]*

Danbom, S.H. and S.N. Domenico (eds.). 1987. Shear-Wave Exploration. Geophysical Developments No. 1. Society of Exploration Geophysicists, Tulsa, OK, 282 pp. [Last chapter contains an annotated bibliography on shear-wave exploration seismology-see Ensley (1987)].

Davis, J.L. 1988. Wave Propagation in Solids and Fluids. Springer Verlag, New York, 400 pp.

Davis, J.L., M.J. Wailer, B.G. Stegman, and R. Singh. 1983. Evaluations of Time-Domain Reflectometry and Acoustic Emission Techniques to Detect and Locate Leaks in Waste Pond Liners. In: Proc. 9th Research Symp. (Land Disposal of Hazardous Waste), EPA/600/9-83/018 (NTIS PB84-188777), pp. 188-202.

Davis, J. L., R. Singh, B.G. Steman, and M.J. Wailer. 1984. Innovative Concepts for Detecting and Locating Leaks in Waste Impoundment Liner Systems: Acoustic Emission Monitoring and Time Domain Reflectometry. EPA/600/2-84/058 (NTIS PB84-161819), 105 pp.

Dickerman, D.C. and H.E. Johnston. 1977. Geohydrologic Data for the Beaver-Pasquiset Ground-Water Reservoir, Rhode Island. Rhode Island Water Resources Board Water Information Series Report 3, 128 pp. [SRR]*

Dix, G.H. 1939a. Refraction and Reflection of Seismic Waves, Pt. I, Fundamentals. Geophysics 4(2):81-101.

Dix, G.H. 1939b. Refraction and Reflection of Seismic Waves, Pt. II, Discussion of Physics of Refraction Prospecting. Geophysics 4(4):238-241.

Dix, G.H. 1952. Seismic Prospecting for Oil. Harper and Brothers, New York, 213 pp.

Dix, C. 1960. Seismic Prospecting. In: Methods and Techniques in Geophysics, Vol. 2, S.K. Runcorn (cd.), Interscience Publishers, New York, pp. 249-278.

Denne, J.E., et al. 1984. Remote Sensing and Geophysical Investigations of Glacial Buried Valleys in Northeastern Kansas. Ground Water 22(1):56-65. [ER, GR, SRR, thermal]

Descour, J.M. and R.J. Miller. 1989. Microseismic Monitoring of Engineering Structures. In: Proc. (2nd) Symp. on the Application of Geophysics to Engineering and Environmental Problems, Soc. Eng. and Mineral Exploration Geophysicists, Golden, CO, pp. 235-261.

Dobecki, T.L. 1988. Seismic Shear Waves for Lithology and Saturation. In: Proc. Second Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 677-695.

Dohr, G. (cd.). 1985. Seismic Shear Waves, Part A: Theory, Part B. Applications. Handbook of Geophysical Exploration, Vols. 15A and 15B, Geophysical Press, London.

Domzalski, W. 1956. Some Problems of Shallow Refraction Investigations. Geophysical Prospecting 4(2):140-166.

Dudley, Jr., W.W. and L.D. McGinnis. 1962. Seismic Refraction and Earth Resistivity Investigation of Hydrogeologic Problems in the Humboldt River Basin, Nevada. Desert Research Institute Technical Report 1, University of Nevada, Las Vegas, NV, 29 pp.*

Duffin, G.L. and G.R. Elder. 1969. Variations in Specific Yield in the Outcrop of the Carrizo Sand in South Texas as Estimated by Seismic Refraction. Texas Dept. of Water Resources Report 229, 61 pp.*

Duguid J.O. 1968. Refraction Determination of Water Table Depth and Alluvium Thickness. Geophysics 33(3):481-488. Discussion in Geophysics 33(6):1019-1021 and 34(3):496.

Eaton, G.P. and J.S. Watkins. 1970. The Use of Seismic Refraction and Gravity Methods in Hydrogeological Investigations. In: Mining and Groundwater Geophysics/1967, L.W. Merely (ed.), Geological Survey of Canada Economic Geology Report 26, pp. 544-568.

EG&G Environmental Equipment Division. 1977. Fundamentals of High Resolution Seismic Profiling. TR760035. EG&G, 31 pp.

Ehrlich, M, and L.G. Rosen. 1987. Application of Seismic, EM and Resistivity Techniques to Design and Ground Water Monitoring Programs at a Landfill in Northeastern Illinois. In: Proc. NWWA Focus Conf. on Midwestern Ground Water Issues (Indianapolis, IN), National Water Well Association, Dublin, OH, pp. 189-206. [SRR]

Emerson, D.W. 1968. The Determination of Ground-Water Levels in Sands by the Seismic Refraction Method. Civil Engineering Transactions CE 10(1) :15-18."

Emilsson, G.R. and R.T. Wroblewski. 1988. Resolving Conductive Contaminant Plumes in the Presence of Irregular Topography. In: Proc. 2nd Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 617-635. [EMI, SRR]

Ensley, R.A. 1987. Classified Bibliography of Shear-Wave Seismology. In: Shear-Wave Exploration, S.H. Danbom, and S.N. Domenico (eds.), Society of Exploration Geophysicists, Tulsa, OK, pp 255-275.

Evans, R.B. and G.E. Schweitzer. 1984. Assessing Hazardous Waste Problems. Environ. Sci. Technol. 18(11) :330A-339A. [EMI, ER, GPR, MAG, MD, SRR]

Evison, F.F. 1952. The Inadequacy of the Standard Seismic Techniques for Shallow Surveying. Geophysics 17(4):867-887.

Ewing, J.I. and G.B. Tirey. 1961. Seismic Profiles. J. Geophysical Research 66:2917-2927. [CSP]

Fagin, S.W. (ed.). 1991. Seismic Modeling of Geologic Structures. Geophysical Developments No. 2. Society of Exploration Geophysicists, Tulsa, OK, 288 pp.

Filler, D.M. and S-S. Kuo. 1989. Subsurface Cavity Explorations Using Non-Destructive Geophysical Methods. In: Proc. Third Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 827-840. [ER, GPR, SRR]

Fish, J.P. and H.A. Carr. 1990. Sound Underwater Images: A Guide to the Generation and Interpretation of Side-Scan Sonar Data. American Search and Survey, Inc., Cataumet, MA, 189 pp.

Fitch, A.A. 1976. Seismic Reflection Interpretation. Gebrüder Borntraeger, Berlin, 148 pp.

Fowler, J.W. and A. Ayubcha. 1986. Selection of Appropriate Geophysical Techniques for the Characterization of Abandoned Waste Sites. In: Proc. Surface and Borehole Geophysical Methods and Ground Water Instrumentation Conf. and Exp., National Water Well Association, Dublin, OH, pp. 625-656. [ER, EMI, SRR, GPR, GR, MAG]

Frohlich, R.K. 1979. Geophysical Studies of the Hydraulic Properties of Glacial Aquifers in the Pawcatuck River Basin, Rhode Island. Rhode Island Water Resources Center Project Report OWRI A-068-RI(l), University of Rhode Island, 38 pp. [SRR]*

Gagne, R.M., S.E. Pullan, and J.A. Hunter. 1985. A Shallow Seismic Reflection Method for Use in Mapping Overburden Stratigraphy. In: 2nd NWWA Geophysics, pp. 132-135.

Gahr, D.A., L.J. Barrows, and A.T. Mazzella. 1988. An Evaluation of Seismic Techniques in an Arid Environment. In: Proc. Second Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 707-723. [SRR, SRL]

Galfi, J. and M. Pales. 1970. Use of Seismic-Refraction Measurements for Ground-Water Prospecting. Bull. Int. Ass. Sci. Hydrology 15(3):41-46.*

Gardner, L.W. 1939. An Areal Plan of Mapping Subsurface Structure by Refraction Shooting. Geophysics 4:247-259.

Ghatge, S.L. and D.L. Pasicznyk. 1986. Integrated Geophysical Methods in the Determination of Bedrock Topography. In: Proc. Surface and Borehole Geophysical Methods and Ground Water Instrumentation Conf. and Exp., National Water Well Association, Dublin, OH, pp. 601-624. [ER, TDEM, IP, SRR, GR, MAG]

Gill, H.E., J. Vecchioli, and W.E. Bonini. 1965. Tracing the Continuity of Pleistocene Aquifers in Northern New Jersey by Seismic Methods. Ground Water 3(4):33-35. [SRR]

Gilmer, T.H. and M.P. Helbling. 1984. Geophysical Investigations of a Hazardous Waste Site in Massachusetts. 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. 618-634. [EMI, ER, MAG, SRR]

Gorin, S.R. and R.H. Gilkeson. 1991. Use of the Seismic Refraction Technique to Optimize Monitoring Well Locations at Hazardous Waste Sites. In: Ground Water Management 5:983-997 (5th NOAC).

Grady, S.J. and F.P. Haeni. 1984. Determining Distribution and Extent of Ground Water Contamination at a Sanitary Landfill, Farmington, Connecticut. In: NWWA/EPA (lst) Conf. Surface and Borehole Geophysical Methods in Ground Water Investigations, National Water Well Association, Worthington, OH, pp. 368-382. [ER, SRR]*

Grady, S.J. and E.H. Handman. 1983. Hydrogeologic Evaluation of Selected Stratified-Drift Deposits in Connecticut. U.S. Geological Survey Water-Resources Investigations Report 83-4010, 56 pp. [SRR]*

Green, R. 1974. The Seismic Refraction Method—A Review. Geoexploration 12:259-284.

Greenhouse, J.P., D.C. Nobes, and G.W. Schneider. 1990. Groundwater Beneath the City A Geophysical Study. In: Proc. Fourth Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods. Ground Water Management 2:1179-1191. [SRR, BH]

Haeni, F.P. 1978. Computer Modeling of Ground-Water Availability of the Pootatuck River Valley, Newtown, Connecticut. U.S. Geological Survey Water-Resources Investigations Report 78-77, 76 pp. [SRR]*

Haeni, F.P. 1986a. Application of Seismic Refraction Methods in Groundwater Modeling Studies in New England. Geophysics 51(2):236-249. *

Haeni, F.P. 1986b. Application of Continuous Seismic Reflection Methods to Hydrologic Studies. Ground Water 24:23-31.

Haeni, F.P. 1986c. Application of Seismic-Refraction Techniques to Hydrologic Studies. U.S. Geological Survey Open File Report 84-746, 144 pp. [Superseded by Haeni (1988a).]

Haeni, F.P. 1988a. Application of Seismic Refraction Techniques to Hydrogeologic Studies. U.S. Geological Survey Techniques of Water-Resources Investigations TWRI 2-D2, 86 pp.

Haeni, F.P. 1988b. Evaluation of the Continuous Seismic-Reflection Method for Determining the Thickness and Lithology of Stratified Drift in the Glaciated Northeast. In: Regional Aquifer Systems of the United States-The Northeast Glacial Aquifers, A.D. Randall, and A.I. Johnson (eds.), American Water Resources Association Monograph Series No. 11, pp. 63-82.

Haeni, P. 1992. Use of Ground-Penetrating Radar and Continuous Seismic-Reflection Profiling on Surface-Water Bodies in Environmental and Engineering Studies. In: SAGEEP '92, Society of Engineering and Mineral Exploration Geophysicists, Golden, CO, pp. 145-162.

Haeni, F.P. and H.R. Anderson. 1980. Hydrogeologic Data for South Central Connecticut. Connecticut Water Resources Bull. 32,43 pp. [SRR]*

Haeni, F.P. and R.L. Melvin. 1984. High Resolution Continuous Seismic Reflection Study of a Stratified Drift Deposit in Connecticut. 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. 237-256.

Haeni, F.P., D.G. Grantham, and K. Ellefson. 1987. Microcomputer Based Version of SIPT—A Program for the Interpretation of Seismic Data. U.S. Geological Survey Open File Report 87-103-438 pp.

Hall, D.W. and D.L. Pasicznyk. 1987. Application of Seismic Refraction and Terrain Conductivity Methods at a Ground Water Pollution Site in North-Central New Jersey. In: Proc. 1st Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 505-524.

Hansen, P. 1986. Use of Continuous Seismic-Reflection Methods in a Hydrologic Study in Massachusetts, A Case Study. In: Proc. Surface and Borehole Geophysical Methods and Ground Water Instrumentation Conf. and Exp., National Water Well Association, Dublin, OH, pp. 381-395.

Harmon, E.J. 1984. Investigation of a Previously Unexplored Basaltic Aquifer Using Complementary Geophysical Methods. 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. 273-287. [ER, MAG, SRR, aeromagnetic survey].

Hasbrouck, W.P. 1986. Shallow Shear-Wave Reflections within the Panoche Fan Area, Central San Joaquin Valley, California. In: Proc. Surface and Borehole Geophysical Methods and Ground Water Instrumentation Conf. and Exp., National Water Well Association, Dublin, OH, pp. 437-448.

Hasbrouck, W.P. 1987. Hammer-Impact Shear-Wave Studies. In: Shear-Wave Exploration, S.H. Danbom, and S.N. Domenico (eds.), Society of Exploration Geophysicists, Tulsa, OK, pp. 97-121.

Hasbrouck, W.P. 1990a. Initial Shallow Seismic Tests in the Panoche Fan Area, Fresno County, California. In: Proc. of a U.S. Geological Survey Workshop on Environmental Geochemistry, B.R. Doe (ed.), U.S. Geological Survey Circular 1033, pp. 139-144. [SRL]

Hasbrouck, W.P. 1990b. Results of Shear-Wave Measurements. In: Proc. (3rd) Symp. on the Application of Geophysics to Engineering and Environmental Problems, Soc. Eng. and Mineral Exploration Geophysicists, Golden, CO, pp. 201-202.

Hasbrouck, W.P. 1991. Four Shallow-Depth, Shear-Wave Feasibility Studies. Geophysics 56(11):1875-1885. [earth fissures, aquiclude mapping, bedrock channel location, fault/fracture characterization]

Hassab, J.C. 1989. Underwater Signal and Data Processing. CRC Press, Boca Raton, FL, 320 pp.

Hasselstrom, B. 1969. Water Prospecting and Rock Investigation by the Seismic Method. Geoexploration 7:113-132. [SRR]

Hawkins, L.V. 1961. The Reciprocal Method of Routine Shallow Seismic Refraction Investigations. Geophysics 26:806-819. Discussion in Geophysics 27(4):534.

Hennon, K., D.W. Bostwick, M. Snoparsky, T.T. Travers, and P. McManus. 1991. Optimizing Seismic Refraction Results Through Pre-Survey Testing. In: Ground Water Management 5:999-1015 (5th NOAC); also, Ground Water Management 7:693-709 (8th NWWA Eastern GW Conference). [SRR and downhole seismic at Superfund site]

Hersey, J.B. 1963. Continuous Reflection Profiling. In: The Sea, Vol. 3, John Wiley & Sons, New York, 963 pp.

Hinchey, E. and G. Gould. 1990. Seismic Refraction Techniques and a Depositional Model for Glaciated Terrain Combine to Site Municipal Water Wells. In: Ground Water Management 3:269-282 (7th NWWA Eastern GW Conference).

Hobson, G.D. 1970. Seismic Methods in Mining and Groundwater Exploration. In: Mining and Groundwater Geophysics/1967, L.W. Merely (cd.), Geological Survey of Canada Economic Geology Report 26, pp. 148-176.

Hobson, G.D., J.E. Wyder, and C.V. Brandon. 1962. Aquifer Exploration in Canada by Geophysical Methods. Am. Water Works Ass. J. 54(9):1073-1081. [ER, SRR]

Huck, P.J. 1982. Assessment of Time Domain Reflectometry and Acoustic Emission Monitoring Leak Detection Systems for Landfill Liners. In: Proc. 8th Research Symp. (Land Disposal of Hazardous Waste), EPA/600/9-82/002 (NTIS PB82-173022), pp. 261-273.

Hughes, W.B. 1991. Application of Marine Seismic Profiling to a Ground Water Contamination Study, Aberdeen Proving Ground, Maryland. Ground Water Monitoring Review 11(1):97-102.

Hughes, W.B. 1992. Use of Marine-Seismic Profiling to Study Ground-Water Contamination at Aberdeen Proving Ground, Maryland. In: SAGEEP ’92, Society of Engineering and Mineral Exploration Geophysicists, Golden, CO, pp. 163-172.

Hunter, J. and S. Pullan. 1989. Optimum Offset Shallow Seismic Reflection Technique. In: Proc. (2nd) Symp. on the Application of Geophysics to Engineering and Environmental Problems, Soc. Eng. and Mineral Exploration Geophysicists, Golden, CO, pp. 143-174.

Hunter, J. A., R.A. Burns, R.L. Good, H.A. MacAulay, and R.M. Gagne. 1982. Optimum Field Techniques for Bedrock Reflection Mapping with the Multichannel Engineering Seismograph. Current Research, Part B. Geological Survey of Canada, Paper 82-lB, pp. 125-129.

Hunter, J. A., S.E. Pullan, R.A. Burns, R.M. Gagne, and R.L. Good. 1984. Shallow Seismic Reflection Mapping of the Overburden-Bedrock Interface with the Engineering Seismograph-Some Simple Techniques. Geophysics 49(8):1381-1385.

Imse, J.P. and E.N. Levine. 1985. Conventional and State-of-the-Art Geophysical Techniques for Fracture Detection. In: Proc. AGWSE Eastern Regional Ground Water Conference (Portland, ME), National Water Well Association, Dublin, OH, pp. 261-276. [ER, GPR, GR, SRR]

Irons, L. and B. Lewis. 1989. Modeling of Shallow High-Resolution Reflection Seismic Method at a Hazardous Waste Site. In: Proc. (2nd) Symp. on the Application of Geophysics to Engineering and Environmental Problems, Soc. Eng. and Mineral Exploration Geophysicists, Golden, CO, pp. 436-447.

Irons, L. and B. Lewis. 1990. Shallow High-Resolution Seismic Reflection Investigation at a Hazardous Waste Site. In: Proc. Fourth Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods. Ground Water Management 2:1129-1142.

Irons, L., B. Lewis, and M. McGuire. 1991. A Shallow High-Resolution Seismic Reflection Program to Characterize Hydrogeology. In: Proc. (4th) Symp. on the Application of Geophysics to Engineering and Environmental Problems, Soc. Eng. and Mineral Exploration Geophysicists, Golden, CO, pp. 81-96.

Johnson, R.B. 1954. Use of the Refraction Seismic Method of Differentiating Pleistocene Deposits in the Arcola and Tuscola Quadrangles, Illinois. Illinois State Geological Survey Report of Investigations 176, 59 pp.

Johnson, E.J. and J.C. Clark. 1992. Improving Subsurface Resolution with the Seismic Reflection Method: Use S-Waves. In: Ground Water Management 11:655-663 (Proc. of the 6th NOAC).

Joiner, TJ., and W.L. Scarborough. 1969. Hydrology of Limestone Terranes: Geophysical Investigations. Geological Survey of Alabama Bulletin 94D. [ER, GR, SRR]

Joiner, TJ., J.C. Warman, W.L. Scarborough, and D.B, Moore. 1967. Geophysical Prospecting for Ground Water in the Piedmont Area, Alabama. Alabama Geological Survey Circular 42,48 pp. [ER, MAG, SRR]

Joiner, TJ., J.C. Warman, and W.L. Scarborough. 1968. An Evaluation of Some Geophysical Methods for Water Exploration in the Piedmont Area. Ground Water 6(1):19-25. [ER, SRR] *

Kanemori, T., F.B. Michelsen, and J.H. Mires. 1992. Effects of Acquisition System Parameters on Refraction Survey Data. In: SAGEEP ’92, Society of Engineering and Mineral Exploration Geophysicists, Golden, CO, pp. 383-400.

Kent, D.C. and L.V.A. Sendlein. 1972. A Basin Study of Ground-Water Discharge from Bedrock into Glacial Drift: Part 1, Definition of Ground-Water Systems. Ground Water 10(4):24-34. [ER, SRR]

Kleinschmidt, J.M. and J.R. Pelton. 1989. High Resolution Seismic Reflection Survey to Map Sand Aquifers of the Municipal Water Supply of Boise, Idaho. In: Proc. (2nd) Symp. on the Application of Geophysics to Engineering and Environmental Problems, Soc. Eng. and Mineral Exploration Geophysicists, Golden, CO, pp. 191-205.

Kleyn, A.H. 1983. Seismic Reflection Interpretation. Elsevier, New York.

Knapp, R.W. and D.W. Steeples. 1986a. High-Resolution Common Depth-Point Seismic Reflection Profiling Instrumentation. Geophysics 51:276-282.

Knapp, R.W. and D.W. Steeples. 1986b. High-Resolution Common Depth-Point Reflection Profiling Field Acquisition Parameter Design. Geophysics 51:283-294.

Koerner, R.M. and A.E. Lord, Jr. 1976. Acoustic Emission Monitoring of Earth Dam Stability. Water Power and Dam Construction 28(4):45-49.

Koerner, R.M. and A.E. Lord, Jr. 1981. Application of Microseismic Techniques to Waste Dam Monitoring-Final Report. Contract J0295043. Bureau of Mines, U.S. Department of the Interior, 187 pp.

Koerner, R. M., A.E. Lord, Jr., and W.M. McCabe. 1976. Acoustic Emission (Microseismic) Monitoring of Earth Dam Stability. In: Proc. Conf. on Evaluation of Dam Safety (Pacific Grove, CA), Engineering Foundation, New York, NY, pp. 274-291.

Koerner, R. M., A.E. Lord, Jr., and W.M. McCabe. 1978. Acoustic Emission Monitoring of Soil Stability. J. of the Geotechnical Engineering Division ASCE 104(GT5):571-582.

Koerner, R. M., W.M. McCabe, and A.E. Lord Jr. 1981a. Acoustic Emission Behavior and Monitoring of Soils. In: Acoustic Emissions in Geotechnical Engineering Practice, V.P. Drnevich and R.E. Gray (eds.), ASTM SIT 750, American Society for Testing and Materials, Philadelphia, PA pp. 93-141.

Koerner, R. M., W.M. McCabe, and L.F. Boldivieso. 1981b. Acoustic Emission Monitoring of Seepage. J. of the Geotechnical Engineering Division ASCE 107(GT4):519-526.

Kopsick, D.A. and T.W. Stander. 1983. Refinement of the Shallow Seismic Reflection Technique in Determining Subsurface Alluvial Stratigraphy. In: Proc. Third Nat. Symp. on Aquifer Restoration and Ground Water Monitoring, National Water Well Association, Dublin, OH, pp. 301-306.

LaMoreaux, P.E. and D.O. Madison. 1984. The Occurrence of Sinkholes in the Vicinity of the Southern Natural Gas Company Dry Valley Pipeline, Shelby County, Alabama. 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. 259-272. [SRR]

Lankston, R.W. 1988. High Resolution Seismic Refraction Data Acquisition and Interpretation. In: Proc. (lst) Symp. on the Application of Geophysics to Engineering and Environmental Problems, Soc. Eng. and Mineral Exploration Geophysicists, Golden, CO, pp. 349-408.

Lankston, R. W. 1989. The Hidden-Layer Problem Myth in Refraction Seismic Surveying Dies Hard. In: Proc. (2nd) Symp. on the Application of Geophysics to Engineering and Environmental Problems, Soc. Eng. and Mineral Exploration Geophysicists, Golden, CO, pp. 176-190.

Lankston, R.W. and M.M. Lankston. 1983. An Introduction to the Utilization of the Shallow of Engineering Seismic Reflection Method. Geo-Compu-Graph, Inc., Fayetteville, AR.

Lankston, R.W. and M.M. Lankston. 1986. The Utility of Deconvolution of Seismic Traces in Ground Water Investigations. In: Proc. Surface and Borehole Geophysical Methods and Ground Water Instrumentation Conf. and Exp., National Water Well Association, Dublin, OH, pp. 417-436.

Haeni, F.P., D.K McKeegan, and D.R. Capron. 1987. Ground-Penetrating Radar Study of the Thickness and Extent of Sediments Beneath Silver Lake, Berlin and Meriden, Connecticut. U.S. Geological Survey Water Resources Investigations 85-4108, 19 pp.

Hager, J.L., E.K Triegel, and M.J. Stell. 1991. Use of Surface Geophysical Techniques to Locate Underground Storage Tanks at the New Castle County Airport, Delaware. In: Ground Water Management 5:1031-1044 (5th NOAC). [GPR, MAG]

Hall, D.H. and Z. Hajnal. 1962. The Gravimeter in Studies of Buried Valleys. Geophysics 27(6):939-951.

Hankins, J.B., R.M. Danielson, and P.A. Gregson. 1991. Delineation of Metal Hydroxide Sludge Disposal Areas Using Electromagnetic and Ground-Penetrating Radar. In: Ground Water Management 7:675-691 (8th NWWA Eastern GW Conference).

Hanninen, P. and S. Autio (eds.). 1992. Fourth International Conference on Ground Penetrating Radar (June 8-13, 1992, Rovaniemi, Finland). Geological Survey of Finland Special Paper 16,365 pp.

Hansen, D.S. 1984. Gravity Delineation of a Buried Valley in Quartzite. Ground Water 22(6):773-779.

Hares, M.A. J. Ben-Asher, A.D. Matthias, and A.W. Warrick. 1985. A Simple Method to Evaluate Daily Positive Soil Heat Flux. Soil Sci. Soc. Am. J. 49:45-47.

Harmon, E.J. 1984. Investigation of a Previously Unexplored Basaltic Aquifer Using Complementary Geophysical Methods. In: NWWA/EPA Conf. on Surface and Borehole Geophysical Methods in Ground Water Investigations (1st, San Antonio TX), National Water Well Association, Dublin, OH, pp. 273-287. [ER, MAG, SRR, aeromagnetic survey].

Harrison, C.H. 1970. Reconstruction of Subglacial Relief from Echo Sounding Records. Geophysics 35(6): 1099-1115. [GPR]

Hasted, T. 1974. Aqueous Dielectrics. Chapman Hall, London.

Hatch, Jr., N.N., W. Owens, S. Shannon, and P. Markey. 1987. Role of Surface Geophysics in Developing Buried Waste Removal Specifications. In: Superfund ’87, Hazardous Materials Control Research Institute, Silver Spring MD, pp. 300-305. [GPR, MAG]

Heigold, P. C., L.D. McGinnes, and R.H. Howard. 1964. Geologic Significance of the Gravity Field on the DeWitt and McLean County Area, Illinois. Illinois Geological Survey Circular 369.

Henry, Jr., G. 1984. Use of the Gravity Method in Mapping Bedrock Topography. 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. 220-236.

Hinze, W.J. 1988. Gravity and Magnetic Methods Applied to Engineering and Environmental Problems. In: Proc. Symp. on Application of Geophysics to Eng. and Environmental Problems, Soc. Eng. and Mineral Exploration Geophysicists, Golden, CO, pp. 1-107.

Hitchcock, A.S. and H.D. Harman, Jr. 1983. Application of Geophysical Techniques as a Site Screening Procedure at Hazardous Waste Sites. In: Proc. Third Nat. Symp. on Aquifer Restoration and Ground Water Monitoring, National Water Well Association, Dublin, OH, pp. 307-313. [ER, MAG]

Hoekstra, P. and A. Delaney. 1974. Dielectric Properties of Soils at UHF and Microwave Frequencies. J. Geophys. Res. 79:1699-1708.

Hogan, G. 1988. Migration of Ground Penetrating Radar Data A Technique for Locating Subsurface Targets. In: Proc. (lst) Symp. on the Application of Geophysics to Engineering and Environmental Problems, Soc. Eng. and Mineral Exploration Geophysicists, Golden, CO, pp. 809-822.

Horton, K.A., R.M. Morey, L. Isaacson, and R.H. Beers. 1981. The Complementary Nature of Geophysical Techniques for Mapping Chemical Waste Disposal Sites: Impulse Radar and Resistivity. In: Proc. (2nd) Nat. Conf. on Management of Uncontrolled Hazardous Waste Sites, Hazardous Materials Control Research Institute, Silver Spring, MD, pp. 158-164. [ER, GPR]

Horton, R., P.J. Wierenga, and D.R. Nielsen. 1983. Evaluation of Methods for Determining the Apparent Thermal Diffusivity of Soil Near the Surface. Soil Sci. Soc. Am. J. 47:25-32.

Houck, R.T. 1984. Measuring Moisture Content Profiles Using Ground-Probing Radar. 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. 637-653.

Howard, K.W.F., M. Hughes, and M.J. Thompson. 1986. Down-Hole Geophysical Methods of Fracture Detection in Low Permeability Bedrock. In: Proc. Surface and Borehole Geophysical Methods and Ground Water Instrumentation Conf. and Exp., National Water Well Association, Dublin, OH, pp. 507-525. [caliper, gamma-gamma, temperature]

Howell, B.F. 1959. Introduction to Geophysics. McGraw-Hill, New York, 399 pp. [S, GR, MAG, geothermal]

Hu, L.Z., M. Ramaswamy, B.G. Sexton, and D.E. Wyatt. 199. Delineate Subsurface Structures with Ground Penetrating Radar. In: Ground Water Management 13:749-762 (Proc. of Focus Conf. on Eastern Regional Ground Water Issues).

Ibrahim, A. and W.J. Hinze. 1971. Mapping Buried Bedrock Topography with Gravity. Ground Water 10(3):18-23.

Imse, J.P. and E.N. Levine. 1985. Conventional and State-of-the-Art Geophysical Techniques for Fracture Detection. In: Proc. AGWSE Eastern Regional Ground Water Conference (Portland, ME), National Water Well Association, Dublin, OH, pp. 261-276. [ER, GPR, GR, SRR]

Jackson, R.D. and D. Kirkham. Method of Measurement of the Real Thermal Diffusivity of Moist Soil. Soil Sci. Soc. Am. Proc. 22:479-482.

Jackson, R.D. and S.A. Taylor. 1986. Thermal Conductivity and Diffusivity. In: Methods of Soil Analysis, Part 1, 2nd ed., A. Klute (ed.), Agronomy Monograph No. 9. American Society of Agronomy, Madison, WI, pp. 945-956.

Jansen, J. 1990. Shallow Geothermal Exploration Techniques for Groundwater Studies. In: Proc. Fourth Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods. Ground Water Management 2:23-37.

Jansen, J. 1992. The Application of Shallow Geothermal Exploration Methods to Detect High Permeability Features in Groundwater Flow Systems. In: SAGEEP '92, Society of Engineering and Mineral Exploration Geophysicists, Golden, CO, pp. 519-530.

Jansen, J. and R. Taylor. 1988. Surface Geophysical Techniques for Fracture Detection. In: Proc. Second Conf. on Environmental Problems in Karst Terranes and Their solutions (NashvilIe, TN), National Water Well Association, Dublin, OH, pp. 419-441. [EMI, VLF, thermal, fracture trace]

Jansen, J. and R. Taylor. 1989. Geophysical Methods for Groundwater Exploration or Groundwater Contamination Studies in Fracture Controlled Aquifers. In: Proc. Third Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 855-869. [EMI, ER, VLF, thermal]

Jessup, A.M. 1990. Thermal Geophysics. Elsevier, New York, 306 pp.

Johnson, D.G. 1987. Use of Ground-Penetrating Radar for Determining Depth to the Water Table on Cape Cod, Massachusetts. In: Proc. First Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 541-554.

Joiner, T.J., and W.L. Scarborough. 1969. Hydrology of Limestone Terranes: Geophysical Investigations. Geological Survey of Alabama Bulletin 94D. [ER, GR, SRR]

Joiner, T.J., J.C. Warman, W.L Scarborough, and D.B. Moore. 1967. Geophysical Prospecting for Ground Water in the Piedmont Area, Alabama. Alabama Geological Survey Circular 42, 48 pp. [ER, MAG, SRR]

Kersten, M.S. 1949. Thermal Properties of Soils. Univ. of Minn. Eng. Exp. Sta. Bull. 28,225 pp.

Keys, W.S. and R.F. Brown. 1978. The Use of Temperature Logs to Trace the Movement of Injected Water. Ground Water 16(1):32-48.

Kick, J.F. 1989. Landfill Investigations in New England Using Gravity Methods. In: Proc. (2nd) Symp. on the Application of Geophysics to Engineering and Environmental Problems, Soc. Eng. and Mineral Exploration Geophysicists, Golden, CO, pp. 339-353.

Kimball, B.A. and R.D. Jackson. 1975. Soil Heat Flux Determination: A Null-Alignment Method. Agric. Metreol. 15:1-9.

Kimball, B.A., R.D. Jackson, R.J. Reginato, F.S. Nakayama, and S.B. Idso. 1976. Comparison of Field-Measured and Calculated Soil-Heat Fluxes. Soil Sci. Soc. Am. J. 49:18-25.

Koerner, R. and A. Lord. 1985. Microwave System for Locating Faults in Hazardous Materials Dikes. EPA/600/2-85/014 (NTIS PB85-173821), 141 pp. [GPR and continuous wave radar]

Koerner, R.M., A.E. Lord, Jr., T.A. Okransinski, and J.S. Reif. 1978. Detection of Seepage and Subsurface Flow of Liquids by Microwave Interference Methods. In: Control of Hazardous Materials Spills, Information Transfer, Inc., Rockville, MD, pp. 287-292.

Koerner, R.M., A.E. Lord, Jr., and J.J. Bowders. 1981. Utilization and Assessment of a Pulsed RF System to Monitor Subsurface Liquids. In: Proc. (2nd) Nat. Conf. on Management of

Uncontrolled Hazardous Waste Sites, Hazardous Materials Control Research Institute, Silver Spring, MD, pp. 165-171.

Koerner, R.M., A.E. Lord, Jr., S. Tyagi, and J.E. Brugger. 1982. Use of NDT Methods to Detect Buried Containers in Saturated Silty Clay Soil. In: Proc. (3rd) Nat. Conf. on Management of Uncontrolled Hazardous Waste Sites, Hazardous Materials Control Research Institute, Silver Spring, MD, pp. 12-16. [GPR, MAG, MD, VLF]

Kracchman, M.B. 1970. Handbook of Electromagnetic Propagation in Conducting Media. U.S. Navy Material Command, NAVMAT P-2302, 128 pp.

Kremar, B. and J. Masin. 1970. Prospecting by the Geothermic Method. Geophysical Prospecting 18(2):255-260.

Kufs, C.T., D.J. Messinger, and S. Del Re. 1986. Statistical Modeling of Geophysical Data. In: Proc. 7th Nat. Conf. on Management of Uncontrolled Hazardous Waste Sites, Hazardous Materials Control Research Institute, Silver Spring, MD, pp.110-114. [EMI, MAG, MD]

Kuo, S-S. and J.G. Stangland. 1986. Use of Ground Penetrating Radar Techniques to Aid in Design of On-Site Disposal Systems. In: Proc. Environmental Problems in Karst Terranes and Their Solutions Conference (Bowling Green, KY), National Water Well Association, Dublin, OH, pp. 502-525.

LaFehr, T.R. 1980. Gravity Method. Geophysics 45(11):1634-1639.

Lahee, F.H. 1961. Field Geology. McGraw-Hill, New York, 926 pp. [GR, MAG]

Lapham, W.W. 1989. Use of Temperature Profiles Beneath Streams to Determine Rates of Vertical Ground-Water Flow and Vertical Hydraulic Conductivity. U.S. Geological Survey Water Supply Paper 2337,34 pp.

Laudon, K.J. 1984. Geophysical Investigations of the Duck Lake Ground Water Subarea Near Omak, Washington. 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. 206-219. [GR, SRR]

Lawrence, L.T. 1984. Subsurface Geophysical Investigations and Site Mitigation. In: Proc. 5th Nat. Conf. on Management of Uncontrolled Hazardous Waste Sites, Hazardous Materials Control Research Institute, Silver Spring, MD, pp. 481-485. [EMI, GPR]

Leckenby, R.J. 1982. Electromagnetic Ground Radar Methods. In Premining Investigations for Hardrock Mining, U.S. Bureau of Mines Information Circular 8891, pp. 36-45. [GPR, cross-hole radar]

Lee, W.H. (ed.). 1965. Terrestrial Heat Flow. Geophysical Monograph Series, American Geophysical Union, 276 pp.

Lennox, D.H. and V. Carlson. 1967. Geophysical Exploration for Buried Valleys in an Area North of Two-Hills Alberta. Geophysics 32(2):331-410. Discussion in Geophysics 35(2):922. [ER, GR, SRR]

Lennox, D.H. and V. Carlson. 1970. Integration of Geophysical Methods for Ground Water Exploration in the Prairie Provinces, Canada. In: Mining and Groundwater Geophysics/1967, L.W. Merely (ed.), Geological Survey of Canada Economic Geology Report 26, pp. pp. 517-535. [ER, GR, SRR]

Lepper, C.M. and R.S. Dennen. 1990. Selection of Antennas for GPR System. In: Proc. (3rd) Symp. on the Application of Geophysics to Engineering and Environmental Problems, Soc. Eng. and Mineral Exploration Geophysicists, Golden, CO, pp. 229-230.

Lettau, B. 1971. Determination of the Thermal Diffusivity in the Upper Layers of a Natural Ground Cover. Soil Science 112:173-177.

Lord, Jr. A.E. and R.M. Koerner. 1982. Electromagnetic Methods in Subsurface Investigations. In: Proc. Conf. on Updating Subsurface Sampling of Soils and Rocks and their In-Situ Testing (Santa Barbara, CA), S.K Saxena (ed), Engineering Foundation, New York, NY, pp. 113-133.

Lord, Jr., A.E. and R.M. Koerner. 1986. Nondestructive Testing (NDT) Location of Containers Buried in Soil. In: Proc. 12th Research Symp. (Land Disposal, Remedial Action, Incineration and Treatment of Hazardous Waste), EPA/600/9-86/022 (NTIS PB87-119491), pp. 161-169. [EMI, GPR, MAG, MD]

Lord, Jr., A.E. and R.M. Koerner. 1987a. Nondestructive Testing (NDT) Techniques to Detect Contained Subsurface Hazardous Waste. EPA/600/2-87/078 (NTIS PB88-102405). [EMI, GPR, MAG, MD, brief review of 13 other methods]

Lord, Jr., A.E., and R.M. Koerner. 1987B. Nondestructive Testing (NDT) for Location of Containers Buried in Soil. In: Proc. 13th Research Symp. (Land Disposal, Remedial Action, Incineration and Treatment of Hazardous Waste), EPA/600/S9-87/015 (NTIS PB87-233151), pp. 224-234. [EMI, GPR, MAG, MD]

Lucius, J.E., G.R. Olhoeft, and S.K. Dukes (eds.). 1990. Third International Conference on Ground Penetrating Radar: Abstracts of the Technical Meeting, Lakewood, CO, May 14-18, 1990. U.S. Geological Survey Open File Report 90-414, 94 pp.

Mabey, D.R. 1960. Gravity Survey of the Western Mojave Desert, California. U.S. Geological Survey Professional Paper 316-D, pp 51-73.

Mabey, D.R. and S.S. Oriel. 1970. Gravity and Magnetic Anomalies from the Soda Springs Regions, Southeastern Idaho. U.S. Geological Survey Professional Paper 646-E, 41 pp.

Marshall, J.P. 1971. The Application of Geophysical Instruments and Procedures to Ground-Water Exploration and Research. Montana Water Resource Research Center Termination Report 5, OWRR A-013-MONT(l), Bozeman, MT. [SRR, GR]

Martinek, B.C. 1988. Ground Based Magnetometer Survey of Abandoned Wells at the Rocky Mountain Arsenal-A Case History. In: Proc. (lst) Symp. on the Application of Geophysics to Engineering and Environmental Problems, Soc. Eng. and Mineral Exploration Geophysicists, Golden, CO, pp. 578-598.

Mattick, R.E., F.H. Olmsted, and A.A.R. Zohdy. 1973. Geophysical Studies in the Yuma Area, Arizona and California. U.S. Geological Survey Professional Paper 726-D, 36 pp. [SRR, ER, GR, SRL, AEM]

McGinnis, L.D., J.P. Kempton, and P.C. Heigold. 1963. Relationship of Gravity Anomalies to a Drift-Filled Bedrock Valley System in Northern Illinois. Illinois State Geological Survey Circular 354, 23 pp.

Michalski, A. 1989. Application of Temperature and Electrical-Conductivity Logging in Ground Water Modeling. Ground Water Monitoring Review 9(3):112-118.

Misener, A.D. and A. E. Beck. 1960. The Measurement of Heat Flow over Land. In: Methods and Techniques in Geophysics, Vol. 1, S.E. Runcorn (ed.), Interscience Publishers, New York, pp. 10-61.

Moffat, D.L. and R.J. Puskar. 1976. A Subsurface Electromagnetic Pulse Radar. Geophysics 41(3):506-518.

Morey, R.M. 1974. Continuous Subsurface Profiling by Impulse Radar. In: Proc. Engineering Foundation Conf. on Subsurface Exploration for Underground Excavation and Heavy Construction (Henniker, NH), American Society Civil Engineers, pp. 213-232. [GPR]

Morey, R.M. and W.S. Harrington, Jr. 1972. Feasibility of Electromagnetic Subsurface Profiling. EPA R2-72-082 (NTIS PB213 892).

Morin, R.H. and W. Barrash. 1986. Defining Patterns of Ground Water and Heat Flow in Fractured Brule Formation, Western Nebraska, Using Borehole Geophysical Methods. In: Proc. Surface and Borehole Geophysical Methods and Ground Water Instrumentation Conf. and Exp., National Water Well Association, Dublin, OH, pp. 545-569.

Morrison, R.D. 1983. Ground Water Monitoring Technology Procedures, Equipment and Applications. Timco Mfg., Prairie Du Sac, WI, 111 pp. [shallow thermal]

Nettleton, L.L. 1971. Gravity and Magnetics for Geologists and Seismologists. Monograph No. 1. Society of Exploration Geophysicists, Tulsa, OK, 121 pp.

Nettleton, L.L. 1976. Gravity and Magnetics in Oil Prospecting. McGraw-Hill, New York, 464 pp.

Newman, J. and J. McDuff. 1988. Electric Wireline Methods for In Situ Capture of Wellbore Samples and Determining Their Flow Rates and Direction. In Proc. 2nd Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 97-122. [caliper, gamma, neutron, temperature, fluid conductivity, flowmeter]

Nightingale, H.I. 1975. Ground-Water Recharge Rates from Thermometry. Ground Water 13(4):340-344.

Norris, S.E. and A.M. Spieker. 1962a. Seasonal Temperature Changes in Wells as Indicator of Semiconfining Beds in Valley-Train Aquifers. U.S. Geological Survey Professional Paper 450-B, pp. 101-102.

Norris, S.E. and A.M. Spieker. 1962b. Temperature-Depth Relations as Indicators of Semiconfining Beds in Valley-Train Aquifers. U.S. Geological Survey Professional Paper 450-B, pp. 103-105.

Nowak, T.J. 1953. The Estimation of Water Injection Profiles from Temperature Surveys. Trans. Am. Inst. Mining Metall. Eng., Petroleum Division 198:203-212.

O'Brien, P.J. 1970. Aquifer Transmissivity Distribution as Reflected by Overlying Soil Temperature Patterns. Pennsylvania State University Ph.D thesis, 178 pp.

O'Brien, K.M. and W.J. Stone. 1984. Role of Geological and Geophysical Data in Modeling a Southwestern Alluvial Basin. Ground Water 22(6):717-727. [GR, SRR]

O'Brien, K.M. and W.J. Stone. 1985. Role of Geological and Geophysical Data in Modeling an Alluvial Basin, Southwest New Mexico. In: Conference on Surface and Borehole Geophysical Methods and Ground Water Investigations (2nd, Fort Worth, TX), National Water Well Association, Dublin, OH, pp. 198-214. [GR, SRR]

Olhoeft, G.R. 1984. Applications and Limitations of Ground Penetrating Radar. In: Expanded Abstracts, 54th Ann. Int. Meeting and Expo. of the Soc. of Explor. Geophys., Atlanta, pp. 147-148.

Olhoeft, G.R. 1986. Direct Detection of Hydrocarbons and Organic Chemicals with Ground Penetrating Radar and Complex Resistivity. In: Proc. (3rd) NWWA/API Conf. on Petroleum Hydrocarbons and Organic Chemicals in Ground Water, National Water Well Association, Dublin, OH, pp. 284-305.

Olhoeft, G.R. 1988. Selected Bibliography on Ground Penetrating Radar. In: Proc. (lst) Symp. Application of Geophysics to Eng. and Environmental Problems, Soc. Eng. and Mineral Exploration Geophysicists, Golden, CO, pp. 462-520.

Olhoeft, G.R. 1990. Tutorial: High Frequency Electrical Properties. In: Proceedings of the 3rd International Conference on Ground Penetrating Radar, U.S. Geological Survey Open-File Report 90-414.

Olhoeft, G.R. 1992. Geophysical Detection of Hydrocarbon and Organic Chemical Contamination. In: SAGEEP '92, Society of Engineering and Mineral Exploration Geophysicists, Golden, CO, pp. 587-595. [complex resistivity, GPR]

Olhoeft, G.R., K.A. Sander, and J.E. Lucius. 1992. Surface and Borehole Radar Monitoring of a DNAPL Spill in DC versus Frequency, Look Angle, and Time. In: SAGEEP '92, Society of Engineering and Mineral Exploration Geophysicists, Golden, CO, pp. 455-469.

Olson, C. G., and J.A. Doolittle. 1985. Geophysical Techniques for Reconnaissance Investigations of Soils and Surficial Deposits in Mountainous Terrain. Soil Sci. Soc. Am. J. 49:1490-1498. [GPR]

Omnes, G. 1977. High Accuracy Gravity Applied to the Detection of Karstic Cavities. In: Karst Hydrogeology: Proceedings of the Twelfth Meeting of the International Association of Hydrogeologists, J.S. Tolson, and F.L. Doyle (eds.), University of Alabama-Huntsville Press, Huntsville, AL, pp. 273-284.

Osborne, J. 1991. Automated Subsurface Mapping. In: Proc. Second International Symposium, Field Screening Methods for Hazardous Waste and Toxic Chemicals. EPA/600/9-91/028 (NTIS PB92-125764)), pp. 205-216.

Palermo, R.S. and M.E. Brickell. 1984. Proton Precession Magnetometry A Geophysical Approach. In: Proc. of the NWWA Tech. Division Eastern Regional Ground Water Conference (Newton, MA), National Water Well Association, Dublin, OH, pp. 234-253.

Parr, A.D., F.J. Molz, J.G. Melville. 1983. Field Determination of Aquifer Thermal Energy Storage Parameters. Ground Water 21:22-35.

Parsons, M.L. 1970. Groundwater Thermal Regime in a Glaciated Complex. Water Resources Research 6:1701-1720.

Peacock D.R. 1965. Temperature Logging. In: Trans. 6th Annual Logging Symposium. Society of Professional Well Log Analysts, Tulsa, OK, pp. F1-F18.

Pease, Jr., R.W. and S.C. James. 1981. Integration of Remote Sensing Techniques with Direct Environmental Sampling for Investigating Abandoned Hazardous Waste Sites. In: Proc. (2nd) Nat. Conf. on Management of Uncontrolled Hazardous Waste Sites, Hazardous Materials Control Research Institute, Silver Spring, MD, pp. 171-176. [ER, GPR, MD, SRR]

Pilon, J.A. (ed.). 1992. Ground Penetrating Radar. Geological Survey of Canada Paper 90-4, 241 pp.

Pitchford, A.M., A.T. Mazzella, and K.R. Scarborough. 1988. Soil-Gas and Geophysical Techniques for Detection of Subsurface Organic Contamination. EPA/600/4-88/019 (NTIS PB88-208194). [GPR, EMI, ER, complex resistivity, SRR, MD, MAG]

Pittman, W.E., Jr., R.H. Church, W.E. Webb, and J.T. McLendon. 1984. Ground-Penetrating Radar: A Review of Its Application in the Mining Industry. U.S. Bureau of Mines Information Circular 8964, 23 pp.

Poeter, E.P. 1989. Delineating Geometry of Unconfined Aquifer Heterogeneities with Microgravity Surveys During Aquifer Testing. In: Proc. Conf. on New Field Techniques for Quantifying the Physical and Chemical Properties of Heterogeneous Aquifers, National Water Well Association, Dublin, OH, pp. 213-227.

Puckett, W.E., M.E. Collins, and G. Schellentrager. 1986. Evaluating Soil-Landscape Patterns on Karst Using Radar Data. Agronomy Abstracts 1986:232.

Ram Babu, H.V., N. Kameswara Rao, and V. Vijay Kumar. 1991. Bedrock Topography from Magnetic Anomalies-An Aid for Groundwater Exploration in Hard-Rock Terrain. Geophysics 56(7):1051-1054.

Randall, A.D. 1986. Aquifer Modeling of the Susquehanna River Valley in Southwest Broome County, New York. U.S. Geological Survey Water-Resource Investigation Report 85-4099, 38 pp. [shallow geothermal]

Redman, J.D., B.H. Kueper, and A.P. Annan. 1991. Dielectric Stratigraphy of a DNAPL Spill and Implications for Detection with Ground Penetrating Radar. Ground Water Management 5:1017-1029 (5th NOAC).

Redwine, J. et al. 1985. Groundwater Manual for the Electric Utility Industry, Volume 3: Groundwater Investigations and Mitigation Techniques. EPRI CS-3901. Electric Power Research Institute, Palo Alto, CA. [SRR, SRL ER, SP, EMI, GPR, GR]

Reford, M.S. 1980. Magnetic Method. Geophysics 45(11) :1640-1658...

Regan, J. M., M.S. Robinette, and T.R. Beaulieu. 1987. The Use of Remote Sensing, Geophysical, and Soil Gas Techniques to Locate Monitoring Wells at Hazardous Waste Sites in New Hampshire.

In: Proc. of the Fourth Annual Eastern Regional Ground Water Conference (Burlington, VT), National Water Well Association, Dublin, OH, pp. 577-591. [EMI, ER, GR, MAG, SRR, fracture trace]

Rehm, B.W., T.R. Stolzenburg, and D.G. Nichols. 1985. Field Measurement Methods for Hydrogeologic Investigations: A Critical Review of the Literature. EPRI EA-4301. Electric Power Research Institute, Palo Alto, CA. [Major methods: ER, EMI, SRR, BH; Other: IR, SP, IP/CR, SRR, GPR, MAG, GR, thermal]

Richard, B.H. and P.J. Wolfe. 1990. Gravity as a Tool to Delineate Buried Valleys. In: Proc. (3rd) Symp. on the Application of Geophysics to Engineering and Environmental Problems, Soc. Eng. and Mineral Exploration Geophysicists, Golden, CO, pp. 59-106.

Roberts, R. G., W.J. Hinze, and D.I. Leap. 1989. A Multi-Technique Geophysical Approach to Landfill Investigations. In: Proc. 3rd Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 797-811. [EMI, ER, GPR, GR, MAG, SRR]

Roberts, R. J.J. Daniels, and L. Peters, Jr. 1992. Improved GPR Interpretation from Analysis of Buried Target Polarization Properties. In: SAGEEP '92, Society of Engineering and Mineral Exploration Geophysicists, Golden, CO, pp. 353-374.

Rodriguez, E.B. 1987. Application of Gravity and Seismic Methods in Hydrogeological Mapping at a Landfill Site in Ontario. In: Proc. 1st Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 487-504.

Rorabaugh, M.I. 1956. Ground Water in Northeastern Louisville, Kentucky. U.S. Geological Survey Water-Supply Paper 1360-B: 101-169. [ground-water temperature as measure of surface water-ground-water relationships]

Rubin, L.A. and J.C. Fowler. 1978. Ground-Probing Radar for Delineation of Rock Features. Eng. Geol. (Amsterdam) 12(2):163-170.

Rudy, R.J. and J.B. Warner. 1986. Detection of Abandoned Underground Storage Tanks in Marion County, Florida. In: Proc. Surface and Borehole Geophysical Methods and Ground Water Instrumentation Conf. and Exp., National Water Well Association, Dublin, OH, pp. 674-688. [EMI, GPR, MAG]

Russell, G.M. 1990. Application of Geophysical Techniques for Assessing Ground-Water Contamination near a Landfill at Stuart Florida. In: Ground Water Management 3:211-225 (7th NWWA Eastern GW Conference). [ER, EMI, VLF, GPR]

Saint-Amant, M. and D.W. Strangway. 1970. Dielectric Properties of Dry Geologic Materials. Geophysics 35(4):624-645.

Sammel, E.A. 1968. Convective Flow and Its Effect on Temperature Logging in Small-Diameter Wells. Geophysics 33(6):1004-1012.

Sampayo, F.E. and H.R. Wilke. 1963. Temperature and Phosphate as Ground-Water Tracers. Ground Water 1(1):56-61.

Saunders, W. R., S. Smith, P. Gilmore, and S. Cox. 1991. The Innovative Application of Surface Geophysical Techniques for Remedial Investigations. In: Ground Water Management 5:947-961 (5th NOAC). [EMI, TDEM, GPR, soil gas]

Schaetele, W.F., C.E. Brett, D.W. Grubbs, and M.S. Seppamen. 1980. Thermal Energy Storage in Aquifers. Pergamon Press, NY, 177 pp.

Schellentrager, G.W., J.A. Doolittle, T.E. Calhoun, and C.A. Wettstein. 1988. Using Ground-Penetrating Radar to Update Soil Survey Information. Soil Sci. Soc. Am. J. 52:746-751.

Schlinger, C.M. 1990. Magnetometer and Gradiometer Surveys for Detection of Underground Storage Tanks. Bull. Ass. Eng. Geol. 28(1):37-50.

Schneider, R. 1962. An Application of Thermometry to Study of Groundwater. U.S. Geological Survey Water-Supply Paper 1544-B.

Schutts, L.D. and D.G. Nichols. 1991. Surface Geophysical Definition of Ground Water Contamination and Buried Waste: Case Studies of Electrical Conductivity and Magnetic Applications. In: Ground Water Management 5:889-903 (5th NOAC).

Sellman, P.V., S.A. Arcone, and A.J. Delaney. 1983. Radar Profiling of Buried Reflections and the Ground Water Table. CRREL Report 83-11. U.S. Army Cold Reg. Res. and Eng. Lab., Hanover, NH.

Sharma, P.V. 1986. Geophysical Methods in Geology, 2nd ed. Elsevier, New York, 428 pp. [First edition 1976]. [S, GR, MAG, ER, GT]

Sheriff, R.E. 1989. Geophysical Methods. Prentice Hall, Englewood Cliffs, NJ, 591+ pp. [GR, MAG, ER, EM, SRR, geothermal]

Shih, S.F. and J.A. Doolittle. 1984. Using Radar to Investigate Organic Soil Thickness in Florida Everglades. Soil Sci. Soc. Am. J. 48:651-656.

Shih, S.F., J.A. Doolittle, D.L. Myhre, and G.W. Schellentrager. 1986. Using Radar for Groundwater Investigations. J. Irr. and Drain. Eng. 112:110-118. [GPR]

Silliman, S. and R. Robinson. 1989. Identifying Fracture Interconnections Between Boreholes Using Natural Temperature Profiling Conceptual Basis. Ground Water 27(3):393-402.

Silliman, S., J. Nicholas, and A. Shapiro. 1987. Estimating Fracture Connectivity Using Measurement of Borehole Temperature During Pumping. In: Proc. NWWA Focus Conf. on Midwestern Ground Water Issues (Indianapolis, IN), National Water Well Association, Dublin, OH, pp. 231-248.

Skolnik, M.I. (ed.). 1990. Radar Handbook, 2nd ed. McGraw-Hill, New York.

Smith, E.M. 1974. Exploration for a Buried Valley by Resistivity and Thermal Probe Surveys. Ground Water 12(2):78-83.

Smith, D,V, and G. Markt. 1988. A Ground Penetrating Radar and Magnetometry Survey at Nuclear Lake, New York—A Case History, In: Proc. (lst) Symp. on the Application of Geophysics to Engineering and Environmental Problems, Soc. Eng. and Mineral Exploration Geophysicists, Golden, CO, pp. 621-641.

Smith, G.D., F. Newhall, and L.H. Robinson. 1960. Soil-Temperature Regimes-Their Characterization and Predictability. SCS-TP-144. USDA Soil Consevation Service, 14 pp.

Soil Conservation Service. 1988. Second International Conference on Ground Penetrating Radar, March 6-10, 1988, Gainesville, FL. U.S. Department of Agriculture, 179 pp.

Sophocleous, M. 1979. A Thermal Conductivity Probe Designed for Easy Installation and Recovery from Shallow Depth. Soil Sci. Soc. Am. J. 43:1056-1058.

Sorey, M.L. 1971. Measurement of Vertical Ground-Water Velocity from Temperature Profiles in Wells. Water Resources Research 7(4):963-970.

Spangler, D.P. and F.J. Libby. 1968. Application of Gravity Survey Methods to Watershed Hydrology. Ground Water 6(6):21-26.

Stallman, R.W. 1963. Computation of Ground-Water Velocity from Temperature Data. In: Methods of Collecting and Interpreting Ground Water Data, R. Bentall (compiler), U.S. Geological Survey Water-Supply Paper 1544-H, pp H36-H46.

Stallman, R.W. 1965. Steady One-Dimensional Fluid Flow in a Semi-Finite Porous Medium with Sinusoidal Surface Temperature. J. Geophys. Res. 70(12):2821-2827.

Stanfill, III, D.F. and K.S. McMillan. 1985. Radar-Mapping of Gasoline and Other Hydrocarbons in the Ground. In: Proc. 6th Nat. Conf. on Management of Uncontrolled Hazardous Waste Sites, Hazardous Materials Control Research Institute, Silver Spring, MD, pp.269-274.

Stearns, B.G. and L.M.J. Dialmann, III. 1986. Geophysical Techniques and Monitoring Network Design at the Sike Disposal Pit Hazardous Waste Site, Crosby, TX. In: Proc. Surface and Borehole Geophysical Methods and Ground Water Instrumentation Conf. and Exp., National Water Well Association, Dublin, OH, pp. 657-673. [ER, GPR]

Stevens, Jr., H.H., J.F. Ficke, and G.F. Smoot. 1975. Water Temperature-Influential Factors, Field Measurement and Data Presentation. U.S. Geological Survey Techniques of Water-Resources Investigations TWRI 1-D1.

Stewart, M.T. 1980. Gravity Survey of a Deep Valley. Ground Water 18(1):24-30.

Stewart, M. and J. Wood. 1986. Geologic and Geophysical Character of Fracture Zones in a Carbonate Aquifer. In: Proc. Focus Conf. on southeastern Ground Water Issues (Tampa, FL), National Water Well Association, Dublin, OH, pp. 289-294. [ER, GR]

Stierman, DJ., L.C. Ruedisili, and J.M. Stangl. 1986. The Application of Surface Geophysics to Mapping Hydrogeologic Conditions of a Glaciated Area in Northwest Ohio. In: Proc. Surface and Borehole Geophysical Methods and Ground Water Instrumentation Conf. and Exp., National Water Well Association, Dublin, OH, pp. 591-600. [ER, SRR, MAG]

Strange, W.E. 1970. The Use of Gravimeter Measurements in Mining and Groundwater Exploration. In: Mining and Groundwater Geophysics/1967, L.W. Merely (ed), Geological Survey of Canada Economic Geology Report 26, pp. 46-50.

Struttmann, T. and T. Anderson. 1989. Comparison of Shallow Electromagnetic and the Proton Precession Magnetometer Surface Geophysical Techniques to Effectively Delineate Buried Wastes.

In: Superfund ’89, Proceedings of the 10th Annual Conference, Hazardous Material Control Research Institute, Silver Spring, MD, pp. 27-34.

Summers, W.K 1971. The Annotated Indexed Bibliography of Geothermal Phenomena. New Mexico Institute of Mining and Technology, Socorro, NW. [More than 14,000 references.]

Supkow, DJ. 1971. Subsurface Heat Flow as a Means for Determining Aquifer Characteristics in the Tucson Basin, Pima County, Arizona. University of Arizona Ph.D thesis, 181 pp.

Sutcliffe, Jr., H. and B.F. Joyner. 1966. Packer Testing in Water Well near Sarasota, Florida. Ground Water 4(2):23-27. [caliper, fluid conductivity, temperature]

Suzuki, S. 1960. Percolation Measurements Based on Heat Flow Through Soil with Special Reference to Paddy Fields. J. Geophysical Research 65(9):2883-2885.

Tareev, B. 1975. Physics of Dielectric Materials. Mir, Moscow.

Taylor, K.R. and M.E. Baker. 1988. Use of Ground-Penetrating Radar in Defining Glacial Outwash Aquifers. In: Proc. of the Focus Conf. on Eastern Regional Ground Water Issues (Stanford, CT), National Water Well Association, Dublin, OH, pp. 77-98.

Taylor, S.A. and R.D. Jackson. 1986a. Temperature. In: Methods of Soil Analysis, Part 1, 2nd ed., A. Klute (ed.), Agronomy Monograph No. 9. American Society of Agronomy, Madison, WI, pp. 927-940.

Taylor, S.A. and R.D. Jackson. 1986b. Heat Capacity and Specific Heat. In: Methods of Soil Analysis, Part 1, 2nd ed., A. Klute (ed.), Agronomy Monograph No. 9. American Society of Agronomy, Madison, WI, pp. 941-944.

Tibbets, B.L. and J.H. Scott. 1972. Geophysical Measurements of Gold-Bearing Gravels, Nevada County, California. U.S. Bureau of Mines Report of Investigation 7584. [SRR, GR]

Trabant, P.K. 1984. Applied High-Resolution Geophysical Methods- Offshore Geoengineering Hazards. International Human Resource Development Corp., Boston, MA, 265 pp. [CSP, GPR]

Trainer, F.W. 1968. Temperature Profiles of Water Wells as Indicators of Bedrock Fractures. U.S. Geological Survey Professional Paper 600-B, pp. 210-214.

Truman, C. C., H.F. Perkins, L.E. Asmussen, and H.D. Allison. 1988. Using Ground-Penetrating Radar to Investigate Variability in Selected Soil Properties. J. Soil and Water Conservation 43:341-345.

Truman, C. C., L.E. Asmussen, and H.D. Allison. 1991. Ground-Penetrating Radar: A Tool for Mapping Reservoirs and Lakes. J. Soil and Water Conservation 46(5):370-373.

Ulriksen, P.F. 1982. Application of Impulse Radar to Civil Engineering. Geophysical Survey Systems Inc., Hudson, NH.

Underwood, J.E. and J.W. Eales. 1984. Detecting a Buried Crystalline Waste Mass with Ground-Penetrating Radar. In: NWWA/EPA Conf. on Surface and Borehole Geophysical Methods in Ground Water Investigations (1st, San Antonio TX), National Water Well Association, Dublin, OH, pp. 654-665,

U.S. Environmental Protection Agency (EPA). 1987. A Compendium of Superfund Field Operations Methods, Part 2. EPA/540/P-87/001 (OSWER Directive 9355.0-14) (NTIS PB88-181557). [EMI, ER, SRR, SRL, MAG, GPR, BH]

U.S. Environmental Protection Agency (EPA). 1993. Subsurface Field Characterization and Monitoring Techniques: A Desk Reference Guide, Volume I: solids and Ground Water. EPA/625/R-93/003a. Available from EPA Center for Environmental Research Information, Cincinnati, OH. [Section 1.5 covers GPR, MAG, GR and Section 1.6 covers thermal methods.]

U.S. Geological Survey (USGS). 1980. Geophysical Measurements. In: National Handbook of Recommended Methods for Water Data Acquisition, Chapter 2 (Ground Water), Office of Water Data Coordination, Reston, VA pp. 2-24 to 2-76. [TC, MT, AMT, EMI, ER, IP, SRR, SRL, GR, BH]

van Beek, L.K.H. 1965. Dielectric Behavior of Heterogeneous Systems. In: Progress in Dielectrics, Vol. 7, J.B. Birks (eds.), CRC Press, Boca Raton, FL, pp. 69-114.

Van Overmeeren, R.A. 1980. Tracing by Gravity of a Narrow Buried Graben Predicted by Seismic Refraction for Groundwater Investigation in North Chile. Geophysical Prospecting 28:392-407.

Van Overmeeren, R.A. 1981. Combination of Electrical Resistivity, Seismic Retraction, and Gravity Measurements for Groundwater Exploration in Sudan. Geophysics 46:1304-1313.

Von Hippel, A.R. 1954a. Dielectrics and Waves. MIT Press, Cambridge, MA, 284 pp.

Von Hippel, A.R. (ed.). 1954b. Dielectrics: Materials and Applications. MIT Press, Cambridge MA, 438 pp.

Wallace, D.E. and D.P. Spangler. 1970. Estimating Storage Capacity in Deep Alluvium by Gravity-Seismic Methods. Bull. Int. Assn. Sci. Hydrology 15(2):91-104.

Walsh, D.C. 1989. Surface Geophysical Exploration for Buried Drums in Urban Environments: Applications in New York City. In: Proc. Third Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 935-949. [EMI, MAG]

Watts, R.D. and A.W. England 1976. Radio-Echo Soundings of Temperate Glaciers: Ice Properties and Sounder Design Criteria. J. Glaciology 17:39-48. [GPR]

Watson, J., D. Stedje, M. Barcelo, and M. Stewart. 1990. Hydrogeologic Investigation of Cypress Dome Wetlands in Well Field Areas North of Tampa Florida. In: Ground Water Management 3:163-176 (7th NWWA Eastern GW Conference). [TDEM, VLF, ER, GPR]

Weaver, H.G. and G.S. CampbeI1. 1985. Use of Peltier Coolers as Soil Heat Flux Transducers. Soil Sci. Soc. Am. J. 49:1065-1066.

West, R.E. and J.S. Sumner. 1972. Ground-Water Volumes from Anomalous Mass Determinations for Alluvial Basins. Ground Water 10(3):24-32. [GR]

Westphalen, O. 1991. The Application of Borehole Geophysics to Identify Fracture Zones and Define Geology at Two New England Sites. In: Ground Water Management 7:535-546. (8th NWWA

Eastern GW Conference). [caliper, SP, SP resistance, temperature, gamma, gamma-gamma, neutron, acoustic televiewer]

White, R.M. and S.S. Brandwein. 1982. Application of Geophysics to Hazardous Waste Investigations. In: Proc. (3rd) Nat. Conf. on Management of Uncontrolled Hazardous Waste Sites, Hazardous Materials Control Research Institute, Silver Spring, MD, pp. 91-93. [EMI, ER, GPR, MAG]

Wierenga, P.J., D.R. Nielsen, and R.M. Hagan. 1969. Thermal Properties of Soils Based upon Field and Laboratory Measurements. Soil Sci. Soc. Am. Proc. 33:354-360.

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]

Williams, J.H., L.D. Carswell, O.B. Lloyd, and W.C. Roth. 1984. Borehole Temperature and Flow Logging in Selected Fractured Rock Aquifers in East Central Pennsylvania. In: NWWA/EPA Conf. on Surface and Borehole Geophysical Methods in Ground Water Investigations (1st, San Antonio, TX), National Water Well Association, Dublin, OH, pp. 842-852.

Wilson, G.V., T.J. Joiner, and J.L. Warner. 1970. Evaluation, by Test Drilling, of Geophysical Methods Used for Ground-Water Development in the Piedmont Area, Alabama. Alabama Geological Survey Circular 65, 15 pp. [ER, MAG, SRR]

Wilson, M.P., D.N. Peterson, and T.F. Ostrye. 1983. Gravity Exploration of a Buried Valley in the Appalachian Plateau. Ground Water 21(5):589-596.

Wire, J. C., J.K. Hofer, and D.J. Moser. 1984 Ground Magnetometer and Gamma-Ray Spectrometer Surveys for Ground Water Investigations in Bedrock. 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. 288-313.

Worthington, P.F. 1975. Procedures for the Optimum Use of Geophysical Methods in Ground-Water Development Programs. Ass. Eng. Geol. Bull. 12(1):23-38. [ER, IP, SRR, GR]

Wrege, B.M. 1986. Surface- and Borehole-Geophysical Surveys Used to Define Hydrogeologic Units in South-Central Arizona. In: Proc. Conf. on southwestern Ground Water Issues (Tempe, AZ), National Water Well Association, Dublin, OH, pp. 485-499. [GR, SRR, SRL, seismic shear]

Wright, D.L., G.R. Olhoeft, and R.D. Watts. 1984. Ground-Penetrating Radar Studies on Cape Cod. 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. 666-680.

Wynn, J.C. 1979. An Experimental Ground-Magnetic and VLF-EM Traverse over a Buried Paleochannel Near Salisbury, Maryland. U.S. Geological Survey Open-File Report 79-105, 8 pp.

Yazicigil, H. and L.V.A. Sendlein. 1982. Surface Geophysical Techniques in Ground Water Monitoring, Part II. Ground Water Monitoring Review 2(1):56-62. [ER, thermal]

Yearsley, E.N., J.J. LoCoco, and R.E. Crowder. 1990. Borehole Geophysics Applied to Fracture Hydrology. In: Ground Water Management 3:255-267 (7th NWWA Eastern GW Conference). [acoustic waveform, temperature, resistivity, brine tracing]

Zobeck, T.M., J.G. Lyon, D.R. Mapes, and A. Ritchie, Jr. 1985. Calibrating Ground-Penetrating Radar for Soil Applications. Soil Sci. Soc. Am. J. 49:1587-1590.

Zohdy, A.A., G.P. Eaton, and D.R. Mabey. 1974. Application of Surface Geophysics to Ground-Water Investigations. U.S. Geological Survey Techniques of Water-Resource Investigations TWRI 2-D1, 116 pp. [ER, GR, MAG, SRR]

# 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.

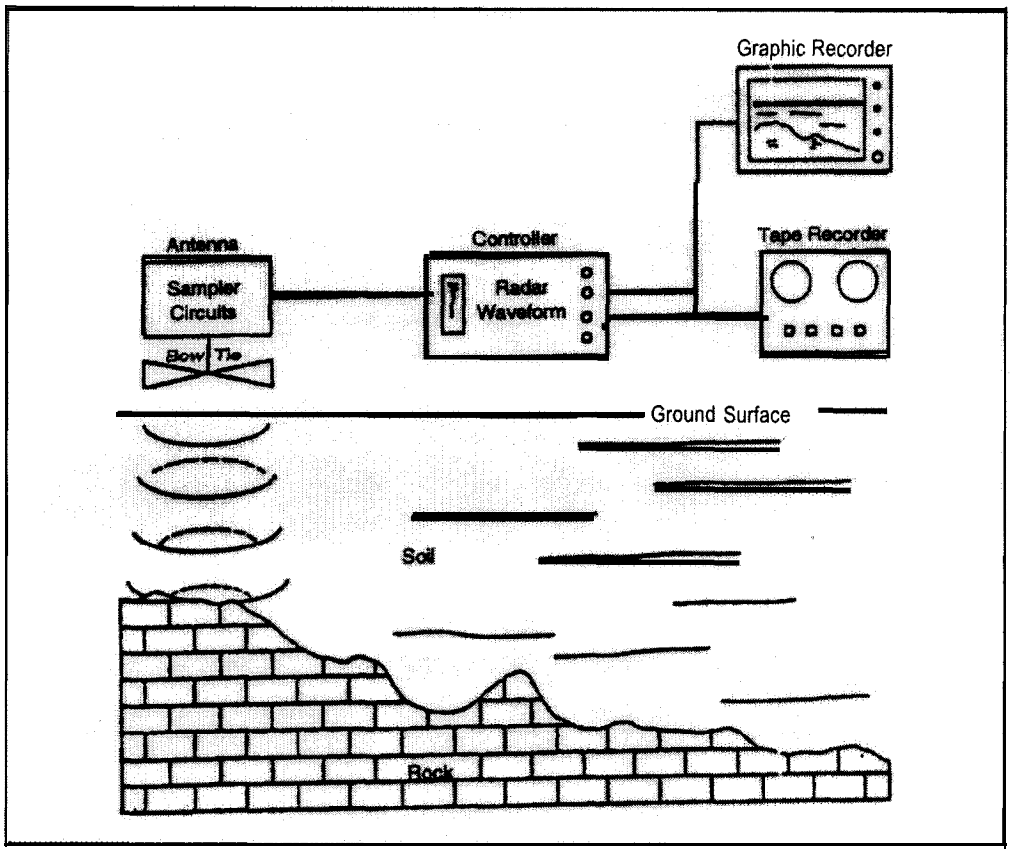


Figure 6-1 Block diagram of ground penetrating radar system. Radar waves are reflected from soil-rock interface (from Benson et al., 1984).

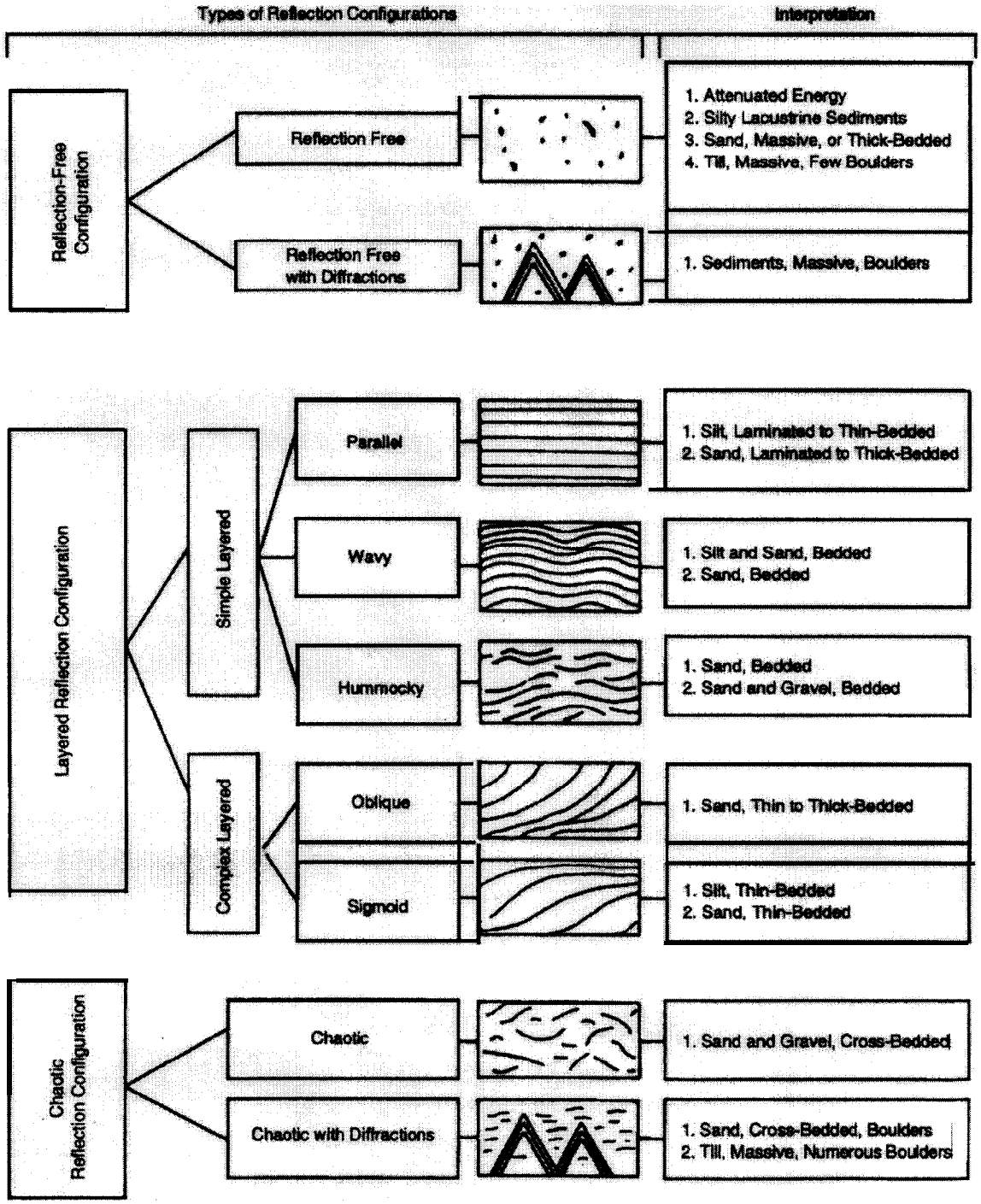


Figure 6-2 Reflection configurations on ground penetrating radar images indicating the lithologic and stratigraphic properties of sediments in the glaciated Northwest (Beres and Haeni, 1991).

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.


Adams, J.M., W.J. Hinze, and L.A. Brown. 1975. Improved Application of Geophysics to Groundwater Resource Inventories in Glaciated Terrains. Water Resources Research Center Tech. Report No. 59 (NTIS PB244-879). Purdue University, West Lafayette, IN. [GR, IP]

Akhadov, Y. 1980. Dielectric Properties of Binary Solutions. Pergamon, New York, 475 pp.

Ali, H.O. 1985. Gravity and Seismic Refraction Measurements for Deep Ground Water Search in Southern Darfur Region, Sudan. In: NWWA Conference on Surface and Borehole Geophysical Methods and Ground Water Investigations (2nd, Fort Worth, TX), National Water Well Association, Dublin, OH, pp. 106-120.

Ali, H.O. and R.I. Whiteley. 1981. Gravity Exploration for Groundwater in the Bara Basin, Sudan. Geoexploration 19:127- 141.

Allen, R.P. and B.A. Rogers. 1989. Geophysical Surveys in Support of a Remedial Investigation/Feasibility Study at the Municipal Landfill in Metamora, Michigan. In: Proc. 3rd Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 1007-1020. [ER, MAG, SRR]

Allen, R.P. and M.A. Seelen. 1992. The Use of Geophysics in the Detection of Buried Toxic Agents at a U.S. Military Installation. In: Current Practices in Ground Water and Vadose Zone Investigations, ASTM STP 1118, D.M. Nielsen and M.N. Sara (eds.), American Society for Testing and Materials, Philadelphia, PA, pp. 59-68. [MAG, EMI, GPR]

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]

Annan, A.P. and SW. Cosway. 1992. Ground Penetrating Radar Survey Design. In: SAGEEP '92; Society of Engineering and Mineral Exploration Geophysicists, Golden, CO, pp. 329-352.

Annan, A.P., J.L. Davis, and D. Gendzwill. 1988. Radar Sounding in Potash Mines, Saskatchewan, Canada. Geophysics 53(12):1556-1564.

Arman, A.P., P. Bauman, J.P. Greenhouse, and J.D. Redman. 1991. Geophysics and DNAPLs. In: Ground Water Management 5:963-977 (5th NOAC). [GPR]

Ani, A.A. 1975. Microgravimetry for Engineering Applications. Geophysical Prospecting 23(3):408-425.

Arzi, A.A. 1977. Remote Sensing of Subsurface Karst by Microgravity (Abstract). In: Karst Hydrogeology: Proceedings of the Twelfth Meeting of the International Association of Hydrogeologists, J.S. Tolson, and F.L. Doyle (eds.), University of Alabama-Huntsville Press, Huntsville, AL, pp. 271-172.

Asmussen, L.E., H.F. Perkins, and H.D. Allison. 1986. Subsurface Descriptions by Ground-Penetrating Radar for Watershed Delineation. Ga. Agric. Exp. Sta. Res. Bull. 362, Athens.

Bair, E.S. and R.R. Parizek. 1978. Detection of Permeability Variations by a Shallow Geothermal Technique. Ground Water 16(4):254-263.

Barrows, L. and J.E. Rocchio. 1990. Magnetic Surveying for Buried Metallic Objects. Ground Water Monitoring Review 10(3):204-211.

Barton, G.J. and T. Ivanhenko. 1991. Electromagnetic Terrain Conductivity and Ground Penetrating Radar Investigations at and Near the CIBA-GEIGY Super-fund Site, Ocean County, New Jersey: Quality Control Assurance Plan and Results. In: Proc. (4th) Symp. on the Application of Geophysics to Engineering and Environmental Problems, Soc. Eng. and Mineral Exploration Geophysicists, Golden, CO, pp. 357-360.

Beck, B.F. and W.L. Wilson. 1988. Interpretation of Ground Penetrating Radar Profiles in Karst Terrane. In: Proc. Second Conf. on Environmental Problems in Karst Terranes and Their Solutions (Nashville, TN), National Water Well Association, Dublin, OH, pp. 347-367.

Beck, A, F. Anglin, and J. Sass. 1971. Analysis of Heat Flow Data*c11 4 in situ thermal Conductivity Measurements. Can. J. Earth Sci. 8:1-19.

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

Benson, R.C., R.A. Glaccum, and M.R. Noel. 1984. 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]

Beres, Jr., M. and F.P. Haeni. 1991. Application of Ground-Penetrating Radar Methods in Hydrogeologic Studies. Ground Water 29:375-386.

Birch, F.S. 1984. Bedrock Depth Estimates from Ground Magnetometer Profiles. Ground Water 22(4):427-432.

Birman, J.H. 1969. Geothermal Exploration of Ground Water. Bull. Geol. Soc. Am. 80(4):617-630.

Bjelm, L., S.G.W. Follin, and C. Svensson. 1983. A Radar in Geological Subsurface Investigations. Bull. Int. Ass. Eng. Geol. 26/27:10-14.

Blasting, J.F. 1987. Characterization of an Abandoned Waste Site Using Proton Magnetometry and Computer Graphics. In: Proc. First Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 573-584. [MAG]

Blizkovsky, M. 1979. Processing and Application in Microgravity Surveys. Geophysical Prospecting 23(3):408-425.

Bogoslovsky, V.V. and AA. Ogilvy. 1977. Magnetometric and Electrometric Methods for the Investigation of the Dynamics of Landslide Processes. Geophysical Prospecting 25(3):280-291. [SP, MAG]

Bowder, J.J., Jr., R.K. Koerner, and A.E. Lord, Jr. 1982. Buried Container Detection Using Ground Probing Radar. J. Hazardous Materials 7: 1-17.

Boyle, J.M. and Z.A. Saleem. 1979. Determination of Recharge Rates Using Temperature-Depth Profiles in Wells. Water Resources Research 15(6):1616-1622.

Bozorth, R.M. 1951. Ferromagnetism. Van Nostrand Co., New York, 968 pp.

Bredehoeft, J.D. and I.S. Papadopulos. 1965. Rates of Vertical Groundwater Movement Estimated from the Earth's Thermal Profile. Water Resources Research 1(2):325-328.

Breiner, S. 1973. Applications Manual for Portable Magnetometers. Geometries, Sunnyvale, CA, 58 pp.

Brewster, M.L., J.D. Redman, and A.P. Annan. 1992. Monitoring of a Controlled Injection of Perchloroethylene in a Sandy Aquifer with Ground Penetrating Radar and Time Domain Reflectometry. In: SAGEEP '92, Society of Engineering and Mineral Exploration Geophysicists, Golden, CO, pp. 611-618.

Brown, R.H., A..A Konoplyantsev, J. Ineson, and V.S. Kovalensky. 1983. Ground-Water Studies: An International Guide for Research and Practice. Studies and Reports in Hydrology No. 7. UNESCO, Paris. [Originally published in 1972, with supplements added in 1973, 1975, 1977, and 1983]. [Thermal methods for evaluation of ground-water covered in Section 5.5.1

Bruehl, D.H. 1983. Use of Geophysical Techniques to Delineate Ground-Water Contamination. In: Proc. Third Nat. Symp. on Aquifer Restoration and Ground Water Monitoring, National Water Well Association, Dublin, OH, pp. 295-300. [ER, GR, SRR]

Bruehl, D.H. 1984. Use of Complementary Geophysical Techniques to Delineate Ground Water, Contamination. In: Proc. of the NWWA Tech. Division Eastern Regional Ground Water Conference (Newton, MA), National Water Well Association, Dublin, OH, pp. 265-273. [ER, SRR, GR]

Buchan, G.D. 1991. Soil Temperature Regime. In: Soil Analysis: Physical Methods, K.A. Smith and C.E. Mullins (eds.), Marcel Dekker, New York, pp. 551-612.

Burgdorf, G.J. and B.H. Richard. 1984. Geophysical Exploration of Buried Valley Systems in Southwestern Ohio for Ground Water Resources. In: NWWA/EPA Conf. on Surface and Borehole Geophysical Methods in Ground Water Investigations (San Antonio TX), National Water Well Association, Dublin, OH, pp. 176-205. [CR, SRR]

Butler, D.K. 1977. Geophysics versus the Cavity Detection Problem. In: Symposium on Detection of Subsurface Cavities, U.S. Army Corps of Engineer, Water Experiment Station, Vicksburg, MS, pp. 27-43. [GR]

Butler, D.K. 1984. Microgravimetric and Gravity Gradient Techniques for Detecting Subsurface Cavities. Geophysics 49:1084-1096.

Butler, D.K. 1991. Engineering and Environmental Applications of Microgravimetry. In: Proc. (4th) Symp. on the Application of Geophysics to Engineering and Environmental Problems, Soc. Eng. and Mineral Exploration Geophysicists, Golden, CO, pp. 139-246.

Cameron, R.M. 1988. The Application of Ground-Probing Radar to the Detection of Hydrocarbon Contamination. In: Proc. (1st) Symp. on the Application of Geophysics to Engineering and Environmental Problems, Soc. Eng. and Mineral Exploration Geophysicists, Golden, CO, pp. 807-808.

Carlslaw, H.S. 1986. Conduction of Heat in Solids, 2nd ed. Oxford University Press, NY, 510 pp. [First edition by Carlslaw and Jaeger published in 1960].

Carmichael, R.S. 1976. Gravity Geophysics for Groundwater Exploration in Glaciated areas. Institute of Water Research, Michigan State University, East Lansing, MI, 34 pp.

Carmichael, R.S. and G. Henry. 1977. Gravity Exploration for Groundwater and Bedrock Topography in Glaciated Areas. Geophysics 42(4):850-859.

Carr, III, J.L., C.S. Ulmer, C.K Eger, and P. Mann. 1990. Delineation of a Suspected Drum and Hazardous Waste Disposal Site Utilizing Multiple Geophysical Methods: Shaver's Farm, Chickmauga, Walker County, Georgia. In: Proc. Fourth Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods. Ground Water Management 2:1097-1111. [EMI, VLF, MAG]

Cartwright, K. 1968a. Thermal Prospecting for Ground Water. Water Resources Research 4(2):395-401.

Cartwright, K. 1968b. Temperature Prospecting for Shallow Glacial and Alluvial Aquifers in Illinois. Illinois State Geological Survey Circular 433, 41 pp.

Cartwright, K. 1970. Groundwater Discharge in the Illinois Basin as Suggested by Temperature Anomalies. Water Resource Research 6(3):912-918.

Cartwright, K. 1973. The Effect of Shallow Groundwater Flow Systems on Rock and Soil Temperatures. Univ. of Illinois Ph.D Thesis, 117 pp.

Cartwright, K. 1974. Tracing Shallow Ground Water Systems by Soil Temperatures. Water Resources Research 10(4):847-855.

Cartwright, K. and M.R. McComas. 1968. Geophysical Surveys in the Vicinity of Sanitary Landfills in Northeastern Illinois. Ground Water 6(5):23-30. [ER, thermal]

Chikazumi, S. 1964. The Physics of Magnetism. John Wiley & Sons, New York,

Cichowicz, N.L., R.W. Pease, Jr., P J. Stollar, and H.J. Jaffe. 1981. Use of Remote Sensing Techniques in a Systematic Investigation of an Uncontrolled Hazardous Waste Site. EPA/600/2-81/187 (NTIS PB82-103896). [ER, SRR, GPR; MD]

Cleff, R. (ed). 1991. An Evaluation of Soil Gas and Geophysical Techniques for Detection of Hydrocarbons. API Publication No. 4509, American Petroleum Institute, Washington, DC. [GPR, EMI, ER, complex resistivity]

Cohen, K.K., N.N. Moebs., and M.A. Trevits. 1992. Magnetometry as a Too1 to Map Subsurface Conditions in an Abandoned Iron Ore Mining District in New Jersey. In: SAGEEP '92, Society of Engineering and Mineral Exploration Geophysicists, Golden, CO, pp. 91- 110.

Colley, G.C. 1963. The Detection of Caves by Gravity Measurements. Geophysical Prospecting 1l(l):l-9.

Collins, M.E. and J.A. Doolittle. 1987. Using Ground-Penetrating Radar to Study Soil Microvariability. Soil Sci. Soc. Am. J. 51:491-493.

Collins, M.E., G.W. Schellentrager, J.A. Doolittle, and SF. Shih. 1986. Using Ground-Penetrating Radar to Study Map Unit Composition in Selected Histosols. Soil Sci. Soc. Am. J. 50:408-411.

Collins, M.E., J.A. Doolittle, and R.V. Rourke. 1989. Mapping Depth to Bedrock on a Glaciated Landscape with Ground-Penetrating Radar. Soil Sci. Soc. Am. J. 53: 1806-1812.

Conaway, J.G. 1977. Deconvolution of Temperature Gradient Logs. Geophysics 42(4):823-837.

Conaway, J.G. and A.E. Beck. 1977. Fine-Scale Correlation Between Temperature Gradient Logs and Lithology. Geophysics 42(7): 1401-1410.

Cook, J.C. 1956. An Electrical Crevasse Detector. Geophysics 21(4):1055-1070. [GPR]

Cook, J.C. 1973. Radar Exploration Through Rock in Advance of Mining. Trans. Soc. Eng. AIME 254(June):140-146. [GPR]

Cook, J.C. 1975. Radar Transparencies of Mines and Tunnel Rocks. Geophysics 40:865-885. [GPR]

Cosgrave, T.M., J.P. Greenhouse, and J.F. Barker. 1987. Shallow Stratigraphic Reflections from Ground Penetrating Radar. In: Proc. 1st Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 555-569.

Dahlstrand, T.K. 1985. Applications of Microgravity Surveys to Subsurface Exploration. In: NWWA Conference on Surface and Borehole Geophysical Methods and Ground Water Investigations (2nd Fort Worth, TX), National Water Well Association, Dublin, OH, pp. 85-105.

Daniel, V.V. 1967. Dielectric Relaxation. Academic Press, NY

Daniels, J.J. 1989. Technical Review: Ground Penetrating Radar. In: Proc. (2st) Symp. on the Application of Geophysics to Engineering and Environmental Problems,. Soc. Eng. and Mineral Exploration Geophysicists, Golden, CO, pp. 62-142.

Daniels, J.J., R. Roberts, and M. Vendl. 1992. Site Studies of Ground Penetrating Radar for Monitoring Petroleum Product Contaminants. In: SAGEEP '92, Society of Engineering and Mineral Exploration Geophysicists, Golden, CO, pp. 597-610.

Davis, B.R., J.L. Lunden, and A.N. Williamson. 1966. Feasibility Study of the Use of Radar to Detect Ground Water. Tech. Report 3-727. U.S. Army Corps of Engineers Waterways Exp. Station, Vicksburg, MS.

Davis, J.L., R.W.D. Killey, A.P. Annan, and C. Vaughn. 1984. Surface and Borehole Ground-Penetrating Radar Surveys for Mapping Geological Structure. In: NWWA/EPA Conf. on Surface and

Borehole Geophysical Methods in Ground Water Investigations (1st, San Antonio TX), National Water Well Association, Dublin, OH, pp. 681-712.

Davis, S.N., D J. Campbell, H.W. Bentley, and T.J. Flynn. 1985. Introduction to Ground-Water Tracers. EPA/600/2-85/022 (NTIS PB86-100591). Also published under the title Ground Water Tracers in NWWA/EPA Series, National Water Well Association, Dublin, OH.

Denne, J.E., et al. 1984. Remote Sensing and Geophysical Investigations of Glacial Buried Valleys in Northeastern Kansas. Ground Water 22(1):56-65. [ER, GR, SRR, thermal]

de Vries, D.A. 1963. Thermal Properties of Soils. In: Physics of Plant Enviromnent, W.R. Van Wijk (ed), North-Holland Publishing Co., Amsterdam, pp. 210-235.

de Vries, D.A. 1975. Heat Transfer in Soils. In: Heat and Mass Transfer in the Biosphere, W.R. Van Wijk and N.A. Afgan (eds.), John Wiley & Sons, New York, pp. 5-28.

Dolphin, L.T., W.B. Beatty, and J.D. Tunzi. Radar Probing of Victoria Peak, New Mexico. Geophysics 43(7):1441-1448.

Domenico, P.A. and V.V. Palciauskas. 1973. Theoretical Analysis of Forced Convective Heat Transfer in Regional Ground-Water Flow. Geol. Soc. Am. Bull. 84(12):3803-3184.

Doolittle, J.A. 1982. Characterizing Soil Map Units with the Ground-Penetrating Radar. Soil Survey Horizons (Soil Science Society of America, Madison, WI) 23(4):3-10.

Doolittle, J.A. 1983. Investigating Histosols with GPR. Soil Survey Horizons (Soil Science Society of America, Madison, WI) 24(3):23-28.

Doolittle, J.A. 1987. Using Ground-Penetrating Radar to Increase the Quality and Efficiency of Soil Surveys. In: Soil Survey Techniques, W.U. Reybold and G.W. Petersen (eds.). SSSA Special Publication No. 20, Soil Science Society of America, Madison, WI, pp. 11-32.

Douglas, D.G., A.A. Burns, C.L. Rino, and J.W. Maresca, Jr. 1992. A Study to Determine the Feasibility of Using A Ground-Penetrating Radar for More Effective Remediation of Subsurface Contamination. EPA/600/R-92/089 (NITS PB92-169382), 115 pp.

Duckworth, K. Electromagnetic Sounding Applied to Mining Problems. Geophysics 35(6):1086-1098.

Eaton, G.P. and J.S. Watkins. 1970. The Use of Seismic Refraction and Gravity Methods in Hydrogeological Investigations. In: Mining and Groundwater Geophysics/l967, L.W. Morely (ed.), Geological Survey of Canada Economic Geology Report 26, pp. 544-568.

Emilsson, G.R. and R.A. Arnott. 1991. In-Situ Specific Conductivity Monitoring on a Observation Well During a Long Term Pumping Test. In Ground Water Management 5:533-547 (5th NOAC). (conductivity-temperature probe]

Emilsson, G.R. and P.R. Morin. 1989. Using Vertical Electric Soundings to Accurately Map a Buried Channel in Coastal Plain Sediments. In: Proc. Focus Conf. on Eastern Regional Ground Water Issues, National Water Well Association, Dublin, OH, pp. 41-54. [ER, MAG]

Environmental Consulting & Technology (EC&T), Inc., Technos, Inc., and UXB International, Inc. 1990. Construction Site Environmental Survey and Clearance Procedures Manual, U.S. Army Toxic and Hazardous Materials Agency, Aberdeen Proving Ground, MD. [GPR, EMI, MAG, MD, soil gas]

Evans, R.B. and G.E. Schweitzer. 1984. Assessing Hazardous Waste Problems. Environ. Sci. Technol. 18(11):330A-339A. [EMI, ER, GPR, MAG, MD, SRR]

Eve, A.S. and D.A. Keys. 1954. Applied Geophysics in the Search for Minerals, 4th ed. Cambridge University Press, New York, 382 pp. [earlier editions 1929, 1931, 1938]. [MAG, ER, EM, GR, S, geothermal]

Fajkewicz, Z.J. 1976. Gravity Vertical Gradient Measurements for the Detection of Small Geologic and Anthropogenic Forms. Geophysics 41(5):1016-1030.

Farouki, O.T. 1981. Thermal Properties of Soils. U.S. Army Corps of Engineers Cold Regions Research and Engineering Laboratory Monograph 81- 1, 151 pp.

Feld, R.H., M. Stammler, G.A. Sandness, and C.S. Kimball. 1983. Geophysical Investigations of Abandoned Waste Sites and Contaminated Industrial Areas in West Germany. In: Proc. (4th) Nat. Conf. on Management of Uncontrolled Hazardous Waste Sites, Hazardous Materials Control Research Institute, Silver Spring, MD, pp. 68-70. [EMI, GPR, MAG]

Filler, D.M. and S-S. Kuo. 1989. Subsurface Cavity Explorations Using Non-Destructive Geophysical Methods. In: Proc. Third Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 827-840. [ER, GPR,- SRR]

Flint, A.L. and S.W. Childs. 1987. Field Procedures for Estimating Soil Thermal Environments. Soil Sci Soc. Am. J. 51:1326-1331.

Fountain, L.S. 1976. Subsurface Cavity Detection: Field Evaluation of Radar, Gravity, and Earth Resistivity Methods. In: Subsidence Over Mines and Caverns, Transportation Research Record 612, Transportation Research Board, National Academy of Sciences, Washington, DC, pp. 38-46.

Fowler, J.W. and A. Ayubcha. 1986. Selection of Appropriate Geophysical Techniques for the Characterization of Abandoned Waste Sites. In: Proc. Surface and Borehole Geophysical Methods and Ground Water Instrumentation Conf. and Exp., National Water Well Association, Dublin, OH, pp. 625-656. [ER, EMI, SRR, GPR, GR, MAG]

Fowler, J.W. and D.L. Pasicznyk. 1985. Magnetic Survey Methods Used in the Initial Assessment of a Waste Disposal Site. In: NWWA Conference on Surface and Borehole Geophysical Methods and Ground Water Investigations (2nd Fort Worth, TX), National Water Well Association, Dublin, OH, pp. 267-281. [EMI, MAG]

Friedel, M.J., J.A. Jessop, R.E. Thill, and D.L. Veith. 1990. Electromagnetic Investigation of Abandoned Mines in the Galena, KS, Area. U.S. Bureau of Mine Report of Investigations 9303, 20 pp. [EMI, GPR]

Frohlich, R.K. 1978. The Dependence of the Residual Gravity on Hydraulic Constants in Glacial Deposits. Water Resources Bull. 14(4):931-941.

Fuchs, M. 1986. Heat Flux. In: Methods of Soil Analysis, Part 1, 2nd ed, A. Klute (ed.), Agronomy Monograph No. 9. American Society of Agronomy, Madison, WI, pp. 957-968.

Fuchs, M. and A. Hadas. 1973. Analysis of the Performance of an Improved Soil Heat Flux Traducer. Soil Sci. Soc. Am. Proc. 37:173-175.

Ghatge, S.L. and D.L. Pasicznyk. 1986. Integrated Geophysical Methods in the Determination of Bedrock Topography. In: Proc. Surface and Borehole Geophysical Methods and Ground Water Instrumentation Conf. and Exp., National Water Well Association, Dublin, OH, pp. 601-624. [ER, TDEM, IP, SRR, GR, MAG]

Gilkeson, R.H. and K. Cartwright: 1982. The Application of Surface Geophysical Methods in Monitoring Network Design. In: Proc. Second Nat. Symp. on Aquifer Restoration and Ground Water Monitoring, National Water Well Association, Dublin, OH, pp. 169-183. [EMI, ER, SP, Thermal]

Gilkeson, R.H. and K. Cartwright. 1983. The Application of Surface Electrical and Shallow Geothermic Methods in Monitoring Network Design. Ground Water Monitoring Review 3(3):30-42.

Gilkeson, R.H., T.H. Larson, and P.C. Heigold 1984. Definition of Contaminant Pathways: An Integrated Geophysical and Geological Study. 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. 567-583. [ER, thermal]

Gilkeson, R.H., P.C. Heigold, and D.E. Layman. 1986. Practical Application of Theoretical Models to Magnetometer Surveys on Hazardous Waste Disposal Sites-A Case History. Ground Water Monitoring Review 6(1):54-61.

Gilkeson, R.H., S.R. Gorin, and D.E. Laymon. 1992. Application of Magnetic and Electromagnetic Methods to Metal Detection. In: SAGEEP '92, Society of Engineering and Mineral Exploration Geophysicists, Golden, CO, pp. 309-328.

Gilmer, T.H. and M.P. Heibling. 1984. Geophysical Investigations of a Hazardous Waste Site in Massachusetts. 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. 618-634. [EMI, ER, MAG, SRR]

Glaccum, R.A., R.C. Benson, and M.R. Noel. 1982. Improving Accuracy and Cost-Effectiveness of Hazardous Waste Site Investigations. Ground Water Monitoring Review 2(3):36-40. [EMI, GPR]

Gorin, S.R. and F.P. Haeni. 1989. Use of Surface-Geophysical Methods to Assess Riverbed Scour at Bridge Piers. U.S. Geological Survey Water Resources Investigations Report 88-4212, 33 pp. [GPR]

Gouge1 J. 1976. Geothermics. McGraw-Hill, New York, 2090 pp.

Guyod, H. 1946. Temperature Well Logging. Oil Weekly Seven parts: Oct. 21, 28; Nov. 4, 11; Dec. 2, 9, 16.

Haeni, P. 1992. Use of Ground-Penetrating Radar and Continuous Seismic-Reflection Profiling on Surface-Water Bodies in Environmental and Engineering Studies. In: SAGEEP '92, Society of Engineering and Mineral Exploration Geophysicists, Golden, CO, pp. 145- 162.

Haeni, F.P., D.K. McKeegan, and D.R. Capron. 1987. Ground-Penetrating Radar Study of the Thickness and Extent of Sediments Beneath Silver Lake, Berlin and Meriden, Connecticut. U.S. Geological Survey Water Resources Investigations 85-4108, 19 pp.

Hager, J.L., E.K. Triegel, and M.J. Stell. 1991. Use of Surface Geophysical Techniques to Locate Underground Storage Tanks at the New Castle County Airport, Delaware. In: Ground Water Management 5:1031-1044 (5th NOAC). [GPR, MAG]

Hall, D.H. and Z. Hajnal. 1962. The Gravimeter in Studies of Buried Valleys. Geophysics 27(6):939-951.

Hankins, J.B., R.M. Danielson, and P.A. Gregson. 1991. Delineation of Metal Hydroxide Sludge Disposal Areas Using Electromagnetics and Ground-Penetrating Radar. In: Ground Water Management 7:675-691 (8th NWWA Eastern GW Conference).

Hanninen, P. and S. Autio (eds.). 1992. Fourth International Conference on Ground Penetrating Radar (June 8-13, 1992 Rovaniemi, Finland). Geological Survey of Finland Special Paper 16, 365 pp.

Hansen, D.S. 1984. Gravity Delineation of a Buried Valley in Quartzite. Ground Water 22(6):773-779.

Hares, M.A. J. Ben-Asher, AD. Matthias, and A.W. Warrick. 1985. A Simple Method to Evaluate Daily Positive Soil Heat Flux. Soil Sci. Soc. Am. J. 49:45-47.

Harmon, E.J. 1984. Investigation of a Previously Unexplored Basaltic Aquifer Using Complementary Geophysical Methods. In: NWWA/EPA Conf. on Surface and Borehole Geophysical Methods in Ground Water Investigations (1st, San Antonio TX), National Water Well Association, Dublin, OH, pp, 273-287. [ER, MAG, SRR, aeromagnetic survey].

Harrison, C.H. 1970. Reconstruction of Subglacial Relief from Echo Sounding Records. Geophysics 35(6):1099-1115. [GPR]

Hasted, T. 1974. Aqueous Dielectrics. Chapman Hall, London.

Hatch, Jr., N.N., W. Owens, S. Shannon, and P. Markey. 1987. Role of Surface Geophysics in Developing Buried Waste Removal Specifications. In: Superfund '87, Hazardous Materials Control Research Institute, Silver Spring MD, pp. 300-305. [GPR, MAG]

Heigold, P.C., L.D. McGinnes, and R.H. Howard. 1964. Geologic Significance of the Gravity Field on the Dewitt and McLean County Area, Illinois. Illinois Geological Survey Circular 369.

Henry, Jr., G. 1984. Use of the Gravity Method in Mapping Bedrock Topography. 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. 220-236.

Hinze, W.J. 1988. Gravity and Magnetic Methods Applied to Engineering and Environmental Problems. In: Proc. Symp. on Application of Geophysics to Eng. and Environmental Problems, Soc. Eng. and Mineral Exploration Geophysicists, Golden, CO, pp. l-107.

Hitchcock, AS. and H.D. Harman, Jr. 1983. Application of Geophysical Techniques as a Site Screening Procedure at Hazardous Waste Sites. In: Proc. Third Nat. Symp. on Aquifer Restoration and Ground Water Monitoring, National Water Well Association, Dublin, OH, pp. 307-3 13. [ER, MAG]

Hoekstra, P. and A. Delaney. 1974. Dielectric Properties of Soils at UHF and Microwave Frequencies. J. Geophys. Res. 79:1699-1708.

Hogan, G. 1988. Migration of Ground Penetrating Radar Data: A Technique for Locating Subsurface Targets. In: Proc. (1st) Symp. on the Application of Geophysics to Engineering and Environmental Problems, Soc. Eng. and Mineral Exploration Geophysicists, Golden, CO, pp. 809-822.

Horton, K.A., R.M. Morey, L. Isaacson, and R.H. Beers. 1981. The Complementary Nature of Geophysical Techniques for Mapping Chemical Waste Disposal Sites: Impulse Radar and Resistivity. In: Proc. (2nd) Nat. Conf. on Management of Uncontrolled Hazardous Waste Sites, Hazardous Materials Control Research Institute, Silver Spring, MD, pp. 158-164. [ER, GPR]

Horton, R., P.J. Wierenga, and D.R. Nielsen. 1983. Evaluation of Methods for Determining the Apparent Thermal Diffusivity of Soil Near the Surface. Soil Sci. Soc. Am. J. 47:25-32.

Houck, R.T. 1984. Measuring Moisture Content Profiles Using Ground-Probing Radar. In: NWWA/EPA Conf. on Surface and Borehole Geophysical Methods in Ground Water Investigations (1st, San Antonio TX), National Water Well Association, Dublin, OH, pp. 637-653.

Howard, K.W.F., M. Hughes, and M.J. Thompson. 1986. Down-Hole Geophysical Methods of Fracture Detection in Low Permeability Bedrock In: Proc. Surface and Borehole Geophysical Methods and Ground Water Instrumentation Conf. and Exp., National Water Well Association, Dublin, OH, pp. 507-525. [caliper, gamma-gamma, temperature]

Howell, B.F. 1959. Introduction to Geophysics. McGraw-Hill, New York, 399 pp. [S, GR, MAG, geothermal]

Hu, L.Z., M. Ramaswamy, B.G. Sexton, and DE. Wyatt, 199. Delineate Subsurface Structures with Ground Penetrating Radar. In: Ground Water Management 13:749-762 (Proc. of Focus Conf. on Eastern Regional Ground Water Issues).

Ibrahim, A. and W.J. Hinze. 1971. Mapping Buried Bedrock Topography with Gravity. Ground Water 10(3):18-23.

Imse, J.P. and E.N. Levine. 1985. Conventional and State-of-the-Art Geophysical Techniques for Fracture Detection. In: Proc. AGWSE Eastern Regional Ground Water Conference (Portland, ME), National Water Well Association, Dublin., OH, pp. 261-276. [ER, GPR, GR, SRR]

Jackson, R.D. and D. Kirkham. Method of Measurement of the Real Thermal Diffusivity of Moist Soil. Soil Sci. Soc. Am. Proc. 22:479-482.

Jackson, R.D. and S.A. Taylor. 1986. Thermal Conductivity and Diffusivity. In: Methods of Soil Analysis, Part 1, 2nd ed, A. Klute (ed), Agronomy Monograph No. 9. American Society of Agronomy, Madison, WI, pp. 945-956.

Jansen, J. 1990. Shallow Geothermal Exploration Techniques for Groundwater Studies. In: Proc. Fourth Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods. Ground Water Management 2:23-37.

Jansen, J. 1992. The Application of Shallow Geothermal Exploration Methods to Detect High Permeability Features in Groundwater Flow Systems. In: SAGEEP '92, Society of Engineering and Mineral Exploration Geophysicists, Golden, CO, pp. 519-530.

Jansen, J. and R. Taylor. 1988. Surface Geophysical Techniques for Fracture Detection. In: proc. Second Conf. on Environmental Problems in Karst Terranes and Their Solutions (Nashville, TN), National Water Well Association, Dublin, OH, pp. 419-441. EEMI, VLF, thermal, fracture trace]

Jansen, J. and R. Taylor. 1989. Geophysical Methods for Groundwater Exploration or Groundwater Contamination Studies in Fracture Controlled Aquifers. In: Proc. Third Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 855-869. [EMI, ER, VLF, thermal]

Jessup; A.M. 1990. Thermal Geophysics. Elsevier, New York, 306 pp.

Johnson, D.G. 1987. Use of Ground-Penetrating Radar for Determining Depth to the Water Table on Cape Cod, Massachusetts. In: Proc. First Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 541-554.

Joiner, T.J., and W.L. Scarbrough. 1969. Hydrology of Limestone Tenanes: Geophysical Investigations. Geological Survey of Alabama Bulletin 94D. [ER, GR, SRR]

Joiner, T.J., J.C. Warman, W.L. Scarbrough, and D.B. Moore. 1967. Geophysical Prospecting for Ground Water in the Piedmont Area, Alabama. Alabama Geological Survey Circular 42, 48 pp. EER, MAG, SRR]

Kersten, M.S. 1949. Thermal Properties of Soils. Univ. of Minn. Eng. Exp. Sta. Bull. 28, 225 pp.

Keys, W.S. and R.F. Brown. 1978. The Use of Temperature Logs to Trace the Movement of Injected Water. Ground Water 16(1):32-48.

Kick, J.F. 1989. Landfill Investigations in New England Using Gravity Methods. In: Proc. (2nd) Symp. on the Application of Geophysics to Engineering and Environmental Problems, Soc. Eng. and Mineral Exploration Geophysicists, Golden, CO, pp. 339-353.

Kimball, B.A. and R.D. Jackson. 1975. Soil Heat Flux Determination: A Null-Alignment Method. Agric. Metreol. 15:1-9.

Kimball, B.A., R.D. Jackson, R.J. Reginato, F.S. Nakayama, and S.B. Idso. 1976. Comparison of Field-Measured and Calculated Soil-Heat Fluxes. Soil Sci. Soc. Am. J. 49: 18-25.

Koemer, R. and A. Lord 1985. Microwave System for Locating Faults in Hazardous Materials Dikes. EPA/600/2-85/014 (NTIS PB85-173821), 141 pp. [GPR and continuous wave radar]

Koemer, R.M., A.E. Lord, Jr., T.A. Okransinski, and J.S. Reif. 1978. Detection of Seepage and Subsurface Flow of Liquids by Microwave Interference Methods. In: Control of Hazardous Materials Spills, Information Transfer, Inc., Rockville, MD, pp. 287-292.

Koerner, R.M., A.E. Lord, Jr., and J.J. Bowders. 1981. Utilization and Assessment of a Pulsed RF System to Monitor Subsurface Liquids. In: Proc. (2nd) Nat. Conf. on Management of

Uncontrolled Hazardous Waste Sites, Hazardous Materials Control Research Institute, Silver Spring, MD, pp. 165-171.

Koerner R.M. A.E. Lord, Jr., S. Tyagi, and J.E. Brugger. 1982. Use of NDT Methods to Detect Buried Containers in Saturated Silty Clay Soil. In: Proc. (3rd) Nat. Conf. on Management of Uncontrolled Hazardous Waste Sites, Hazardous Materials Control Research Institute, Silver Spring, MD, pp. 12-16. [GPR, MAG, MD, VLF]

Kracchman M.B. 1970. Handbook of Electromagnetic Propagation in Conducting Media. U.S. Navy Material Command, NAVMAT P-2302,128 pp.

Kremar, B. and J. Masin. 1970. Prospecting by the Geothermic Method. Geophysical Prospecting 18(2):255-260.

Kufs, C.T D.J. Messinger, and S. Del Re. 1986. Statistical Modeling of Geophysical Data. In: Proc. 7th Nat. Conf. on Management of Uncontrolled Hazardous Waste Sites, Hazardous Materials Control Research Institute, Silver Spring, MD, pp. 110-114. [EMI, MAG, MD]

Kuo, S-S. and J.G. Stangland. 1986. Use of Ground Penetrating Radar Techniques to Aid in Design of On-Site Disposal Systems. In: Proc. Environmental Problems in Karst Terranes and Their Solutions Conference (Bowling Green, KY), National Water Well Association, Dublin, OH, pp. 502-525.

LaFehr, T.R. 1980. Gravity Method. Geophysics 45(11):1634-1639.

Lahee, F.H. 1961. Field Geology. McGraw-Hill New York, 926 pp. [GR, MAG]

Lapham, W.W. 1989. Use of Temperature Profiles Beneath Streams to Determine Rates of Vertical Ground-Water Flow and Vertical Hydraulic Conductivity. U.S. Geological Survey Water Supply Paper 2337, 34 pp.

Laudon K.J. 1984. Geophysical Investigations of the Duck Lake Ground Water Subarea Near Omak, 'Washington. 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. 206-219. [GR, SRR]

Lawrence L.T. 1984. Subsurface Geophysical Investigations and Site Mitigation. In: Proc. 5th Nat. Conf. on Management of Uncontrolled Hazardous Waste Sites, Hazardous Materials Control Research Institute, Silver Spring, MD, pp. 481-485. [EMI, GPR]

Leckenby R.J. 1982. Electromagnetic Ground Radar Methods. In: Premining Investigations for Hardrock Mining, U.S. Bureau of Mines Information Circular 8891, pp. 36-45. [GPR, cross-hole radar]

Lee, W.H. (ed.). 1965. Terrestrial Heat Flow. Geophysical Monograph Series, American Geophysical Union, 276 pp.

Lennox, D H and V. Carlson. 1967. Geophysical Exploration for Buried Valleys in an Area North of Two-Hills Alberta. Geophysics 32(2):331-410. Discussion in Geophysics 35(2):922. [ER, GR, SRR]

Lennox, D.H. and V. Carlson. 1970. Integration of-Geophysical Methods for Ground Water Exploration in the Prairie Provinces, Canada. In: Mining and Groundwater Geophysics/l967, L.W. Morely (ed.), Geological Survey of Canada Economic Geology Report 26, pp. pp. 517-535. [ER, GR, SRR]

Lepper, C.M. and R.S. Dennen. 1990. Selection of Antennas for GPR System. In: Proc. (3rd) Symp. on the Application of Geophysics to Engineering and Environmental Problems, Soc. Eng. and Mineral Exploration Geophysicists, Golden, CO, pp. 229-230.

Lettau, B. 1971. Determination of the Thermal Diffusivity in the Upper Layers of a Natural Ground Cover. Soil Science 112:173-177.

Lord, Jr. A.E. and R.M. Koerner. 1982. Electromagnetic Methods in Subsurface Investigations. In: Proc. Conf. on Updating Subsurface Sampling of Soils and Rocks and their In-Situ Testing (Santa Barbara, CA), S.K. Saxena (ed.), Engineering Foundation, New York, NY, pp. 113-133.

Lord, Jr., A.E. and R.M. Koerner. 1986. Nondestructive Testing (NDT) Location of Containers Buried in Soil.. In: Proc. 12th Research Symp. (Land Disposal, Remedial Action, Incineration and Treatment of Hazardous Waste), EPA/600/9-86/022 (NTIS PB87-119491), pp. 161-169. [EMI, GPR, MAG, MD]

Lord, Jr., A.E. and R.M. Koerner. 1987a. Nondestructive Testing (NDT) Techniques to Detect Contained Subsurface Hazardous Waste. EPA/600/2-87/078 (NTIS PB88-102405). [EMI, GPR, MAG, MD, brief review of 13 other methods]

Lord, Jr., A.E., and R.M. Koerner. 1987B. Nondestructive Testing (NDT) for Location of Containers Buried in Soil. In: Proc. 13th Research Symp. (Land Disposal, Remedial Action, Incineration and Treatment of Hazardous Waste), EPA/600/S9-87/015 (NTIS PB87-233151), pp. 224-234. [EMI, GFR, MAG, MD]

Lucius, J.E., G.R. Olhoeft, and SK. Dukes (eds.). 1990. Third International Conference on Ground Penetrating Radar: Abstracts of the Technical Meeting, Lakewood, CO, May 14-18,. 1990. U.S. Geological Survey Open File Report 90-414, 94 pp.

Mabey, D.R. 1960. Gravity Survey of 'the Western Mojave Desert, California. U.S. Geological Survey Professional Paper 316-D, pp 51-73.

Mabey, D.R. and S.S. Oriel. 1970. Gravity and Magnetic Anomalies from the Soda Springs Regions, Southeastern Idaho. U.S. Geological Survey Professional Paper 646-E 41 pp.

Marshall, J.P. 1971. The Application of Geophysical Instruments and Procedures to Ground-Water Exploration and Research. Montana Water Resource Research Center Termination Report 5, OWRR A-013-MONT(l), Bozeman, MT. [SRR, GR]

Martinek, B.C. 1988. Ground Based Magnetometer Survey of Abandoned Wells at the Rocky Mountain Arsenal-A Case History. In: Proc. (1st) Symp. on the Application of Geophysics to Engineering and Environmental Problems, Soc. Eng. and Mineral Exploration Geophysicists, Golden, CO, pp. 578-598.

Mattick, R.E., F.H. Olmsted, and A.A.R. Zohdy. 1973. Geophysical Studies in the Yuma Area, Arizona and California. U.S. Geological Survey Professional Paper 726-D, 36 pp. [SRR, ER, GR, SRL, AEM]

McGinnis, L.D., J.P. Kempton, and P.C. Heigold 1963. Relationship of Gravity Anomalies to a Drift-Filled Bedrock Valley System in Northern Illinois. Illinois State Geological Survey Circular 354, 23 pp.

Michalski, A. 1989. Application of Temperature and Electrical-Conductivity Logging in Ground Water Modeling. Ground Water Monitoring Review 9(3): 112-118.

Misener, AD. and A. E. Beck. 1960. The Measurement of Heat Flow over Land. In: Methods and Techniques in Geophysics, Vol. 1, SE. Runcom (ed), Interscience Publishers, New York, pp. 10-61.

Moffat, D.L. and RJ. Puskar. 1976. A Subsurface Electromagnetic Pulse Radar. Geophysics 41(3):506-518.

Morey, R.M. 1974. Continuous Subsurface Profiling by Impulse Radar. In: Proc. Engineering Foundation Conf. on Subsurface Exploration for Underground Excavation and Heavy Construction (Henniker, NH), American Society Civil Engineers, pp. 213-232. [GPR]

Morey, R.M. and W.S. Warrington, Jr. 1972. Feasibility of Electromagnetic Subsurface Profiling. EPA R2-72-082 (NTIS PB213 892).

Morin, R.H. and W. Barrash. 1986. Defining Patterns of Ground Water and Heat Flow in Fractured Brule Formation, Western Nebraska, Using Borehole Geophysical Methods. In: Proc. Surface and Borehole Geophysical Methods and Ground Water Instrumentation Conf. and Exp., National Water Well Association, Dublin, OH pp. 545-569.

Morrison, R.D. 1983. Ground Water Monitoring Technology: Procedures, Equipment and Applications, Timco Mfg., Prairie Du Sac, WI, 111 pp. [shallow thermal]

Nettleton, L.L. 1971. Gravity and Magnetics for Geologists and Seismologists. Monograph No. 1. Society of Exploration Geophysicists, Tulsa, OK, 121 pp.

Nettleton, L.L. 1976. Gravity and Magnetics in Oil Prospecting. McGraw-Hill, New York, 464 pp.

Newman, J. and J. McDuff. 1988. Electric Wireline Methods for In Situ Capture of Wellbore Samples and Determining Their Flow Rates and Direction. In: Proc, 2nd Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 97-122. [caliper, gamma, neutron, temperature, fluid conductivity, flowmeter]

Nightingale, H.I. 1975. Ground-Water Recharge Rates from Thermometry. Ground Water 13(4):340-344.

Norris, S.E. and AM. Spieker. 1962a. Seasonal Temperature Changes in Wells as Indicator of Semiconfining Beds in Valley-Train Aquifers. U.S. Geological Survey professional paper 450-B, pp. 101-102

Norris, S.E. and AM. Spieker. 1962b. Temperature-Depth Relations as Indicators of Semiconfining Beds in Valley-Train Aquifers. U.S. Geological Survey Professional Paper 450-B, pp. 103-105.

Nowak, T.J. 1953. The Estimation of Water! Injection Profiles from Temperature Surveys. Trans. Am. Inst. Mining Metall. Eng., Petroleum Division 198:203-212.

O'Brien, P.J. 1970. Aquifer Transmissivity Distribution as Reflected by Overlying Soil Temperature Patterns. Pennsylvania State University Ph.D thesis, 178 pp.

O'Brien, K.M. and W.J. Stone, 1984. Role of Geological and Geophysical Data in Modeling a Southwestern Alluvial Basin. Ground Water 22(6):717-727. [GR, SRR]

O'Brien, KM. and W.J. Stone. 1985. Role of Geological and Geophysical Data in Modeling an Alluvial Basin, Southwest New Mexico. In: Conference on Surface and Borehole Geophysical Methods and Ground Water Investigations (2nd Fort Worth, TX), National Water Well Association, Dublin, OH, pp. 198-214. [GR, SRR]

Olhoeft, G.R. 1984. Applications and Limitations of Ground Penetrating Radar. In: Expanded Abstracts, 54th Ann. Int. Meeting and Expo. of the Soc. of Explor. Geophys., Atlanta, pp. 147-148.

Olhoeft, G.R. 1986. Direct Detection of Hydrocarbons and Organic Chemicals with Ground Penetrating Radar and Complex Resistivity. In: Proc. (3rd) NWWA/API Conf. on Petroleum Hydrocarbons and Organic Chemicals in Ground Water, National Water Well Association, Dublin, OH, pp. 284-305.

Olhoeft, G.R. 1988. Selected Bibliography on Ground Penetrating Radar. In: Proc. (1st) Symp. Application of Geophysics to Eng. and Environmental Problems, Soc. Eng. and Mineral Exploration Geophysicists, Golden, CO, pp. 462-520.

Olhoeft, G.R. 1990. Tutorial: High Frequency Electrical Properties. In: Proceedings of the 3rd International Conference on Ground Penetrating Radar, U.S. Geological Survey Open-File Report 90-414.

OlhoeR, G.R. 1992. Geophysical Detection of Hydrocarbon and Organic Chemical Contamination. In: SAGEEP '92, Society of Engineering and Mineral Exploration Geophysicists, Golden, CO, pp. 587-595. [complex resistivity, GPR]

Olhoeft, G.R., K.A. Sander, and J.E. Lucius. 1992. Surface and Borehole Radar Monitoring of a DNAPL Spill in DC versus Frequency, Look Angle, and Time. In: SAGEEP '92, Society of Engineering and Mineral Exploration Geophysicists, Golden, CO, pp. 455-469.

Olson, C.G., and J.A. Doolittle. 1985. Geophysical Techniques for Reconnaissance Investigations of Soils and Surficial Deposits in Mountainous Terrain. Soil Sci. Soc. Am. J. 49: 1490-1498. EGPR]

Omnes, G. 1977. High Accuracy Gravity Applied to the Detection of Karstic Cavities. In: Karst Hydrogeology: Proceedings of the Twelfth Meeting of the International Association of Hydrogeologists, J.S. Tolson, and FL. Doyle (eds.), University of Alabama-Huntsville Press, Huntsville, AL, pp. 273-284.

Osborne, J. 1991. Automated Subsurface Mapping. In: Proc. Second International Symposium, Field Screening Methods for Hazardous Waste and Toxic Chemicals. EPA/600/9-91/028 (NTIS PB92-125764)), pp. 205-216.

Palermo, R.S. and M.E. Brickell. 1984. Proton Precession Magnetometry: A Geophysical Approach. In: Proc. of the NWWA Tech. Division Eastern Regional Ground Water Conference (Newton, MA), National Water Well Association, Dublin, OH, pp. 234-253.

Parr, A.D., F.J. Molz, J.G. Melville. 1983. Field Determination of Aquifer Thermal Energy Storage Parameters. Ground Water 21:22-35.

Parsons, M.L. 1970. Groundwater Thermal Regime in a Glaciated Complex. Water Resources Research 6:1701-1720.

Peacock, D.R. 1965. Temperature Logging. In: Trans. 6th Annual Logging Symposium. Society of Professional Well Log Analysts, Tulsa, OK, pp. Fl-F18.

Pease, Jr., R.W. and S.C. James. 1981. Integration of Remote Sensing Techniques with Direct Environmental Sampling for Investigating Abandoned Hazardous Waste Sites. In: Proc. (2nd) Nat, Conf. on Management of Uncontrolled Hazardous Waste Sites, Hazardous Materials Control Research Institute, Silver Spring, MD, pp. 171-176. [ER, GPR, MD, SRR]

Pilon, J.A. (ed.). 1992. Ground Penetrating Radar. Geological Survey of Canada Paper 90-4, 241 pp

Pitchford, A.M, A.T. Mazzella, and K.R. Scarbrough. 1988. Soil-Gas and Geophysical Techniques for Detection of Subsurface Organic Contamination. EPA/600/4-88/019 (NTIS PB88-208194). [GPR, EMI, ER, complex resistivity, SRR, MD, MAG]

Pittman, W.E., Jr., R.H. Church, W.E. Webb, and J.T. McLendon. 1984. Ground-Penetrating Radar: A Review of Its Application in the Mining Industry. U.S. Bureau of Mines Information Circular 8964, 23 pp.

Poeter, E.P. 1989. Delineating Geometry of Unconfined Aquifer Heterogeneities with Microgravity Surveys During Aquifer Testing. In: Proc. Conf. on New Field Techniques for Quantifying the Physical and Chemical Properties of Heterogeneous Aquifers, National Water Well Association, Dublin, OH, pp. 213-227.

Puckett, W.E., M.E. Collins, and G. Schellentrager. 1986. Evaluating Soil-Landscape Patterns on Karst Using Radar Data. Agronomy Abstracts 1986:232.

Ram Babu, H.V., N. Kameswara Rao, and V. Vijay Kumar. 1991. Bedrock Topography from Magnetic Anomalies-An Aid for Groundwater Exploration in Hard-Rock Terrain. Geophysics 56(7): 1051-1054,

Randall, AD. 1986. Aquifer Modeling of the Susquehanna River Valley in Southwest Broome County, New York. U.S. Geological Survey Water-Resource Investigation Report 85-4099, 38 pp. [shallow geothermal]

Redman, J.D., B.H. Kueper, and A.P. Annan. 1991. Dielectric Stratigraphy of a DNAPL Spill and Implications for Detection with Ground Penetrating Radar. Ground Water Management 5: 1017-1029 (5th NOAC).

Redwine, J. et al. 1985. Groundwater Manual for the Electric Utility Industry, Volume 3: Groundwater Investigations and Mitigation Techniques. EPRI CS-3901. Electric Power Research Institute, Palo Alto, CA [SRR, SW ER, SP, EMI, GPR, GR]

Reford, M.S. 1980. Magnetic Method. Geophysics 45(11): 1640-1658.

Regan, J.M., M.S. Robinette, and T.R. Beaulieu. 1987. The Use of Remote Sensing, Geophysical, and Soil Gas Techniques to Locate Monitoring Wells at Hazardous Waste Sites in New Hampshire

In: Proc. of the Fourth Annual Eastern Regional Ground Water Conference (Burlington, VT), National Water Well Association, Dublin, OH, pp. 577-591. [EMI, ER, GR, MAG, SRR, fracture trace]

Rehm, B.W., T.R. Stolzenburg, and D.G. Nichols. 1985. Field Measurement Methods for Hydrogeologic Investigations: A Critical Review of the Literature. EPRI EA-4301. Electric Power Research Institute, Palo Alto, CA [Major methods: ER, EMI, SRR, BH; Other: IR, SP, [P/CR, SRR, GPR, MAG, GR, thermal]

Richard, B.H. and P.J. Wolfe. 1990. Gravity as a Tool to Delineate Buried Valleys. In: Proc. (3rd) Symp. on the Application of Geophysics to Engineering and Environmental Problems, Soc. Eng. and Mineral Exploration Geophysicists, Golden, CO, pp. 59-106.

Roberts, R.G., W.J. Hinze, and D.I. Leap. 1989. A Multi-Technique Geophysical Approach to Landfill Investigations. In: Proc. 3rd Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 797-811. FMI, ER, GPR, GR, MAG, SRR]

Roberts, R. J.J. Daniels, and L. Peters, Jr. 1992. Improved GPR Interpretation from Analysis of Buried Target Polarization Properties. In: SAGEEP '92, Society of Engineering and Mineral Exploration Geophysicists, Golden, CO, pp. 353-374.

Rodriguez, E.B. 1987. Application of Gravity and Seismic Methods in Hydrogeological Mapping at a Landfill Site in Ontario. In: Proc. 1st Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 487-504.

Rorabaugh, M.I. 1956. Ground Water in Northeastern Louisville, Kentucky. U.S. Geological Survey Water-Supply Paper 1360-B:l0l-169. [ground-water temperature as measure of surface water-ground-water relationships]

Rubin, L.A. and J.C. Fowler. 1978. Ground-Probing Radar for Delineation of Rock Features. Eng. Geol. (Amsterdam) 12(2):163-170.

Rudy, R.J. and J.B. Warner. 1986. Detection of Abandoned Underground Storage Tanks in Marion County, Florida. In: Proc. Surface and Borehole Geophysical Methods and Ground Water-Instrumentation Conf. and Exp., National Water Well Association, Dublin, OH, pp. 674-688. [EMI, GPR, MAG]

Russell, G.M. 1990. Application of Geophysical Techniques for Assessing Ground-Water Contamination near a Landfill at Stuart Florida. In: Ground Water Management 3:211-225 (7th NWWA Eastern GW Conference). [ER, EMI, VLF, GPR]

Saint-Amant, M. and D.W. Strangway. 1970. Dielectric Properties of Dry Geologic Materials. Geophysics 35(4):624-645.

Sammel, E.A. 1968. Convective Flow and Its Effect on Temperature Logging in Small-Diameter Wells. Geophysics 33(6):1004-1012.

Sampayo, F.E. and H.R. Wilke. 1963. Temperature and Phosphate as Ground-Water Tracers. Ground Water 1(1):56-61.

Saunders, W.R., S. Smith, P. Gilmore, and S. Cox. 1991. The Innovative Application of Surface Geophysical Techniques for Remedial Investigations. In: Ground Water Management 5:947-961 (5th NOAC). [EMI, TDEM, GPR, soil gas]

Schaetele, W.F., C.E. Brett, D.W. Grubbs, and M.S. Seppamen. 1980. Thermal Energy Storage in Aquifers. Pergamon Press, NY, 177 pp.

Schellentrager, G.W., J.A. Doolittle, T.E. Calhoun, and CA. Wettstein. 1988. Using Ground-Penetrating Radar to Update Soil Survey Information. Soil Sci. Soc. Am. J. 52:746-751.

Schlinger, C.M. 1990. Magnetometer and Gradiometer Surveys for Detection of Underground Storage Tanks. Bull. Ass. Eng. Geol. 28(1):37-50.

Schneider, R. 1962. An Application of Thermometry to Study of Groundwater. U.S. Geological Survey Water-Supply Paper 1544-B.

Schutts, L.D. and D.G. Nichols. 1991. Surface Geophysical Definition of Ground Water Contamination and Buried Waste: Case Studies of Electrical Conductivity and Magnetic Applications. In: Ground Water Management 5:889-903 (5th NOAC).

Sellman, P.V., S.A. Amone, and A.J. Delaney. 1983. Radar Profiling of Buried Reflections and the Ground Water Table. CRREL Report 83-11. U.S. Army Cold Reg. Res. and Eng. Lab., Hanover, NH.

Sharma, P.V. 1986. Geophysical Methods in Geology, 2nd ed. Elsevier, New York, 428 pp. [First edition 19761. [S, GR, MAG, ER, GT]

Sheriff, R.E. 1989. Geophysical Methods. Prentice Hall, Englewood Cliffs, NJ, 591 + pp. [GR, MAG, ER, EM, SRR, geothermal]

Shih, S.F. and J.A. Doolittle. 1984. Using Radar to Investigate Organic Soil Thickness in Florida Everglades. Soil Sci. Soc. Am. J. 48:651-656.

Shih, SF., J.A. Doolittle, D.L. Myhre, and G.W. Schellentrager. 1986. Using Radar for Groundwater Investigations. J. Irr. and Drain. Eng. 112: 110-118. [GPR]

Silliman, S. and R. Robinson. 1989. Identifying Fracture Interconnections Between Boreholes Using Natural Temperature Profiling: Conceptual Basis. Ground Water 27(3):393-402.

Silliman, S., J. Nicholas, and A. Shapiro. 1987. Estimating Fracture Connectivity Using Measurement of Borehole Temperature During Pumping. In: Proc. NWWA Focus Conf. on Midwestern Ground Water Issues (Indianapolis,. IN), National Water Well Association, Dublin, OH, pp. 231-248.

Skolnik, M.I. (ed.). 1990. Radar Handbook, 2nd ed. McGraw-Hill, New York.

Smith, E.M. 1974. Exploration for a Buried Valley by Resistivity and Thermal Probe Surveys. Ground Water 12(2):78-83.

Smith, D.V. and G. Markt. 1988. A Ground Penetrating Radar and Magnetometry Survey at Nuclear Lake, New York-A Case History. In: Proc. (1st) Symp. on the Application of Geophysics to Engineering and Environmental Problems, Soc. Eng. and Mineral Exploration Geophysicists, Golden, CO, pp. 621-641.

Smith, G.D., F. Newhall, and L.H. Robinson. 1960. Soil-Temperature Regims--Their Characterization and Predictability. SCS-TP-144. USDA Soil Conservation Service, 14 pp.

Soil Conservation Service. 1988. Second International Conference Ground Penetrating Radar, March 6-10, 1988, Gainesville, FL. U.S. Department of Agriculture, 179 pp.

Sophocleous, M. 1979. A Thermal Conductivity Probe Designed for Easy Installation and Recovery from Shallow Depth. Soil Sci. Soc. Am. J, 43:1056-1058.

Sorey, M.L. 1971. Measurement of Vertical Ground-Water Velocity from Temperature Profiles in Wells. Water Resources Research 7(4):963-970.

Spangler, D.P. and F.J. Libby. 1968. Application of Gravity Survey Methods to Watershed Hydrology. Ground Water 6(6):21-26.

Stallman, R.W. 1963. Computation of Ground-Water Velocity from Temperature Data. In: Methods of Collecting and Interpreting Ground Water Data, R. Bentall (compiler), U.S. Geological Survey Water-Supply Paper 1544-H, pp H36-H46.

Stallman, R.W. 1965. Steady One-Dimensional Fluid Flow in a Semi-Finite Porous Medium with Sinusoidal Surface Temperature. J. Geophys. Res. 70(12):2821-2827.

Stanfill, III, D.F. and KS. McMillan. 1985. Radar-Mapping of Gasoline and Other Hydrocarbons in the Ground. In: Proc. 6th Nat. Conf. on Management of Uncontrolled Hazardous Waste Sites, Hazardous Materials Control Research Institute, Silver Spring, MD, pp. 269-274.

Stearns, B.G. and L.M.J. Dialmann, III. 1986. Geophysical Techniques and Monitoring Network Design at the Sike Disposal Pit Hazardous Waste Site, Crosby, TX. In: Proc. Surface and Borehole Geophysical Methods and Ground Water Instrumentation Conf. and Exp., National Water Well Association, Dublin, OH, pp. 657-673. [ER, GPR]

Stevens, Jr., H.H., J.F. Ficke, and G.F. Smoot. 1975. Water Temperature--Influential Factors, Field Measurement, and Data Presentation. U.S. Geological Survey Techniques of Water-Resources Investigations TWRI 1-Dl.

Stewart, M.T. 1980. Gravity Survey of a Deep Valley. Ground Water 18(1):24-30.

Stewart, M. and J. Wood 1986. Geologic and Geophysical Character of Fracture Zones in a Carbonate Aquifer. In: Proc. Focus Conf. on Southeastern Ground Water Issues (Tampa, FL), National Water Well Association, Dublin, OH, pp. 289-294. [ER, GR]

Stierman, D.J., L.C. Ruedisili, and J.M. Stangl. 1986. The Application of Surface Geophysics to Mapping Hydrogeologic Conditions of a Glaciated Area in Northwest Ohio. In: Proc. Surface and Borehole Geophysical Methods and Ground Water Instrumentation Conf. and Exp., National Water Well Association, Dublin, OH, pp. 591-600. [ER, SRR, MAG]

Strange, W.E. 1970. The Use of Gravimeter Measurements in Mining and Groundwater Exploration. In: Mining and Groundwater Geophysicsi/l967, L.W. Morely (ed.), Geological Survey of Canada Economic Geology Report 26, pp. 46-50.

Struttmann, T. and T. Anderson. 1989. Comparison of Shallow Electromagnetic and the Proton Precession Magnetometer Surface Geophysical Techniques to Effectively Delineate Buried Wastes.

In: Superfund ‘89, Proceedings of the 10th Annual Conference, Hazardous Material Control Research Institute, Silver Spring, MD, pp. 27-34.

Summers, W.K. 1971. The Annotated Indexed Bibliography of Geothermal Phenomena. New Mexico Institute of Mining and Technology, Socorro, NW. [More than 14,000 references.]

Supkow, D.J. 1971. Subsurface Heat Flow as a Means for Determining Aquifer Characteristics in the Tucson Basin, Pima County, Arizona. University of Arizona Ph.D thesis, 181 pp.

Sutcliffe, Jr., H. and B.F. Joyner. 1966. Packer Testing in Water Well near Sarasota, Florida. Ground Water 4(2):23-27. [caliper, fluid conductivity, temperature]

Suzuki, S. 1960. Percolation Measurements Based on Heat Flow Through Soil with Special Reference to Paddy Fields. J. Geophysical Research 65(9):2883-2885.

Tareev, B. 1975. Physics of Dielectric Materials. Mir, Moscow.

Taylor, K.R. and M.E. Baker. 1988. Use of Ground-Penetrating Radar in Defining Glacial Outwash Aquifers. In: Proc. of the Focus Conf. on Eastern Regional Ground Water Issues (Stanford, CT), National Water Well Association, Dublin, OH, pp. 77-98.

Taylor, S.A. and R.D. Jackson. 1986a. Temperature. In: Methods of Soil Analysis, Part 1, 2nd ed., A. Klute (ed.), Agronomy Monograph No. 9. American Society of Agronomy, Madison, WI, pp. 927-940.

Taylor, S.A. and R.D. Jackson. 1986b. Heat Capacity and Specific Heat. In: Methods of Soil Analysis, Part 1, 2nd ed., A. Klute (ed), Agronomy Monograph No. 9. American Society of Agronomy, Madison, WI, pp. 941-944.

Tibbets, B.L. and J.H. Scott. 1972. Geophysical Measurements of Gold-Bearing Gravels, Nevada County, California. U.S. Bureau of Mines Report of Investigation 7584. [SRR, GR]

Trabant, P.K. 1984. Applied High-Resolution Geophysical Method&Offshore Geoengineering Hazards. International Human Resource Development Corp., Boston, MA, 265 pp. [CSP, GPR]

Trainer, F.W. 1968. Temperature Profiles of Water Wells as Indicators of Bedrock Fractures. U.S. Geological Survey Professional Paper 600-B, pp. 210-214.

Truman, C.C., H.F. Perkins, L.E. Asmussen, and H.D. Allison. 1988. Using Ground-Penetrating Radar to Investigate Variability in Selected Soil Properties. J. Soil and Water Conservation 43:341-345.

Truman, C.C., L.E. Asmussen, and H.D. Allison. 1991. Ground-Penetrating Radar: A Tool for Mapping Reservoirs and Lakes. J. Soil and Water Conservation 46(5):370-373.

Ulriksen, P.F. 1982. Application of Impulse Radar to Civil Engineering. Geophysical Survey Systems Inc., Hudson, NH.

Underwood, J.E. and J.W. Eales. 1984. Detecting a Buried Crystalline Waste Mass with Ground-Penetrating Radar. 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. 654-665.

U.S. Environmental Protection Agency (EPA). 1987. A Compendium of Super-fund Field Operations Methods, Part 2. EPA/540/P-87/001 (OSWER Directive 9345.0-14) (NTIS PB88-181557). [EMI, ER, SRR, SRL, MAG, GPR, BH]

U.S. Environmental Protection Agency (EPA). 1993. Subsurface Field Characterization and Monitoring Techniques: A Desk Reference Guide, Volume I: Solids and Ground Water. EPAl625/R-93/003a. Available from EPA Center for Environmental Research Information, Cincinnati, OH. [Section 1.5 covers GPR, MAG, GR and Section 1.6 covers thermal methods.]

U.S. Geological Survey (USGS). 1980. Geophysical Measurements. In: National Handbook of Recommended Methods for Water Data Acquisition, Chapter 2 (Ground Water), Office of Water Data Coordination, Reston, VA, pp. 2-24 to 2-76. [TC, MT, AMT, EMI, ER, IP, SRR, SRL, GR, BH]

van Beek, L.K.H. 1965. Dielectric Behavior of Heterogeneous Systems. In: Progress in Dielectrics, Vol. 7, J.B. Birks (eds.), CRC Press, Boca Raton, FL, pp. 69-114.

Van Overmeeren, R.A. 1980. Tracing by Gravity of a Narrow Buried Graben Predicted by Seismic Refraction for Groundwater Investigation in North Chile. Geophysical Prospecting 28: 1392-407.

Van Overmeeren, R.A. 1981, Combination of Electrical Resistivity, Seismic Refraction, and Gravity Measurements for Groundwater Exploration in Sudan. Geophysics 46: 1304- 1313.

Von Hippel, A.R. 1954a. Dielectrics and Waves. MIT Press, Cambridge, MA, 284 pp.

Von Hippel, A.R. (ed.). 1954b. Dielectrics: Materials and Applications. MIT Press, Cambridge MA, 438 pp

Wallace, D.E. and D.P. Spangler. 1970. Estimating Storage Capacity in Deep Alluvium by Gravity-Seismic Methods. Bull. Int. Assn. Sci. Hydrology 15(2):91-104.

Walsh, D.C. 1989. Surface Geophysical Exploration for Buried Drums in Urban Environments: Applications in New York City, In: Proc. Third Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 935-949. [EMI, MAG]

Watts, R.D. and A.W. England. 1976. Radio-Echo Soundings of Temperate Glaciers: Ice Properties and Sounder Design Criteria. J. Glaciology 17:39-48 (GPR]

Watson, J., D. Stedje, M. Barcelo, and M. Stewart. 1990. Hydrogeologic Investigation of Cypress Dome Wetlands in Well Field Areas North of Tampa Florida. In: Ground Water Management 3: 163- 176 (7th NWWA Eastern GW Conference). [TDEM, VLF, ER, GPR]

Weaver, H.G. and G.S. Campbell. 1985. Use of Peltier Coolers as Soil Heat Flux Transducers. Soil Sci. Soc. Am. J. 49:1065-1066.

**West, R.E. and J.S. Sumner. 1972. Ground-Water Volumes from Anomalous Mass Determinations for Alluvial Basins. Ground Water 10(3):24-32. [GR]**

Westphalen, 0. 1991. The Application of Borehole Geophysics to Identify Fracture Zones and Define Geology at Two New England Sites. In: Ground Water Management 7:535-546. (8th NWWA

Eastern GW Conference). [caliper, SP, SP resistance, temperature, gamma, gamma-gamma, neutron, acoustic televiewer]

White, R.M. and S.S. Brandwein. 1982. Application of Geophysics to Hazardous Waste Investigations. In: Proc. (3rd) Nat. Conf. on Management of Uncontrolled Hazardous Waste Sites, Hazardous Materials Control Research Institute, Silver Spring, MD, pp. 91-93. [EMI, ER, GPR, MAG]

Wierenga, P.J., D.R. Nielsen, and R.M. Hagan. 1969. Thermal Properties of Soils Based upon Field and Laboratory Measurements. Soil Sci. Soc. Am. Proc. 33:354-360.

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]

Williams, J.H., L.D. Carswell,, O.B. Lloyd, and W.C. Roth. 1984. Borehole Temperature and Flow Logging in Selected Fractured Rock Aquifers in East Central Pennsylvania. 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. 842-852.

Wilson, G.V., T.J. Joiner, and J.L. Warner. 1970. Evaluation, by Test Drilling, of Geophysical Methods Used for Ground-Water Development in the Piedmont Area, Alabama. Alabama Geological Survey Circular 65, 15 pp. [ER, MAG, SRR]

Wilson, M.P., D.N. Peterson, and T.F. Ostrye. 1983. Gravity Exploration of a Buried Valley in the Appalachian Plateau. Ground Water 21(5):589-596.

Wire, J.C., J.K. Hofer, and D J. Moser. 1984 Ground Magnetometer and Gamma-Ray Spectrometer Surveys for Ground Water Investigations in Bedrock. 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. 288-313.

Worthington, P.F. 1975. Procedures for the Optimum Use of Geophysical Methods in Ground-Water Development Programs. Ass. Eng. Geol. Bull. 12(1):23-38. [ER, IP, SRR, GR]

Wrege, B.M. 1986. Surface- and Borehole-Geophysical Surveys Used to Define Hydrogeologic Units in South-Central Arizona; In: Proc. Conf. on Southwestern Ground Water Issues (Tempe, AZ), National Water Well Association, Dublin, OH, pp. 485-499. [GR, SRR, SRL, seismic shear]

Wright, D.L., G.R. Olhoeft, and R.D. Watts. 1984. Ground-Penetrating Radar Studies on Cape Cod. 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. 666-680.

Wynn, J.C. 1979. An Experimental Ground-Magnetic and VLF-EM Traverse over a Buried Paleochannel Near Salisbury, Maryland. U.S. Geological Survey Open-File Report 79-105, 8 pp.

Yazicigil, H. and L.V.A. Sendlein. 1982. Surface Geophysical Techniques in Ground Water Monitoring, Part II. Ground Water Monitoring Review 2(1):56-62. [ER, thermal]

Yearsley, E.N., J.J. LoCoco, and R.E. Crowder. 1990. Borehole Geophysics Applied to Fracture Hydrology. In: Ground Water Management 3:255-267 (7th NWWA Eastern GW Conference). [acoustic waveform, temperature, resistivity, brine tracing]

Zobeck, T.M., J.G. **Lyon,** D.R. Mapes, and A. Ritchie, Jr. 1985. Calibrating Ground-Penetrating Radar for Soil Applications. Soil Sci. Soc. Am. J. 49: 1587-1590.

Zohdy, A.A., G.P. Eaton, and D.R. Mabey. 1974. Application of Surface Geophysics to Ground-Water Investigations. U.S. Geological Survey Techniques of Water-Resource Investigations TWRI 2-Dl, 116 pp. [ER, GR, MAG, SRR]

# 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.

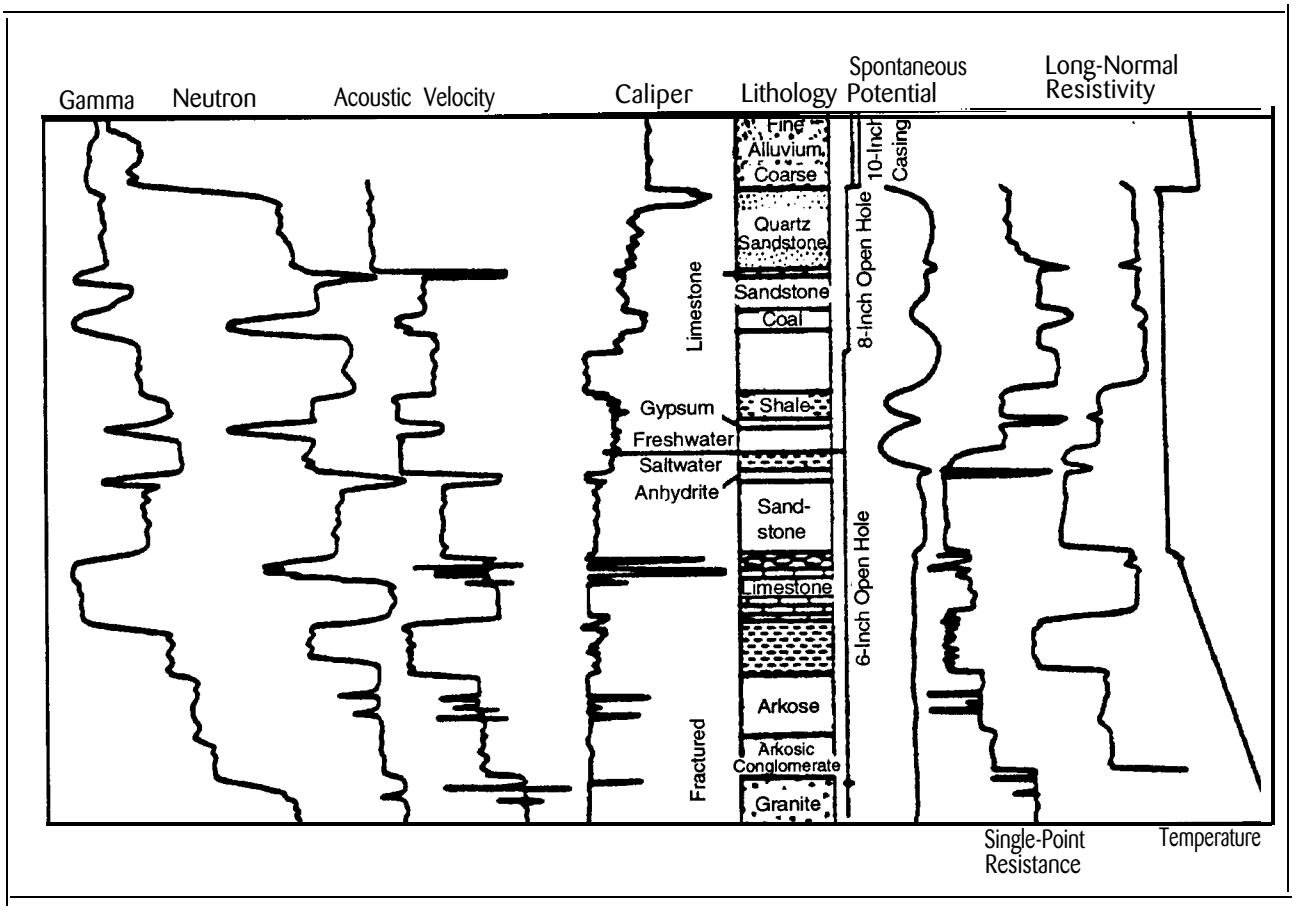


Figure 7-1 Typical response of a suite of hypothetical geophysical well logs to a sequence of sedimentary rocks (from Keys, 1990).

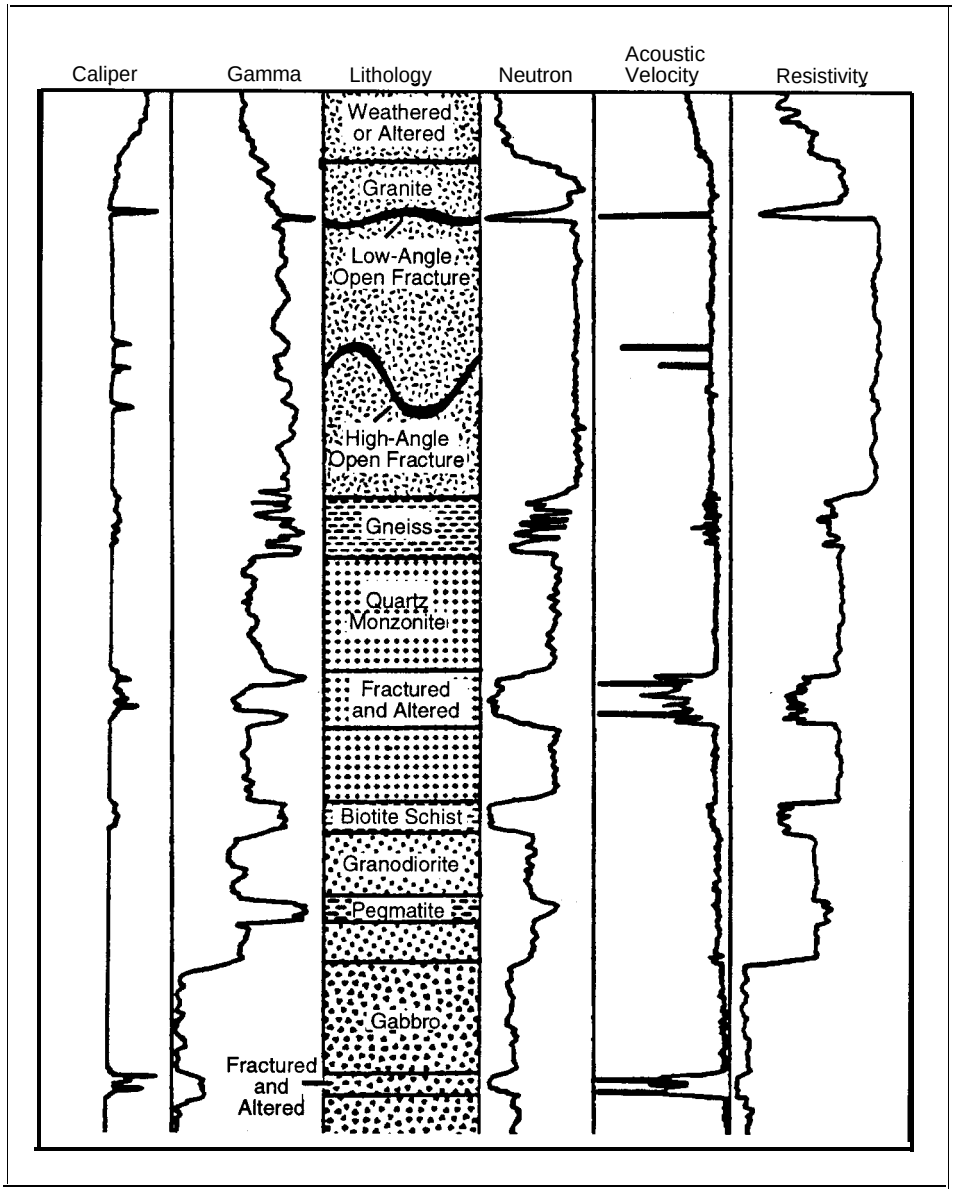


Figure 7-2 Typical response of a suite of hypothetical geophysical well logs to various altered and fractured crystalline rocks (from Keys, 1990).

**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 |
|---|---|---|
| Electric Logs | | |
| 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) |
| Electromagnetic Logs | | |
| 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 |
|---|---|
| Acoustic Logs | |
| 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) |
| Borehole Seismic Methods | |
| Seismic Profiling (VSP) | Texts: Balch and Lee (1984), Gal'perin (1979), Hardage (1985), Toksoz and Stewart (1984); Papers: 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 | Cross-Hole Shear: Bates et al. (1991), CH2M Hill (1991), Hoar and Stokoe (1977), Stokoe (1980), Stokoe and Nazarian (1985), Woods (1978), Woods and Stokoe (1985); Other Cross-Hole: 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 (19~~69) 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.***


Abragam, A. 1961. The Principles of Nuclear Magnetism. Clarendon Press, Oxford England 599 pp.

Adams, J.A.S. and P. Gasparini. 1970. Methods in Geochemistry and Geophysics: Gamma Ray Spectrometry of Rocks. Elsevier, NY, 280 pp.

Adams, W.M., S.W. Wheatcraft, and J.W. Hess. 1983. Downhole Sensing Equipment for Hazardous Waste Site Investigations. In: Proc. (4th) Nat. Conf. on Management of Uncontrolled Hazardous Waste Sites, Hazardous Materials Control Research Institute, Silver Spring, MD, pp. 108-113.

Adams, M.L., M.S. Turner, and M.T. Morrow. 1988. The Use of Surface and Downhole Geophysical Techniques to Characterize Flow in a Fracture Bedrock Aquifer System. In: Proc. 2nd Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 825-847. [caliper, gamma, VSP, borehole camera]

Alderman, J.W. 1986. FM Radiotelemetry Coupled with Sonic Transducers for Remote Monitoring of Water Levels in Deep Aquifers. Ground Water Monitoring Review 6(2):114-116.

Alger, R.P. 1966. Interpretation of Electric Logs in Fresh Water Wells in Unconsolidated Formations. In: Trans. 7th Annual Logging Symposium, Society of Professional Well Log Analysts, Houston, TX.

Anderson, D.L. and A.M. Dziewonski. 1984. Seismic Tomography. Scientific American 251(4):60.

Asch, T. and H.F. Morrison. 1989. Mapping and Monitoring Electrical Resistivity with Surface and Subsurface Electrode Arrays. Geophysics 54:235-244.

Asch, T., H.F. Morrison, and S. Dickey. 1986. Interpretation of Borehole-to-Surface DC Resistivity Measurements at a Contaminant Site A Case Study. In: Proc. Surface and Borehole Geophysical Methods and Ground Water Instrumentation Conf. and Exp., National Water Well Association, Dublin, OH, pp. 127-149.

Asquith, G. and C. Gibson. 1982. Basic Well Log Analysis for Geologists. American Association of Petroleum Geologists, Tulsa, OK 216 pp.

Atkins, Jr., E.R. 1961. Techniques of Electric Log Interpretation. J. Petrol. Tech. 13(2):188-123.

Bade, J.F. 1963. Cement Bond Logging Techniques-How They Compare and Some Variables Affecting Interpretation. J. Petrol. Tech. 15(1):17-22.

Baffa, J.J. 1948. The Utilization of Electrical and Radioactivity Methods of Well Logging for Ground-Water Supply Development. J. New England Water Works Assn. 62:207-219.

Balch, A.H. and M.W. Lee (eds.). 1984. Vertical Seismic Profiling Techniques, Applications, and Case Histories. International Human Resource Development Corporation, Boston, MA, 488 pp.

Barnes, B.A. and P. Livingston. 1947. Value of the Electrical Log for Estimating Ground-Water Supplies and the Quality of Ground Water. Trans. Am. Geophysical Union 28:903-911.

Bateman, R.M. 1985. Log Quality Control. International Human Resources Development **Corp., Boston,** 398 pp.

Bates, R, D. Phillips, and B. Hoekstra. 1991. Geophysical Surveys for Fracture Mapping and Solution Cavity Delineation. In: Ground Water Management 7:659-673 (8th NWWA Eastern GW Conference). [shear-wave refraction, cross-borehole tomography]

Beesley, K 1986. Downhole Geophysics. In: Ground Water: Occurrence, Development and Protection, T.W. Brandon (ed.), Institute of Water Engineers and Scientists Water Practice Manual 5, London, Chapter 9.

Belcher, D.J., T.R. Cuykendall, and H.S. Sack. 1952. Nuclear Methods for Measuring Soil Density and Moisture in Thin Soil Layers. Civil Aeronautics Administration Technical Development Report No. 161, Washington, DC, 8 pp.

Bennett, G.D. and E.P. Patten, Jr. 1960. Borehole Geophysical Methods for Analyzing Specific Capacity of Multiaquifer Wells. U.S. Geological Survey Water Supply Paper 1536-A.

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]

Bevc, D. and H.F. Morrison. 1991. Borehole-to-Surface Electrical Resistivity Monitoring of a Salt Water Injection Experiment. Geophysics 56(6):769-777.

Beydoun, W. B., C.H. Cheng, and M.N. Toksoz. 1985. Detection of Open Fractures with Vertical Seismic Profiling. J. Geophys. Res. 90:4557-4566.

Biella, G. A. Lozei, and I. Tabaco. 1983. Experimental Study of Some Hydrogeophysical Properties of Unconsolidated Porous Media. Ground Water 21(6):741-751.

Bigelow, E.L. 1985. Making More Intelligent Use of Log Derived Dip Information, Parts I-V. Log Analyst 26(1):41-51, 26(2):25-41; 26(3):18-31; 26(4):21-43; 26(5):25-64.

Birdwell Division. 1973. Geophysical Well Log Interpretation. BirdWell Division, Seismograph Service Corporation, Tulsa, OK. [Birdwell Division is no longer in operation.] [SP, resistivity, gamma, gamma-gamma, neutron, fluid conductivity, temperature, 3-D velocity]

Blankennagel, R.K 1968. Geophysical Logging and Hydraulic Testing, Pahute Mesa, Nevada Test Site. Ground Water 6(4):24-31.

Bleakley, W.B. et al. 1965. The Sidewall Epithermal Neutron Porosity Log. Soc. Petrol. Eng. AIMME Preprint No. 1180, 20 pp.

Blizard, E.P. 1958. Nuclear Radiation Shielding. In: Nuclear Engineering, H. Etherington (ed.), McGraw-Hill, New York.

Bois, P., M. La Porte, M. Lavergne, and G. Thomas. 1972. Well to Well Seismic Measurements. Geophysics 37:471-480.

Bredehoeft, J.D. 1964. Variations in the Permeability of the Tensleep Sandstone in the Bighorn Basin, Wyoming, As Interpreted from Core analysis and Geophysical Logs. U.S. Geological Survey Professional Paper 501-D, pp. D166-D170.

Briggs, R.D. 1964. The Downhole TV Camera. In: Trans. 5th Annual Logging Symp., Society of Professional Well Log Analysts, Tulsaj OK pp. N1.

Brother, M.R., J.Q. Robinson, and W.G. Soukup. 1990. Detection of Fractures in Sedimentary Rock with Conventional Borehole Geophysics. In: Proc. Fourth Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods. Ground Water Management 2:939-952.

Brown, D.L. 1971. Techniques for Quality-of-Water Interpretations from Calibrated Geophysical Logs, Atlantic Coastal Area. Ground Water 9(4):25-38.

Brown, R.H., A.A. Konoplyantsev, J. Ineson, and V.S. Kovalensky. 1983. Ground-Water Studies: An International Guide for Research and Practice. Studies and Reports in Hydrology No. 7. UNESCO, Paris. [Originally published in 1972, with supplements added in 1973, 1975, 1977, and 1983.] [Section 9 covers borehole geophysical techniques.]

Butler, D.K. and J.R. Curro, Jr. 1981. Crosshole Seismic Testing-Procedures and Pitfalls. Geophysics 46(1):23-29.

Bureau of Reclamation. 1981. Ground Water Manual—A Water Resources Technical Publication, 2nd ed. U.S. Department of the Interior, Bureau of Reclamation, Denver, CO.

Callahan, J.T., R.L. Wait, and M.J. McCollum. 1963. Television-A New Tool for the Ground-Water Geologist. Ground Water 1(4):4-6.

Campbell, M.D. and J.H. Lehr. 1973. Water Well Technology. McGraw-Hill, New York, 681 pp. [Annotated bibliography contains over 600 references.]

Canadian Well Logging Society. (Various dates.) Biannual Formation Evaluation Symposium Series. CWLS, Calgary, Canada. [Published symposia include 2nd (1968), 6th (1977), 7th (1979), 8th (1981), 9th (1983), llth (1987), 12th (1989), and 13th (1991)]

Carswell, A. and W.M. Moon. 1989. Application of Multioffset Vertical Seismic Profiling in Fracture Mapping. Geophysics 54:737-746.

Carter, V.B. 1966, Supplementary Sample Logs. Ground Water 4(3):49-51. [electric logs]

Chapman, H.T. and A.E. Robinson. 1962. A Thermal Flowmeter for Measuring Velocity for Flow in a Well. U.S. Geological Survey Water-Supply Paper 1544-E, 12 pp.

Chombart, L.G. 1960. Well Logs in Carbonate Reservoirs. Geophysics 25(4):779-853.

CH2M Hill. 1991. Proceedings: NSF/EPRI Workshop on Dynamic SoiI Properties and Site Characterization, Vol 1. EPRI NP-7337. Electric Power Research Institute, Palo Alto, CA Chapter 3 (Low- and High-Strain Cyclic Material Properties covers uphole-downhole seismic methods).

Collier, H.A. 1989a. A Guide to Selecting the Proper Borehole Resistivity Logging Suite. In: Proc. (2nd) Symp. on the Application of Geophysics to Engineering and Environmental Problems, Soc. Eng. and Mineral Exploration Geophysicists, Golden, CO, pp. 310-325.

Collier, H.A. 1989b. Assessment of the Dielectric Tool as a Porosity Log. In: Proc. Third Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 151-165.

Collier, H.A. 1992. Proper Application of Borehole Geophysical Techniques to the Evaluation of a Carbonate Aquifer A Case History. In: SAGEEP '92, Society of Engineering and Mineral Exploration Geophysicists, Golden, CO, pp. 55-70.

Collier, H.A. and R.P. Alger. 1988. Recommendations for Obtaining Valid Data from Borehole Geophysical Logs. In Proc. 2nd Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 897-924.

Collier, H. and M. Ridder. 1992. Utilization of the Borehole Televiewer in Fracture Analysis. In: Ground Water Management 13:765-779 (Proc. of Focus Conf. on Eastern Regional Ground Water Issues).

Cregon, D.J. and H. Moir. 1961. Evaluation of Limestone Formation Characteristics from Well Logs. J. Petrol. Tech. 12(11):1087-1092.

Croft, M.G. 1971. A Method of Calculating Permeability from Electric Logs. U.S. Geological Survey Professional Paper 750-B, pp. 265-269

Crosby, III, J.W. and J.V. Anderson 1971. Some Applications of Geophysical Well Logging to Basalt Hydrogeology. Ground Water 9(5):12-20.

Crowder, R.E. and L. Irons. 1988. Borehole Geophysical Logging Case Histories for Hazardous Waste Investigations. In: Proc. (lst) Symp. on the Application of Geophysics to Engineering and Environmental Problems, Soc. Eng. and Mineral Exploration Geophysicists, Golden, CO, pp. 747-753.

Crowder, R.E. and L. Irons. 1989. Economic Considerations of Borehole Geophysics for Engineering and Environmental Projects. In: Proc. (2nd) Symp. on the Application of Geophysics to Engineering and Environmental Problems, Soc. Eng. and Mineral Exploration Geophysicists, Golden, CO, pp. 325-338.

Crowder, R. E., L. Brouillard, and L. Irons. 1987. Utilizing A Borehole Geophysical Logging Program in Poorly Consolidated Sediments for a Hazardous Waste Investigation: A Case History. In: Proc. 2nd Int. Symp. on Borehole Geophysics for Minerals, Geotechnical and Groundwater Applications. pp. 65-75.

Crowder, R.E., J.J. LoCoco, and E.N. Yearsley. 1991. Application of Full Waveform Borehole Sonic Logs to Environmental and Subsurface Engineering Investigations. In: Proc. (4th) Symp. on the Application of Geophysics to Engineering and Environmental Problems, Soc. Eng. and Mineral Exploration Geophysicists, Golden, CO, pp. 53-64.

Cybriwksy, Z.A., E.N. Levine, and M.N. Toksoz. 1984. Detection of Permeable Rock Fracture Zones within Crystalline Bedrock by 3D Vertical Seismic Profiling. In: Proc. of the NWWA Tech.

Division Eastern Regional Ground Water Conference (Newton, MA), National Water Well Association, Dublin, OH, pp. 274-291.

Daily, W. and E. Owen. 1991. Cross-Borehole Resistivity Tomography. Geophysics 56(8):1228-1235.

Dakhnov, V.N. 1962. Geophysical Well Logging: The Application of Geophysical Method, Electrical Well Logging. Colorado School of Mines, Golden, CO, 445 pp.

Daniels, J.J. 1977. Three-Dimensional Resistivity and Induced-Polarization Using Buried Electrodes. Geophysics 42:1006-1019. Geophysics 48(1):87-97.

Daniels, J.J. 1983. Hole-to-Surface Resistivity Measurements. Geophysics 48(1):87-97.

Darr, P. S., R.H. Gilkeson, and E. Yearsley. 1990. Intercomparison of Borehole Geophysical Techniques in a Complex Depositional Environment. In: Proc. Fourth Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods. Ground Water Management 2:985-1001.

Davis, R.W. 1989. Developments in Cross Borehole Tomography. In: Proc. (2nd) Symp. on the Application of Geophysics to Engineering and Environmental Problems, Soc. Eng. and Mineral Exploration Geophysicists, Golden, CO, pp. 262-274.

Davis, S.N. and R.J.M. DeWiest. 1966. Hydrogedogy. John Wiley& Sons, New York, 463 pp. [Chapter 8 covers surface and borehole geophysical methods.]

Davis, J.L., R.W.D. Killey, A.P. Annan, and C. Vaughn. 1984. Surface and Borehole Ground-Penetrating Radar Surveys for Mapping Geological Structure. 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. 681-712.

Davison, C. C., W.S. Keys, and F.L. Paillet. 1982. Use of Borehole Geophysical Logs and Hydrologic Tests to Characterize Crystalline Rock for Nuclear Waste Storage, Whiteshell Nuclear Establishment, Manitoba, and Chalk River Nuclear Laboratory, Ontario, Canada. Office of Nuclear Waste Isolation Paper ONWI-418, 103 pp.

Dearborn, L.L. 1988. Borehole Geophysical Investigations of Fractured Rock at an EPA Superfund Site in Massachusetts. In: Proc. 2nd Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 875-895.

DeLuca, R.J. and B.K. Buckley. 1985. Borehole Logging to Delineate Fractures in a Contaminated Bedrock Aquifer. In: NWWA Conf. on Surface and Borehole Geophysical Methods in Ground Water Investigations (2nd Fort Worth, TX), National Water Well Association, Dublin, OH, pp. 387-398.

Desaubies, Y., A. Tarantola, and J. Zinn-Justin (eds.). 1990. Oceanographic and Geophysical Tomography. Elsevier, New York, 463 pp.

Devaney, A.J. 1984. Geophysical Diffraction Tomography. IEEE Trans. Geosci. Remote Sensing GE-22:3-13.

Dexter, J.J. and P.M. Kearl. 1988. Measurement of Groundwater Velocity with a Calorimetric Borehole Dilution Instrument. In: Proc. of the Focus Conf. on southwestern Ground Water Issues (Albuquerque, NM), National Water Well Association, Dublin, OH, pp. 251-268.

Dickinson, W., R.W. Dickinson, P.A. Mote, and J.S. Nelson. 1987. Horizontal Radials for Geophysics and Hazardous Waste Remediation. In: Superfund '87, Proceedings of the 8th Annual Conference, Hazardous Material Control Research Institute, Silver Spring, MD, pp. 371-375.

Dines, K.A. and R.J. Lytle. 1979. Computerized Geophysical Tomography. Proc. IEEE 67(7):1065-1073. [EM tomography]

Dines, K.A. and R.J. Lytle. 1981. Analysis of Electrical Conductivity Imaging. Geophysics 46(7):1025-1036. [EM tomography]

DiNitto, R.G. 1983. Evaluation of Various Geotechnical and Geophysical Techniques for Site Characterization Studies Relative to Planned Remedial Action Measures. In: Proc. 4th Nat. Conf. on Management of Uncontrolled Hazardous Waste Sites, Hazardous Materials Control Research Institute, Silver Spring, MD, pp. 130-134.

Diodato, D.M. and R.R. Parizek. 1992. Hydrogeologic Parameters of Reclaimed Coal Strip Mines from Borehole Geophysical Surveys. In: SAGEEP '92, Society of Engineering and Mineral Exploration Geophysicists, Golden, CO, pp. 71-90.

Doveton, S.H. 1986. Log Analysis of Subsurface Geology Concepts and Computer Models. John Wiley & Sons, New York, 273 pp.

Dresser Atlas. 1974. Log Review 1. Dresser Atlas Division, Dresser Industries, Houston, TX. [induction, resistivity, acoustic velocity, gamma-gamma neutron-gamma, diplog, neutron lifetime]

Dresser Atlas. 1975. Log Interpretation Fundamentals. Dresser Atlas Division, Dresser Industries, Houston, TX, 125 pp.

Dresser Atlas. 1979. Log Interpretation Charts. Dresser Atlas Division, Dresser Industries, Houston, TX.

Dresser Atlas. 1982. Well Logging and Interpretation Techniques The Course for Home Study. Dresser Atlas Division, Dresser Industries, Houston, TX, 350 pp.

Driscoll. F.G. 1986. Groundwater and Wells, 2nd ed. Johnson Filtration Systems Inc., St. Paul, MN, 1089 pp. [Chapter 8 covers borehole geophysical methods: resistivity, SP, gamma, gamma-gamma, neutron, acoustic, temperature, caliper and fluid velocity.]

Duval, J.S. 1980. Radioactivity Method. Geophysics 45(11):1690-1694.

Duval, J. 1989. Radiometries in Geology. In: Proc. (2nd) Symp. on the Application of Geophysics to Engineering and Environmental Problems, Soc. Eng. and Mineral Exploration Geophysicists, Golden, CO, pp. 1-61.

Dyck A.V. 1991. Drill-Hole Electromagnetic Methods. In: Electromagnetic Methods in Applied Geophysics, Vol. 2, Applications, M.N. Nabighian (ed.), Society of Exploration Geophysicists, Tulsa, OK Part B, pp. 881-930.

Dyck J. H., W.S. Keys, and W.A. Meneley. 1972. Application of Geophysical Logging to Groundwater Studies in Southern Saskatchewan. Canadian J. Earth Sciences 9(1):78-94.

Edwards, J.M. and S.G. Stroud. 1966. New Electronic Casing Caliper Log Introduced for Corrosion Detection. J. Petrol. Tech. 18(8):933-938.

Ellis, D.V. 1987. Well Logging for Earth Scientists. Elsevier, New York, 532 pp. [SP, resistivity, induction, gamma, neutron, acoustic]

Ellis, D.V. 1990. Neutron and Gamma Ray Scattering Measurements for Subsurface Geochemistry. Science 250(October 5):82-87. [gamma-gamma, gamma spectrometry, neutron]

Emerson, D.W. and S.S. Webster. 1970. Interpretation of Geophysical Logs in Bores in Unconsolidated Sediments. Australian Water Resources Council Research Project 68fl-Phase I, 212 pp.

Emilsson, G.R. and R.A. Arnott. 1991. In-Situ Specific Conductivity Monitoring on a Observation Well During a Long Term Pumping Test. In: Ground Water Management 5:533-547 (5th NOAC). [conductivity-temperature probe]

Erickson, C.R. 1946. Vertical Water Velocity in Deep Wells. J. Am. Water Works Ass. 38:1263-1272.

Evans, H.B. 1970. Status and Trends in Logging. Geophysics 35(1):93-112.

Everett, L.G. 1985. Groundwater Monitoring Handbook for Coal and Oil Shale Development. Elsevier, New York. [Section 8 covers borehole geophysical methods: temperature, caliper, gamma, flow, radioactive tracer, 3-D velocity (acoustic waveform), acoustic, gamma-gamma, electric, acoustic-televiewer.]

Fiedler, A.G. 1928. The Au Deep-Well Current Meter and Its Use in the Roswell Artesian Basin, New Mexico. U.S. Geological Survey Water-Supply Paper 596, pp. 24-32.

Foster, N.H. and E.A. Beaumont (eds.). 1990. Formation Evaluation I Log Evaluation; II: Log Interpretation. Reprint Series Nos. 16 and 17, American Association of Petroleum Geologists, Tulsa, OK, (I) 742 pp., (11) 600 pp. [resistivity, SP, gamma, porosity, dip meter, other logs]

Freedman, R. and J.P. Vogiatzis. 1979. Theory of Microwave Dielectric Constant ***Logging*** Using the Electromagnetic Wave Propagation Method. Geophysics 44(5):969-986.

Frimpter, M.H. 1969. Casing Detector and Self-Potential Logger. Ground Water 7(6):24-27.

Fujimoto, K., J.A. Wilson, and J.P. Ashmore. 1985. Radiation Exposure Risks to Nuclear Well Loggers. Health Physics 48(4):437-445.

Gal'perin, E.I. 1974. Vertical Seismic Profiling. Society of Exploration Geophysicists, Tulsa, OK 278 pp.

Gardner, R.P. and K.F. Roberts. 1967. Density and Moisture Content Measurement by Nuclear Methods. Nat. Coop. Highway Res. Program Report 43.

Gernand, J. 1991. Characterization of a Bedrock Aquifer by Rock Coring, Downhole Video and Borehole Geophysics. In: Ground Water Management 7:547-561 (8th NWWA Eastern GW

Conference). [caliper, gamma, temperature, fluid resistivity, resistivity, SP resistivity, SP, acoustic waveform]

Gonduin, M. and C. Scale. 1958. Streaming Potential and the SP Log. J. Petrol Tech. 10(8):170-179.

Gorder, Z.A. 1963. Television Inspection of a Gravel Pack Well. J. Am. Water Works Ass. 55:31-34.

Greenhouse, J.P., L. Faulkner, and J. Wong. 1985. Geophysical Monitoring of an Injected Contaminant Plume with a Disposable E-Log. In: NWWA Conf. on Surface and Borehole Geophysical Methods in Ground Water Investigations (2nd Fort Worth, TX), National Water Well Association, Dublin, OH, pp. 64-84. [EMI, ER, BH]

Greenhouse, J.P., D.C. Nobes, and G.W. Schneider. 1990. Groundwater Beneath the City A Geophysical Study. In: Proc. Fourth Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods. Ground Water Management 2:1179-1191. [SRR, BH]

Guthrie, M. 1986. Use of a GeoFlowmeter for the Determination of Ground Water Flow Direction, Ground Water Monitoring Review 6(2):81-86.

Guyod, H. 1952. Electrical Well Logging Fundamentals. WeIl Instruments Developing Co., Houston, TX, 164 pp.

Guyod, H. 1957a. Resistivity Determination from Electric Logs. (Published by) Hubert Guyod, Houston, TX.

Guyod, H. 1957b. Electric Detective: Investigation of Groundwater Supplies with Electric Well Logs. Water Well J. 11(3):12-13+ and 11(5):14-15+.

Guyod, H. 1958. Electric Analogue for Resistivity Logging. (Published by) Hubert Guyod, Houston, TX.

Guyod, H. 1965. Interpretation of Electric and Gamma Ray Logs in Water Wells. Am. Geophysical Union Technical Paper. Mandrel Industries, Inc. Houston, TX,

Guyod, H. 1966. Interpretation of Electric and Gamma Ray Logs in Water Wells. The Log Analyst 6(5):29-44.

Guyod, H. and J.A. Pranglin. 1959. Analysis Charts for the Determination of True Resistivity from Electric Logs. (Published by) Hubert Guyod Houston TX, 202 pp.

Guyod, H. and L.E. Shane. 1969. Geophysical Well Logging, Vol. I, Introduction to Geophysical Well Logging and Acoustical Logging. (Published by) Hubert Guyod Houston TX, 256 pp. [Part I covers general well logging equipment principles; Part II covers acoustical logging.]

Haase, C.S. and J.L. King. 1986. Application of Borehole Geophysics to Fracture Identification and Characterization-in Low Porosity Limestone and Dolostones. In: Proc. Surface and Borehole Geophysical Methods and Ground Water Instrumentation Conf. and Exp., National Water Well Association, Dublin, OH, pp. 487-506. [neutron, resistivity, gamma-gamma, acoustic waveform, acoustic televiewer]

Halevy, E., H. Moser, O. Zellhofer, and A. Zuber. 1967. Borehole Dilution Techniques: A Critical Review. In: Isotopes in Hydrology, IAEA Proceedings Series, International Atomic Energy Agency, Vienna, pp. 531-564.

Hallenberg, J.K. 1983. Geophysical Logging for Mineral and Engineering Applications. Penn Well Books, 264 pp.

Hallenberg, J.K. 1984. Formation Evaluation Programs. Pem Well Books, 120 pp.

Hamilton, R.G. and J.I. Myung. 1979. Summary of Geophysical Well Logging. Birdwell Division, Seismograph Service Corporation, Tulsa OK, 32 pp.

Hansen, H.J. 1967. The Electric Log Geophysics' Contribution to Ground Water Prospering and Evaluation. Maryland Geological Survey Information Circular No. 4, 11 pp.

Hardage, B.A. 1985. Vertical Seismic Profiling, Part A Principles, 2nd enlarged edition. Seismic Exploration, Vol. 14A Geophysical Press, London, 450 pp. [lst edition 1982]

Havranek T.J. and W. Smith. 1989. Application of Downhole Geophysical Methods and Discrete Zone Sampling Techniques in the Investigation of a Fractured Bedrock Aquifer. In: Proc. (6th) NWWA/API Conf. on Petroleum Hydrocarbons and Organic Chemicals in Ground Water: Prevention, Detection and Restoration, National Water Well Association, Dublin, OH, pp. 109-123.

Head, W.J. and B.A. Kososki. 1979. Borehole Gravity A New Tool for the Ground-Water Hydrologist (Abstract). Trans. Am. Geophys. Union 60:248.

Head, W.J. and R.H. Merkel. 1977. Hydrologic Characteristics of the Madison Limestone, The Minnelusa Formation, and Equivalent Rocks as Determined by Well-Logging Formation Evaluation. J. Research of the U.S. Geological Survey 5(4):473-485.

Hearst, J.R. and R.C. Carlson. 1982. Measurement and Analysis of Gravity in Boreholes. Developments in Geophysical Exploration Methods 4:269-303.

Hearst, J.R. and P.H. Nelson. 1985. Well Logging for Physical Properties. McGraw-Hill, New York, 571 PP.

Heeley, R.W. and B.A. Marshall. 1985. The Use of Geophysical Techniques in an Accelerated Search for Ground Water in the Connecticut River Valley, Massachusetts. In: NWWA Conference on Surface and Borehole Geophysical Methods and Ground Water Investigations (2nd Fort Worth, TX), National Water Well Association, Dublin, OH, pp. 249-264. [ER, GR, SRR, BH]

Helander, D.P. 1983. Fundamentals of Formation Evaluation. Oil & Gas Consultants International Publications, Tulsa, OK 332 pp. [SP, resistivity, acoustic, radiation]

Hennon, K., D.W. Bostwick, M. Snoparsky, T.T. Travers, and P. McManus. 1991. Optimizing Seismic Refraction Results Through Pre-Survey Testing. In: Ground Water Management 5:999-1015 (5th NOAC); also, Ground Water Management 7:693-709 (8th NWWA Eastern GW Conference). [SRR and downhole seismic]

Henrich, W.J. 1986. Delineation of Transmissive Layers with Borehole Geophysics. In: Proc. Surface and Borehole Geophysical Methods and Ground Water Instrumentation Conf. and Exp., National Water Well Association, Dublin, OH, pp. 570-579. [normal, lateral resistivity, gamma, neutron]

Hess, A.E. 1982. A Heat-Pulse Flowmeter for Measuring Low Velocities in Boreholes. U.S. Geological Survey Open File Report 82-699,44 pp.

Hess, A.E. 1984. Use of Low Velocity Borehole Flowmeter in the Study of Hydraulic Conductivity in Fractured Rock. In: NWWA/EPA Conf. on Surface and Borehole Geophysical Methods in Ground Water Investigations (1st San Antonio, TX), National Water Well Association, Dublin, OH, pp. 812-832.

Hess, A.E. 1986. Identifying Hydraulically Conductive Fractures with a Slow-Velocity Borehole Flowmeter. Canadian Geotechnical J. 23:69-78.

Hess, K.M. 1989. Use of a Borehole Flowmeter to Determine Spatial Heterogeneity of Hydraulic Conductivity and Macrodispersion in a Sand and Gravel Aquifer, Cape Cod, Massachusetts. In: Proc. Conf. on New Field Techniques for Quantizing the Physical and Chemical Properties of Heterogeneous Aquifers, National Water Well Association, Dublin, OH, pp. 497-508.

Hess, A.E. and F.L. Paillet. 1989. Characterizing Flow Paths and Permeability Distribution in Fractured Rock Aquifers Using a Sensitive, Thermal Borehole Flowmeter. In: Proc. Conf. on New Field Techniques for Quantifying the Physical and Chemical Properties of Heterogeneous Aquifers, National Water Well Association, Dublin, OH, pp. 445-462.

Hess, K.M. and S.H. Wolf. 1991. Techniques to Determine Spatial Variations in the Hydraulic Conductivity of Sand and Gravel. EPA/600/2-91/006 (NTIS PB91-109123).

Hess, J.W., D.D. Spencer, S.W. Wheatcraft, and W.M. Adams. 1984. Evaluation of the Applicability of Some Existing Borehole Instruments to Hazardous Waste Site Characterization and Monitoring. 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. 762-787.

Hilchie, D.W. 1968. Caliper Logging-Theory and Practice. The Log Analyst 9(1):3-12.

Hilchie, D.W. 1979. Old (Pre-1958) Electrical Log Interpretation. Institutes for Energy Development, Tulsa, OK.

Hilchie, D.W. 1982a. Applied Open Hole Log Interpretation for Geologists and Engineers, 2nd ed. D.W. Hilchie, Inc., Golden, CO, 400+ pp. 1st edition 1978 [SP, induction, acoustic, gamma, gamma-gamma, neutron, dipmeter]

Hilchie, D.W. 1982b. Advanced Well Log Interpretation. D.W. Hilchie, Inc., Golden, CO, 353 pp.

Hoar, R.J. and K.H. Stokoe, 11. 1977. Generation and Measurement of Shear Waves In Situ. In: Dynamic Geotechnical Testing, ASTM STP 654, American Society for Testing and Materials, Philadelphia, PA, pp. 3-29.

Hodges, R.E. and W.E. Teasdale. 1991. Considerations Related to Drilling Methods in Planning and Performing Borehole-Geophysical Logging for Ground-Water Studies. U.S. Geological Survey Water Resource Investigations Report 91-409 (NTIS PB92-155688), 22 pp. [Caliper, gamma, gamma-spectral, gamma-gamma, neutron, electric, acoustic velocity, acoustic televiewer, temperature, flowmeters]

Holser, W.T., R.J.S. Brown, R.A. Roberts, O.A. Fredrickson, and R.R. Unterberger. 1972. Radar Logging of a Salt Dome. Geophysics 37(5):889-906.

Holzhausen, G.R. and H.N. Egan. 1986. Fracture Characterization in Boreholes Using Oscillatory Pressure Behavior. In: Proc. Surface and Borehole Geophysical Methods and Ground Water Instrumentation Conf. and Exp., National Water Well Association, Dublin, OH, pp. 451-473.

Howard, K.W.F., M. Hughes, and M.J. Thompson. 1986. Down-Hole Geophysical Methods of Fracture Detection in Low Permeability Bedrock. In: Proc. Surface and Borehole Geophysical Methods and Ground Water Instrumentation Conf. and Exp., National Water Well Association, Dublin, OH, pp. 507-525. [caliper, gamma-gamma temperature]

Huber, W.F. 1982. The Use of Downhole Television in Monitoring Applications. In: Proc. Second Nat. Symp. on Aquifer Restoration and Ground Water Monitoring, National Water Well Association, Dublin, OH, pp. 285-286.

Hufschmied, P. 1986. Estimation of Three-Dimensional Statistically Anisotropic Hydraulic Conductivity Field by Means of Single Well Pumping Tests Combined with Flowmeter Measurements. Hydrogeologie No. 2, pp. 163-174.

Imse, J.P. and E.N. Levine. 1985. Conventional and State-of-the-Art Geophysical Techniques for Fracture Detection. In: 2nd Annual Eastern Regional Groundwater Conference (Portland, ME), National Water Well Association, Dublin, OH, pp. 261-276.

Ineson, J. and D.A. Gray. 1963. Electrical Investigations of Borehole Fluids. J. Hydrology 1:204-218.

International Atomic Energy Agency (IAEA). 1968. Guidebook of Nuclear Techniques in Hydrology. Technical Report No. 91. IAEA Vienna.

International Atomic Energy Agency (IAEA). 1971. Nuclear Well Logging in Hydrology. Technical Report No. 126. IAEA Vienna, 92 pp.

Jackson, J.A. 1984. Nuclear Magnetic Resonance Well ***Logging. The Log*** Analyst 25(5):16-30.

Jackson, M.J., D.R. Tweeton, and S. Biilington. 1992. Seismic Crosshole Tomography Using Wavefront Migration and Fuzzy Constraints: Application to Fracture Detection and Characterization. In: Ground Water Management 11:741-754 (Proc. of the 6th NOAC).

Jann, R.H. 1966. Method for Deep Well Alignment Tests. Am. Water Works Ass. J. 58(4):440-445.

Jensen, Jr., O.F. and W. Ray. 1965. Photographic Examination of Wells. Am. Water Works Ass. J. 57:441-447.

Jessop, J.J., M.J. Friedel, M.R. Jackson, and D.R. Tweeton. 1992. Fracture Detection with Seismic Crosshole Tomography for Solution Control in a Stope. In: SAGEEP ’92, Society of Engineering and Mineral Exploration Geophysicists, Golden, CO, pp. 487-508.

Johnson, A.L 1967. Specific Yield—Compilation of Specific Yields for Various Materials. U.S. Geological Survey Water-Supply Paper 1662-D, 74 pp.

Johnson, A.I. 1968. An Outline of Geophysical Logging Methods and Their Uses in Hydrogeological Studies. U.S. Geological Survey Water-Supply Paper 1892, pp. 158-164.

Johnson, A.I. and J.P. Gnaedinger. 1964. Bibliography. In: Symposium on Soil Exploration, ASTM STP 351, American Society for Testing and Materials, Philadelphia, PA pp. 137-155. [electrical

borehole logging (48 refs); nuclear borehole logging (40 refs), borehole camera (13 refs); neutron moisture measurement (50 refs)]

Jones, P.H. and T.D. Buford. 1951. Electrical Logging Applied to Ground-Water Exploration. Geophysics 16(1):115-139.

Jones, O.R. and A.D. Schneider. 1969. Determining Specific Yield of The Ogallala Aquifer by the Neutron Method. Water Resources Research 5(6):1267-1272.

Jones, P.H. and H.E. Skibitzke. 1956. Subsurface Geophysical Methods in Groundwater Hydrology. Advances in Geophysics 1:241-300.

Jones, J.W., E.S. Simpson, and S.P. Neuman. 1984. Geophysical Investigations of Fractured Crystalline Rock Near Oracle, Arizona. 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. 877-888.

Jorgensen, D. 1989. Using Geophysical Logs to Estimate Porosity, Water Resistivity, and Intrinsic Permeability. U.S. Geological Survey Water-Supply Paper 2321, 24 pp.

Kaufman, A.A. and G.V. Keller. 1989. Induction Logging. Elsevier, New York.

Kearl, P. M., N.E. Korte, and T.A. Cronk. 1992. Suggested Modifications to Ground Water Sampling Procedures Based on Observations from the Colloidal Boroscope. Ground Water Monitoring Review 12(2):155-161.

Keech, D.A. 1988. Hydrocarbon Thickness on Groundwater by Dielectric Well Logging. In: Proc. (5th) NWWA/API Conf. on Petroleum Hydrocarbons and Organic Chemicals in Ground Water Prevention, Detection and Restoration, National Water Well Association, Dublin, OH, pp. 275-289.

Kelly, D.R. 1969. A Summary of Geophysical Logging Methods. Pennsylvania Geological Survey Bull. M61, 88 pp.

Kendall, H.A. 1965. Application of SP Curves to Corrosion Detection. J. Petrol. Tech. 17(9):1029-1032

Kerfoot, W.B. 1982. Comparison of 2-D and 3-D Ground-Water Flowmeter Probes in Fully-Penetrating Monitoring Wells. In: Proc. Second Nat. Symp. on Aquifer Restoration and Ground Water Monitoring, National Water Well Association, Dublin, OH, pp. 264-268.

Kerfoot, W.B. 1984. Darcian Flow Characteristics Upgradient of a Kettle Pond Determined by Direct Ground Water Flow Measurement. Ground Water Monitoring Review 4(4):188-192.

Kerfoot, W.B. 1988. Monitoring Well Construction and Recommended Procedures for Direct Ground-Water Flow Measurement Using a Heat-Pulse Flowmeter. In: Ground-Water Contamination: Field Methods, A.G. Collins and A.I. Johnson, (eds.), ASTM STP 963, American Society for Testing and Materials, Philadelphia, PA pp. 146-161.

Kerfoot, W.B. 1992. The Use of Borehole Flowmeters and Slow-Release Dyes to Determine Bedrock Flow for Wellhead Protection. In: Ground Water Management 11:755-763 (Proc. of the 6th NOAC). [thermal flowmeter]

Kerfoot, W.B. and L. Kiely. 1989. A Direct-Reading Borehole Flowmeter. In: Proc. Conf. on New Field Techniques for Quantifying the Physical and Chemical Properties of Heterogeneous Aquifers, National Water Well Association, Dublin, OH, pp. 579-584.

Kerfoot, W.B., G. Beaulieu, and L. Kiely. 1991. Direct-Reading Borehole Flowmeter Results in Field Applications. In: Ground Water Management 5:1073-1084 (5th NOAC). [thermal flowmeter]

Keys, W.S. 1967a. The Application of Radiation Logs to Groundwater Hydrology. In: Isotopes in Hydrology, IAEA Proceedings Series, International Atomic Energy Agency, Vienna pp. 477-488.

Keys, W.S. 1967b. Borehole Geophysics as Applied to Groundwater. In: Mining and Groundwater Geophysics/1967, L.W. Morely (ed.), Geological Survey of Canada Economic Geology Report 26, pp. 598-612.

Keys, W.S. 1968. WelI Logging in Ground Water Hydrology. Ground Water 6(1):10-18.

Keys, W.S. 1986. Analysis of Geophysical Logs of Water Wells with a Microcomputer. Ground Water 24(3):750-760.

Keys, W.S. 1990. Borehole Geophysics Applied to Ground-Water Investigations. U.S. Geological Survey Techniques of Water-Resource Investigations TWRI 2-E2, 150 pp. [Supersedes report originally published in 1988 under the same title as U.S. Geological Survey Open-File Report 87-539, 303 pp., which was published in 1989 with the same title by the National Water Well Association, Dublin, OH, 313 pp.] [Complements Keys and MacCary (1971).]

Keys, W.S. and R.F. Brown. 1971. The Use of Well Logging in Recharge Studies of the Ogallala Formation in West Texas. U.S. Geological Survey Professional Paper 750-B, pp. 270-277.

Keys, W.S. and R.F. Brown. 1973. Role of Borehole Geophysics in Underground Waste Storage and Artificial Recharge. In: Symposium on Underground Waste Management and Artificial Recharge, J. Braunstein, (ed.), IAHS Pub. No. 110, Int. Assn. of Hydrological Sciences, pp. 147-191.

Keys, W.S. and L.M. MacCary. 1971. Application of Borehole Geophysics to Water Resource Investigations. U.S. Geological Survey Techniques of Water-Resources Investigations TWRI 2-El [reprinted, 1990; see also Keys, 1990].

Kierstein, R.A. 1984. True Location and Orientation of Fractures Logged with the Acoustic Televiewer (Including Programs to Correct Fracture Orientation). U.S. Geological Survey Water-Resources Investigations Report 83-4275, 73 pp.

Killeen, P.G. 1982. Gamma-Ray Logging and Interpretation. Developments in Geophysical Exploration Methods 3:95-150.

Killeen, P.G. (ed.). 1985. Borehole Geophysics for Mining and Geotechnical Applications. Geological Survey of Canada Paper 85-27.

Killow, H.W. 1966. Fluid Migration Behind Casing Revealed by Gamma Ray Logs. The Log Analyst 6(5):46-49.

King, W.C. and A.J. Witten. 1989. High Resolution Subsurface Imaging with Geophysical Diffraction Tomography. In: Proc. Third Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 813-826.

King, W.C. and A.J. Witten. 1990. Geophysical Diffraction Tomography A Complimentary Remote Sensing Technique for Hazardous Waste Site Characterization. In: Proc. Fourth Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods. Ground Water Management 2:115-126.

King, W. C., A.J. Witten, and G.D. Reed. 1989. Detection and Imaging of Buried Wastes Using Seismic Wave Propagation. J. Environ. Eng. 115(3):527-548.

Kovács, G., J. Gálfi, and N. Pataki. 1982. Subterranean Hydrology. Water Resource Publications, Littleton, CO. [borehole]

Kwader, T. 1984a. Estimating Aquifer Permeability from Formation Resistivity Factors. In: NWWA/EPA Conf. on Surface and Borehole Geophysical Methods in Ground Water Investigations (1st, San Antonio, TX), National Water Well Association, Dublin, OH, pp. 713-721.

Kwader, T. 1984b. The Use of Geophysical Logs for Determining Formation Water Quality. 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. 833-841.

Kwader, T. 1985. Resistivity-Porosity Cross Plots for Determining In Situ Formation Water Quality-Case Examples. In: NWWA Conf. on Surface and Borehole Geophysical Methods in Ground Water Investigations (2nd Fort Worth, TX), National Water Well Association, Dublin, OH, pp. 415-424.

Kwader, T. 1986. The Use of Geophysical Logs for Determining Formation Water Quality. Ground Water 24(1):11-15.

Labo, J. 1987. A Practical Introduction to Borehole Geophysics. Society of Exploration Geophysicists, Tulsa, OK 336 pp. [gamma-gamma gravity, acoustic, VSP, dipmeter]

Landry, P.G. 1992. The Applications of Acoustic Cement Bond Logging to Well Casing Evaluation and Remediation Programs. In: Ground Water Management 11:717-728 (Proc. of the 6th NOAC).

Lattman, L.H. and R.R. Parizek. 1964. Relationship Between Fracture Traces and the Occurrence of Ground Water in Carbonate Rocks. J. Hydrology 2:73-91.

Leap, D.I. and P.G. Kaplan. 1988. A Single-Well Tracing Method for Estimating Regional Advective Velocity in a Confined Aquifer: Theory and Preliminary Laboratory Verification. Water Resources Research 23(7):993-998.

Leckenby, R.J. 1982. Electromagnetic Ground Radar Methods. In: Premining Investigations for Hardrock Mining, U.S. Bureau of Mines Information Circular 8891, pp. 36-45. [GPR, cross-hole radar]

Lee, G.W., J.T. Mickham, and B.S. Levy. 1984. Detection of Fractures and Solution Channels in Karst Terrains Using Natural Gamma Ray and Hole Caliper Borehole Logs. 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. 801-811.

Le Masne, D. and C. Poirmeur. 1988. Three-Dimensional Model Results for an Electrical Hole-to-Surface Method: Application to the Interpretation of a Field Survey. Geophysics 53:85-103.

LeRoy, L.W., D.O. LeRoy, S.D. Schwochow, and J.W. Raese (eds.). 1987. Subsurface Geology, 5th ed. Colorado School of Mines, Golden, CO. [lst ed. LeRoy and Cran (1947), 2nd ed. LeRoy (1951), 3rd ed. Huan and LeRoy (1958), 4th ed. 1977]

Levine, E.N., Z.A. Cybriwsky, and N.N. Toksoz. 1984. Detection of Permeable Rock Fractures and Estimation of Hydraulic Conductivity and Yield by 3-D Vertical Seismic Profiling. In: NWWA/EPA Conf. on Surface and Borehole Geophysical Methods in Ground Water Investigations (1st San Antonio, TX), National Water Well Association, Dublin, OH, pp. 853-876.

Linck, C.J. 1963. Geophysics as an Aid to the Small Water Well Contractor. Ground Water 1(1):33-37. [SP, gamma, caliper, flowmeter]

Lindsey, G.P. 1985. Dry Hole Resistivity Logging. In: NWWA Conf. on Surface and Borehole Geophysical Methods in Ground Water Investigations (2nd Fort Worth, TX), National Water Well Association, Dublin, OH, pp. 371-376.

Lines, L.R. and J.A. Scales (eds.) 1987. Geophysical Imaging. Symposium of Geophysical Society of Tulsa, available from Society of Exploration Geophysicists, Tulsa, OK, 225 pp. [tomography, inversion, migration, and computer-related issues]

Lloyd, D.P. 1970. Down-the-Hole TV: The Greatest Show on Earth. Ground Water Age. 8(6):28-35.

Lynch, E.J. 1962. Formation Evaluation. Harper and Row, New York, 422 pp.

Lytle, R.J., E.F. Laine, D.L. Lager, and D.T. Davis. 1979. Cross-Borehole Electromagnetic Probing to Locate High-Contrast Anomalies. Geophysics 44(10):1667-1676.

Lytle, R.J., D.L. Lager, E.F. Laine, J.D. Salisbury, and J.T. Okada. 1981. Fluid-Flow Monitoring Using Electromagnetic Probing. Geophysical Prospecting 29:627-638. [cross-hole radar]

MacCary, L.M. 1971. Resistivity and Neutron Logging in Silurian Dolomite in Northwest Ohio. U.S. Geological Survey Professional Paper 750-D, pp. D190-D197.

MacCary, L.M. 1978. Interpretation of Well Logs in a Carbonate Aquifer. U.S. Geological Survey Water-Resources Investigation Report 78-8,35 pp.

MacCary, L.M. 1980. Use of Geophysical Logs to Estimate Water-Quality Trends in Carbonate Aquifers. U.S. Geological Survey Water-Resources Investigation Report 80-57, 29 pp.

MacCary, L.M. 1983. Geophysical Logging in Carbonate Aquifers. Ground Water 21(3): 334-342.

MacCary, L.M. 1984a. Apparent Water Resistivity, Porosity, and Ground-Water Temperature of the Madison Limestone and Underlying Rocks in Parts of Montana, Nebraska, North Dakota, South Dakota, and Wyoming. U.S. Geological Survey Professional Paper 1273-D, 14 pp.

MacCary, L.M. 1984b. Relation of Formation Factor to Depth of Burial in Aquifer of the Texas Gulf Coast. In: NWWA/EPA Conf. on Surface and Borehole Geophysical Methods in Ground Water Investigations (1st, San Antonio, TX), National Water Well Association, Dublin, OH, pp. 722-742.

Mahannah, J.L., A.J. Witten, and W.C. King. 1988. Use of Geophysical Diffraction Tomography for Hazardous Waste Site Characterization. In: Superfund ’88, Hazardous Material Control Research Institute, Silver Spring, MD, pp. 152-156.

Majer, E.L., T.V. McEvilly, F.S. Eastwood, and L.R. Myer. 1988. Fracture Detection Using P-Wave and S-Wave Vertical Seismic Profiling at the Geysers. Geophysics 53:76-84.

Markstrom, A. 1992 The Use of Natural Radiation Detection in Determining Clay Content of Complex Glacial Deposits. In: Ground Water Management 11:689-699 (Proc. of the 6th NOAC). [gamma log]

Marsh, C.R. and R.R. Parizek. 1968. Induction-Tuned Method to Determine Casing Lengths in Hydrogeologic Investigations. Ground Water 6(6): 11-17.

McCann, D.M., R. Baria P.D. Jackson, and A.S.P. Green. 1986. Applications of Cross-Hole Seismic Measurements in Site Investigation Surveys. Geophysics 51:914-929.

McLinn, E.L. and C.D. Palmer. 1988. An Electrical Resistivity Borehole-Dilution Device for the Determination of Ground-Water Flux. In: Proc. 2nd Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 851-874.

McLinn, E.L. and C.D. Palmer. 1989. Laboratory Testing and Comparison of Specific-Conductance and Electrical Resistivity Borehole-Dilution Devices. In: Proc. Conf. on New Field Techniques for Quantifying the Physical and Chemical Properties of Heterogeneous Aquifers, National Water Well Association, Dublin, OH, pp. 475-298.

McNeill, J.D. 1986. Geonics EM39 Borehole Conductivity Meter: Theory of Operation. Technical Note TN-20. Geonics Limited, Mississaugua, Ontario, 11 pp.

McNeill, J.D. 1989. Application of the Geonics EM39 Borehole Conductivity Logger at Two Groundwater Contamination Sites. Technical Note TN-24. Geonics Limited, Mississaugua, Ontario.

McNeil], J.D. and M. Bosnar. 1988. Comparison of Geoelectric Sections Obtained Across a Fault with EM39 Borehole Induction Logger and TEM47 Time-Domain System in Central Loop Sounding Mode. Technical Note TN-23. Geonics Limited Mississaugua, Ontario.

McNeill, J.D., M. Bosnar, F.B. Snelgrove. 1990. Resolution of an Electromagnetic Borehole Conductivity Logger for Geotechnical and Ground Water Applications. Technical Note TN-25. Geonics Limited, Mississaugua, Ontario.

Melville, J. G., F.J. Molz and O. Güven. 1985. Laboratory Investigation and Analysis of a Ground-Water Flowmeter. Ground Water 23(4):486-495.

Merin, I.S. 1992. Conceptual Model of Ground Water Flow in Fractured Siltstone Based on Analysis of Rock Cores, Borehole Geophysics and Thin Sections. Ground Water Monitoring Review 12(4): 118-125. [caliper, gamma-gamma temperature and neutron logs]

Meyer, W.R. 1962. Use of a Neutron Moisture Probe to Determine the Storage Coefficient of an Unconfined Aquifer. U.S. Geological Survey Professional Paper 450-E, pp. 174-176.

Michalski, A. 1989. Application of Temperature and Electrical-Conductivity Logging in Ground Water Modeling. Ground Water Monitoring Review 9(3):112-118.

Michalski, A., R. Britton and A.H. Uminski. 1992. Integrated Use of Multiple Techniques for Contaminant Investigations in Fractured Aquifers A Case Study from the Newark Basin, New Jersey. In: Ground Water Management 13:809-826 (Proc. of Focus Conf. on Eastern Regional Ground Water Issues). [borehole television, fluid conductivity, temperature logs]

Mickam, J.T., B.S. Levy, and G.W. Lee, Jr. 1984. Surface and Borehole Geophysical Methods in Ground Water Investigations. Ground Water Monitoring Review 4(4):167-171. [caliper, gamma]

Minerals and Geotechnical Logging Society (MGLS) Symposia Series. 1985-1991. Proc. 1st Int. Symp. Borehole Geophysics for Minerals, Geotechnical and Groundwater Applications (Ottawa, 1985); 2nd (Golden, CO, 1987); 3rd (Las Vegas, NV, 1989); 4th (Ontario, 1991). Available from Society of Professional Well Log Analysts.

Moltyaner, G.L. 1989. Aquifer Parameter Estimation with the Aid of Radioactive Tracers. In: Proc. Conf. on New Field Techniques for Quantifying the Physical and Chemical Properties of Heterogeneous Aquifers, National Water Well Association, Dublin, OH, pp. 509-528.

Molz, F.J., R.H. Morin, A.E. Hess, J.G. Melville, and O. Güven. 1989. The Impeller Meter for Measuring Aquifer Permeability Variations: Evaluation and Comparison with Other Tests. Water Resources Research 25(7):1677-1683.

Molz, F.J., O. Güven, and J.G. Melville. 1990. A New Approach and Methodologies for Characterizing the Hydrogeologic Properties of Aquifers. EPA/600/2-90/002 (NTIS PB90-187063). [flowmeter]

Montgomery, R.J., D.A. Wierman, R.W. Taylor, and H.A. Koch. 1985. Uses of Downhole Geophysical Methods in Determining the Internal Structure of a Large Landfill. In: NWWA Conf. on Surface and Borehole Geophysical Methods in Ground Water Investigations (2nd Fort Worth, TX), National Water Well Association, Dublin, OH, pp. 377-386.

Morahan, T. and R. C. Dorrier. 1984. The Application of Television Borehole Logging to Ground Water Monitoring Programs. Ground Water Monitoring Review 4(4):172-175.

Moran, J.H. and R. Chemali. 1985. Focused Resistivity Logs. Developments in Geophysical Exploration Methods 6:225-260.

Morin, R.H. and W. Barrash. 1986. Defining Patterns of Ground Water and Heat Flow in Fractured Brule Formation, Western Nebraska, Using Borehole Geophysical Methods. In: Proc. Surface and Borehole Geophysical Methods and Ground Water Instrumentation Conf. and Exp., National Water Well Association, Dublin, OH, pp. 545-569.

Morrison, R.D. 1983. Groundwater Monitoring Technology. Timco Mfg., Inc. Prairie du Sac, WI, 105 pp. [gamma-gamma, neutron probe, nuclear magnetic resonance]

Mullins, J.E. 1966. Stereoscopic Deep Well Photography in Opaque Fluids. In: Trans. 7th Annual Logging Symp., Society of Professional Well Log Analysts, Tulsa, OK pp. V1-V8.

National Water Well Association (NWWA). 1984. NWWA/EPA Conference on Surface and Borehole Geophysical Methods in Ground Water Investigations (San Antonio, TX). National Water Well Association, Dublin, OH.

National Water Well Association (NWWA). 1985. NWWA Conference on Surface and Borehole Geophysical Methods in Ground Water Investigations (Fort Worth, TX). National Water Well Association, Dublin, OH.

National Water Well Association (NWWA). 1986. Surface and Borehole Geophysical Methods and Ground Water Instrumentation Conference and Exposition (Denver, CO). NWWA, Dublin, OH.

Nelson, R.A. 1982. Advances in Borehole Geophysics for Hydrology. In: Recent Trends in Hydrogeology, T.N. Narasimhan (ed.), GSA Special Paper 189, Geological Society of America, Boulder, CO, pp. 207-219. [ATV, dipmeter, EMI log]

Nelson, R.A. 1985. Geologic Analysis of Naturally Fractured Reservoirs. Contributions in Petroleum Geology and Engineering, Vol. 1, Gulf Publishing, Houston, TX, 320 pp.

Newman, J. and J. McDuff. 1988. Electric Wireline Methods for In Situ Capture of Wellbore Samples and Determining Their Flow Rates and Direction. In: Proc. 2nd Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 97-122. [caliper, gamma, neutron, temperature, fluid conductivity, flowmeter]

Newton, G.R., J.E. Skinner, and D. Silverman. 1954. Subsurface Formation Density Logging (Abstract). Geophysics 19(3):636-37.

Nielsen, D.M. and L. Aller. 1984. Methods for Determining the Mechanical Integrity of Class II Injection Wells. EPA/600/2-84/121 (NTIS PB84-215755), 263 pp. Also published in NWWA/EPA Series by National Water Well Association, Dublin, OH. [temperature, noise log, EM thickness, flowmeter, radioactive tracers, cement bond caliper, borehole television, seismic televiewer, radioactive tracing]

Norris, S.E. 1972. The Use of Gamma Logs in Determining the Character of Unconsolidated Sediments and Well Construction Features. Ground Water 10(6):14-21.

Olhoeft, G.R. 1988. Interpretation of Hole-to-Hole Radar Measurements. In: Proc. of the 3rd Technical Symposium on Tunnel Detection, Colorado School of Mines, Golden, CO (January 12-15, 1988), pp. 616-629.

Olhoeft, G.R. and J.H. Scott. 1980. Nonlinear Complex Resistivity Logging. In: Trans of SPWLA 21st Annual Logging Symposium.

Olhoeft, G.R., K.A. Sander, and J.E. Lucius. 1992. Surface and Borehole Radar Monitoring of a DNAPL Spill in DC versus Frequency, Look Angle, and Time. In: SAGEEP ’92, Society of Engineering and Mineral Exploration Geophysicists, Golden, CO, pp. 455-469.

Paillet, F.L. 1984. Well Log Characterization of Fractured Rock Hydrology. 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. 743-761.

Paillet, F.L. 1989a. A Generalized Approach to Geophysical Well Log Analysis and Interpretation in Hydrogeology. In: Proc. Conf. on New Field Techniques for Quantifying the Physical and Chemical Properties of Heterogeneous Aquifers, National Water Well Association, Dublin, OH, pp. 99-120.

Paillet, F.L. 1989b. Analysis of Geophysical Well Logs and Flow Meter Measurements in Boreholes Penetrating Subhorizontal Fracture Zones, Lac Du Bonnet Batholith, Manitoba, Canada. U.S. Geological Survey Water Resources Investigation Report 89-4211.

Paillet, F.L. and J.E. White. 1982. Acoustic Modes of Propagation in the Borehole and Their Relationship to Rock Properties. Geophysics 47(8):1215-1228.

Paillet, F.L., A.E. Hess, C.H. Cheng, and E.L. Hardin. 1985. Effects of Lithology on Televiewer-Log Quality and Fracture Interpretation. In: Proc. SPWLA 26th Annual Logging Symposium, Society of Professional Well Log Analysts, Houston, TX, pp. JJJ1-JJJ31.

Paillet, F.L., C.H. Cheng, A.E. Hess, and E.L. Hardin. 1986. Comparison of Fracture Permeability Estimates Based on Tube-Wave Generation in Vertical Seismic Profiles, Acoustic Waveform-Log Attenuation, and Pumping Test Analysis. In: Proc. Surface and Borehole Geophysical Methods and Ground Water Instrumentation Conf. and Exp., National Water Well Association, Dublin, OH, pp. 398-416.

Paillet, F.L., A.E. Hess, C.H. Cheng, and E.L. Hardin. 1987. Characterization of Fracture Permeability with High Resolution Vertical Flow Measurements During Borehole Pumping. Ground Water 25:28-40. [thermal flowmeter]

Parizek, R.P. and S.H. Siddiqui. 1970. Determining the Sustained Yield of Wells in Carbonate and Fractured Aquifers. Ground Water 8(5):12-20.

Patten, Jr., E.P. and G.D. Bennett. 1962. Methods of Flow Measurements in Well Bores. U.S. Geological Survey Water-Supply Paper 1544-C, 28 pp.

Patten, Jr., E.P. and G.D. Bennett. 1963. Application of Electrical and Radioactive Well Logging to Groundwater Hydrology. U.S. Geological Survey Water-Supply Paper 1544-D, 60 pp. [resistivity, SP, fluid conductivity, gamma]

Pedlar, W.H., MJ. Barvenik, C.F. Tsang, and F.V. Hale. 1990. Determination of Bedrock Hydraulic Conductivity and Hydrochemistry Using a Wellbore Fluid Logging Method. In: Proc. Fourth Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods. Ground Water Management 2:39-53.

Pedlar, W.H., C.L. Head and L.L. Williams. 1992. Hydrophysical Logging A New Wellbore Technology for Hydrogeologic and Contaminant Characterization of Aquifers. In: Ground Water Management 11:701-715 (Proc. of the 6th NOAC). [fluid conductivity]

Peterson, B.R. 1991. Borehole Geophysical Logging Methods for Determining Apparent Water Resistivity and Total Dissolved Solids: A Case Study. In: Ground Water Management 5:1047-1056 (5th NOAC). [gamma, caliper, gamma-gamma induction] --

Peterson, F.L. and C. Lao. 1970. Electric Well Logging of Hawaiian Basaltic Aquifers. Ground Water 8(2):11-18.

Pfannkuch, H.-O. 1966. The Application of Geophysics to Water Resources. In Proc. 2nd Annual American Water Resource Conference, American Water Resource Association Proc. Series 2, pp. 287-297.

Pickell, J.J. and J.G. Heacock. 1960. Density Logging. Geophysics 25:891-904.

Pickett, G.R. 1960. The Use of Acoustic logs in the Evaluation of Sandstone Reservoirs. Geophysics 25:250-274.

Pickett, G.R. 1966. Prediction of Intrazone Fluid Communication Behind Casing by Use of Cement Bond Log. In: Trans. 7th Annual Logging Symp., Society of Professional Well Log Analysts, Tulsa, OK pp. J1-J27.

Pickett, G.R. 1970. Applications for Borehole Geophysics in Geophysical Exploration. Geophysics 35(1):81-92.

Pirson, S.J. 1963. Handbook of Well. Log Analysis for Oil and Gas Formation Evaluation. Prentice-Hall, Englewood Cliffs, NJ, 326 pp.

Pirson, S.J. 1983. Geologic Well Log Analysis, 3rd ed. Gulf Publishing Co., Houston, TX. [SP, Eh, dipmeter; earlier editions 1970, 1977]

Poeter, E.P. 1987. Perched Water Identification with Radiation Logs. In: Proc. of the NWWA Focus Conf. on Northwestern Ground Water Issues (Portland, OR), National Water Well Association, Dublin, OH, pp. 312-327. [neutron, gamma-gamma]

Poeter, E.P. 1988. Perched Water Identification with Nuclear Logs. Ground Water 26(1):15-21. [neutron, gamma-gamma]

Poirmeur, C. and G. Vasseur. 1988. Three-Dimensional Modeling of a Hole-to-Hole Electrical Method: Application to the Interpretation of a Field Survey. Geophysics 53:402-414.

Poland, J.F. and R.B. Morrison. 1940. An Electrical Resistivity-Apparatus for Testing Well-Waters. Trans. Am. Geophys. Union 21:35-46.

Poole, V.L., K. Cartwright, and D. Leap. 1989. Use of Geophysical Logs to Estimate Water Quality of Basal Pennsylvanian Sandstones, southwestern Illinois. Ground Water 27(5):682-688. [See also 1990 discussion by J. Logan and reply in Ground Water 28(1) :118-119.]

Potts, R.L. 1991. Use of Borehole Geophysics for Stratigraphic Analysis and Horizon Delineation. In: Ground Water Management 7563-579 (8th NWWA Eastern Ground Water Conference). [caliper, SP, SP resistance, gamma]

Pratt, R.G. and M.H. Worthington. 1988. The Application of Diffraction Tomography to Crosshole Seismic Data. Geophysics 53:1284-1294.

Prensky, S.E. (Various dates.) Log Analyst Geologic Applications Bibliographies. Geological Applications of Well Logs-An Introductory Bibliography and Survey of Well Logging Literature Through September 1986, Arranged by Subject and First Author (Log Analyst, 1987: Parts A and B 28(1) :71-107 Part C 28(2):219-248); Annual Update, October 1986 through September 1987 (Log Analyst, 1987: 28(6):558-575); Bibliographic Update for October 1987 through September 1988 (Log Analyst, 1988: 29(6):426-443); Bibliography of Well Log Applications: October 1988-September 1989 Annual Update (Log Analyst, 1989 30(6):448-470); October 1989-September 1990 Annual Update (Log Analyst, 1990:31(6):395-424).

Pryor, W.A. 1956. Quality of Groundwater Estimated from Electric Resistivity Logs. Illinois State Geological Survey Circular 215, 15 pp.

Quirein, J.A., J.S. Gardner, and J.T. Watson. 1982. Combined Natural Gamma Ray Spectral/Lith-Density Measurements Applied to Complex Lithologies. Soc. of Petrol. Eng. of AIMME, Paper SPE 11143, 14 pp.

Rabe, C.L. 1956. A Relation Between Gamma Radiation and Permeability of Denver-Julesburg Basin. Trans. Petrol. Div. AIMME 210:358-460.

Redwine, J. et al. 1985. Groundwater Manual for the Electric Utility Industry, Vol. 3: Groundwater Investigations and Mitigation Techniques. EPRI CS-3901. Electric Power Research Institute, Palo Alto, CA. [Section 3 covers surface and borehole geophysical methods.]

Reed, P.C. 1985. Comparative Analysis of Surface Resistivity Surveys and Natural-Gamma Radiation Borehole Logs in Illinois. In: Conference on Surface and Borehole Geophysical Methods and Ground Water Investigations (2nd, Fort Worth, TX), National Water Well Association, Dublin, OH, pp. 215-227.

Reed, P.E., P.D. DuMontelle, M.L. Sargent and M.M. Killey. 1983. Nuclear Logging and Electrical Earth Resistivity Techniques in the Vadose Zone in Glaciated Earth Materials. In: Proc. NWWA/EPA Conf. on Characterization and Monitoring in the Vadose (Unsaturated) Zone (lst, Las Vegas, NV), National Water Well Association, Dublin, OH, pp. 580-601.

Rehfeldt, K.R. 1989. Application of the Borehole Flowmeter Method to Measure the Spatially Variable Hydraulic Conductivity at the Macro-Dispersion Experiment (MADE) Site. In: Proc. Conf. on New Field Techniques for Quantifying the Physical and Chemical Properties of Heterogeneous Aquifers, National Water Well Association, Dublin, OH, pp. 419-444.

Rehm, B.W., T.R. Stolzenburg, and D.G. Nichols. 1985. Field Measurement Methods for Hydrogeologic Investigation: A Critical Review of the Literature. EPRI EA-4301. Electric Power Research Institute, Palo Alto, CA. [Section 5 covers electrical, nuclear, acoustic, and flow logs.]

Respold, H. 1989. Well Logging in Groundwater Development. International Contributions to Hydrogeology, Vol. 9, International Association of Hydrogeologists, Verlag Heinz Heise, Hannover, West Germany, 147 pp.

Richardson, Jr., W.K, G.L. Kirkpatrick, and S.P. Cline. 1989. Integration of Borehole Geophysics and Aquifer Testing to Define a Fractured Bedrock Hydrogeologic System. In: Superfund ’89, Proceedings of the 10th Annual Conference, Hazardous Material Control Research Institute, Silver Spring, MD, pp. 277-281.

Rider, M.H. 1986. The Geological Interpretation of Well Logs. Halstead Press, New York, 175 pp. [SP, resistivity, induction, gamma, spectral gamma, gamma-gamma, neutron, acoustic]

Ring, G.T. and T.C. Sale. 1987. Evaluation of Well Field Contamination Using Downhole Geophysical Logs and Depth-Specific Samples. In: Superfund ’87, Proceedings of the 8th Annual Conference, Hazardous Material Control Research Institute, Silver Spring, MD, pp. 320-325.

Ritchey, J.D., 1986. Electronic Sensing Devices Used for In Situ Ground Water Monitoring. Ground Water Monitoring Review 6(2):108-113.

Robbins, S.L. 1986. The Use of Borehole Gravimetry in Water Well and Waste Disposal Site Evaluations. In: Proc. Surface and Borehole Geophysical Methods and Ground Water Instrumentation Conf. and Exp., National Water Well Association, Dublin, OH, pp. 474-496.

Robbins, G.A. and J.M. Hayden. 1988. Application of Cross-Well Voltage Measurements for Assessing Fracture Flow Hydrology. In Proc. of the Focus Conf. on Eastern Regional Ground Water Issues (Stanford CT), National Water Well Association, Dublin, OH, pp. 28-38.

Ross, S.H. and G. Adcock. 1969. Direct Conductance Method of Measuring Casing Lengths. Ground Water 7(4):26-27.

Ross, H.P. and S.H. Ward 1984. Borehole Electrical Geophysical Methods: A Review of the State-of-the-Art and Preliminary Evaluation of the Application to Fracture Mapping in Geothermal Systems. Earth Science Laboratory, Univ. of Utah Res. Inst. Rep. 12196-2.

Roy, A. 1975. New Results in Resistivity Well Logging. Geophysical Prospecting 23(3):426-448. Corrections and Comments in Geophysical Prospecting 24(1):210, 24(2):401-408, 25(3):553-559, 26(2):481-485.

Roy, A. 1982. Focused Resistivity Logs. Developments in Geophysical Exploration Methods 3:61-94.

Russell, W.L. 1941. Well Logging by Radioactivity. Am. Assn. Petrol. Geol. Bull. 25(9):1768-1788.

Rutkowski, M.A. and R.W. Taylor. 1990. A Geophysical Study of the Radioactive Contamination of the Sandstone Aquifer of Eastern Wisconsin. In: Ground Water Management 3:343-357 (7th NWWA Eastern GW Conference). [gamma, gamma-gamma,neutron, spectral gamma]

Sandberg, E. V., O.L. Olsson, and L.R. Falk. 1991. Combined Interpretation of Fracture Zones in Crystalline Rocks Using Single-Hole, Crosshole Tomography, and Directional Borehole-Radar Data. The Log Analyst, March-April, pp. 108-118.

Schaar, R.G. 1992. The Borehole Televiewer and the Formation Microscanner: Two Innovative Ways to Detect and Evaluate Subsurface Fractures. In: Ground Water Management 11:17-30 (Proc. of the 6th NOAC).

Schimschal, U. 1981. The Relationship of Geophysical to Hydraulic Conductivity at the Brantley Dam Site, New Mexico. Geoexploration 19:115-125. [neutron probe]

Schlichter, C. 1963. Principles of Magnetic Resonance. Harper and Row, New York, 397 pp.

Schlumberger Limited. 1972. Log Interpretation. Vol. I, Principles. Schlumberger Limited, New York.

Schlumberger Limited. 1974. Log Interpretation. Vol. II, Applications. Schlumberger Limited, New York.

Schlumberger Limited. 1989a. Log Interpretation Principles/Applications. Schlumberger Educational Services, Houston, TX. [Earlier edition published in 1987.] [SP, resistivity, induction, dielectric, gamma, gamma-gamma, neutron, acoustic-velocity, VSP]

Schlumberger Limited. 1989b. Cased Hole Log Interpretation Principles/Applications. Schlumberger Educational Services, Houston, TX. [gamma, spectral gamma, neutron, neutron lifetime, acoustic velocity, spinner flowmeter, temperature, various well construction logs]

Schlumberger Limited. 1991. Log Interpretation Charts. Schlumberger Limited, New York. [Earlier charts published in 1972, 1976, 1979, 1984.]

Schneider, GJ. 1982. In Situ Neutron Activation Analysis. In Premining Investigations for Hardrock Mining, U.S. Bureau of Mines Information Circular 8891, pp. 46-54. [neutron activation, spectral gamma]

Schneider, G.W. and J.P. Greenhouse. 1992. Geophysical Detection of Perchloroethylene in a Sandy Aquifer Using Resistivity and Nuclear Logging Techniques. In: SAGEEP '92, Society of Engineering and Mineral Exploration Geophysicists, Golden, CO, pp. 619-628.

Sciacca, J. 1991. Application of Geophysical Logs in Determining Depositional Environments for Hydrogeologic Investigations of contaminated Sites. In: Ground Water Management 5:1057-1071 (5th NOAC). [gamma, SP, SP resistance, resistivity]

Scott, J.H. 1977. Borehole Compensation Algorithms for a Small-Diameter, Dual Detector Density Well-Logging Probe. Trans. SPWLA 18th Annual Logging Symposium, pp. S1-S17. [gamma-gamma]

Scott, J.H. and B.L. Tibbets. 1974. Well Log Techniques for Mineral Deposit Evaluation: A Review. U.S. Bureau of Mines Information Circular 3627, 45 pp.

Scott, J.H., R.L. Seeley, and J.J. Barth. 1981. A Magnetic Susceptibility Well Logging System for Mineral Exploration. In: Trans. SPWLA 22nd Annual Logging Symposium.

Segesman, F.F. 1980. Well-Logging Method. Geophysics 45(11):1667-1684.

Senger, J.A. 1985. Defining Glacial Stratigraphy with the Neutron Log. In: NWWA Conf. on Surface and Borehole Geophysical Methods in Ground Water Investigations (2nd Fort Worth, TX), National Water Well Association, Dublin, OH, pp. 355-370.

Serra, O. 1984a. Fundamentals of Well-Log Interpretation, 1: The Acquisition of Logging Data. Developments in Petroleum Science, Vol. 15A. Elsevier, New York, 423 pp. [SP, resistivity, gamma, gamma spectrometry, gamma-gamma neutron, neutron activation/lifetime, acoustic, dielectric caliper, temperature, dipmeter, acoustic televiewer, VSP, nuclear magnetic resonance]

Serra, O. 1984b. Fundamentals of Well-Log Interpretation, 2: The Interpretation of Logging Data. Developments in Petroleum Science, Vol. 15B. Elsevier, New York, 684 pp. [Chapters focus on log interpretation for specific applications-sedimentary structure, fractures, etc.]

Serra, O., J. Baldwin, and J. Quirein. 1980. Theory and Interpretation, and Practical Application of Natural Gamma Spectroscopy. In: Proc. 21st Annual Logging Symposium, Society of Professional Well Log Analysts, Houston, TX.

Sloto, R.A., P. Macchiaroli, and M.T, Towle. 1992. Identification of a Multiaquifer Ground-Water Cross-Contamination Problem in the Stockton Formation by Borehole Geophysical Methods, Hatboro, PA. In: SAGEEP '92, Society of Engineering and Mineral Exploration Geophysicists, Golden, CO, pp. 21-37.

Snelgrove, F.B. and J.D. McNeill. 1985. Theory and Design Considerations of a Borehole Electromagnetic Conductivity Probe. In: NWWA Conf. on Surface and Borehole Geophysical Methods in Ground Water Investigations (2nd Fort Worth, TX), National Water Well Association, Dublin, OH, pp. 339-354.

Society of Professional Well Log Analysts (SPWLA). 1960 to present. Annual Logging Symposium Transactions. SPWM Houston, TX. [32nd was held in 1991; recent price, $75 for two-volume set.]

Society of Professional Well Log Analysts (SPWLA). 1978a. Gamma Ray, Neutron, and Density Logging. Reprint Volume Series, SPWM Houston, TX.

Society of Professional Well Log Analysts (SPWLA). 1978b. Acoustic Logging. Reprint Volume Series, SPWW Houston, TX.

Society of Professional Well Log Analysts (SPWLA). 1979. The Art of Ancient Log Analysis. SPWLA, Houston, TX, 131 pp.

Society of Professional Well Log Analysts (SPWLA). 1985. Glossary of Terms and Expressions Used in Well Logging, Revised. SPWLA Houston, TX. [lst ed. 1975]

Society of Professional Well Log Analysts (SPWLA). 1990. Borehole Imaging. Reprint Volume Series, SPWLA Houston, TX. [optical, acoustic, electrical]

Spencer, S.M. 1985. Stratigraphic Determinations and Correlations Based on Borehole Geophysics. In: NWWA Conf. on Surface and Borehole Geophysical Methods in Ground Water Investigations (2nd Fort Worth, TX), National Water Well Association, Dublin, OH, pp. 326-338.

Stegner, R. and R. Becker. 1988. Borehole Geophysical Methodology Analysis and Comparison of New Technologies for Ground Water Investigation. In: Proc. 2nd Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 987-1014.

Stewart, R.R. 1991. Seismic Tomography. Course Notes No. 3. Society of Exploration Geophysicists, Tulsa, OK ,190 pp.

Stewart, R. R., R.M. Turpening, and M.N. Toksoz. 1981. Study of Subsurface Fracture Zone by Vertical Seismic Profiling. Geophys. Res. Lett. 8:1132-1135.

Stokoe, II, K.H. 1980. Field Measurement of Dynamic Soil Properties. In: Proc. Second ASCE Conf. on Civil Engineering and Nuclear Power, Vol II: Geotechnical Topics (Knoxville, TN), pp. 7-1-1 to 7-1-31.

Stokoe, II, K.H. and S. Nazarian. 1985. Use of Rayleigh Waves in Liquefaction Studies. In: Measurement and Use of Shear Wave Velocity in Evaluation Dynamic Soil Properties, R.D. Wood (ed.), Proc. Geotechnical Engineering Division, ASCE, pp. 1-17.

Stowell, J.R. 1989a. An Overview of Borehole Geophysical Methods for Solving Engineering and Environmental Problems. In: Proc. Third Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 871-890.

Stowell, J.R. 1989b. An Overview of Borehole Methods for Solving Engineering and Environmental Problems. In: Proc. (2nd) Symp. on the Application of Geophysics to Engineering and Environmental Problems, Soc. Eng. and Mineral Exploration Geophysicists, Golden, CO, pp. 290-309.

Streitz, A. 1987. Off-End Surface Seismic Reflection Sounding with Vertical Seismic Profiling in Glacial Terrain. In: Proc. First Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 525-537. [SRR, VSP]

Stromswold, D.C. and R.D. Wilson. 1981. Calibration and Data Correction Techniques for Spectral Gamma-Ray Logging. Trans. SPWLA 22nd Annual Logging Symposium, pp. M1-M18.

Sturges, F.C. 1967. Underground Surveys with Borehole Cameras. In: 12th Symp. on Exploration Drilling, Univ. of Minnesota School of Mines and Metal. Eng., Minneapolis, pp. 39-52.

Suprahitho, M. and S.A. Greenhalgh. 1986. Theoretical Vertical Seismic Profiling Seismograms. Geophysics 51(6):1252-1265.

Sutcliffe, Jr., H. and B.F. Joyner. 1966. Packer Testing in Water Well near Sarasota, Florida. Ground Water 4(2):23-27. [caliper, fluid conductivity, temperature]

Syms, M.C. 1982. Downhole Flowmeter Analysis Using an Associated .Caliper Log. Ground Water 20(5):606-610.

Taylor, T.A. 1986. Application of Gamma-Spectral Logging to Ground-Water Investigations. In: Proc. Surface and Borehole Geophysical Methods and Ground Water Instrumentation Conf. and Exp., National Water Well Association, Dublin, OH, pp. 527-544.

Taylor, K. 1989. Review of Borehole Methods for Characterizing the Heterogeneity of Aquifer Hydraulic Properties. In: Proc. Conf. on New Field Techniques for Quantifying the Physical and Chemical Properties of Heterogeneous Aquifers, National Water Well Association, Dublin, OH, pp. 121-132.

Taylor, T.A. and J.A. Dey. 1985. Bibliography of Borehole Geophysics as Applied to Ground-Water Hydrology. U.S. Geological Survey Circular 926, 62 pp.

Taylor, K. and S. Wheatcraft. 1986. Use of Borehole Geophysics to Define Hydrologic Conditions-A Field Example. In: Proc. Surface and Borehole Geophysical Methods and Ground Water Instrumentation Conf. and Exp., National Water Well Association, Dublin, OH, pp. 215-238. [gamma-gamma, induction]

Taylor, K.C., S.W. Wheatcraft, and L.G. McMillion. 1985. A Strategy for the Hydrologic Interpretation of Well Logs. In: NWWA Conf. on Surface and Borehole Geophysical Methods in Ground Water Investigations (2nd Fort Worth, TX), National Water Well Association, Dublin, OH, pp. 314-325.

Taylor, K.C., F. Molz, and J.S. Hayworth. 1988. A Single Well Electrical Tracer Test for the Determination of Hydraulic Conductivity and Porosity as a Function of Depth. In: Proc. 2nd Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 925-938.

Taylor, K. C., J.W. Hess, and A. Mazzella. 1989. Field Evaluation of a Slim-Hole Borehole Induction Tool. Ground Water Monitoring Review 9(1):100-104.

Taylor, K., J. Hess, and S. WheatCraft. 1990. Evaluation of Selected Borehole Geophysical Methods for Hazardous Waste Site Investigations and Monitoring. EPA/600/4-20/029, 82 pp. U.S. EPA Environmental Monitoring Systems Laboratory, Las Vegas, NV.

TearPock, D. and R.E. Bischke. 1991. Applied Subsurface Geological Mapping. Prentice Hall, Englewood Cliffs, NJ, 648 pp. [Focuses on construction of geological maps from various sources, including geophysical measurements.]

Teasdale, W.E. and A.I. Johnson. 1970. Evaluation of Installation Methods for Neutron-Meter Access Tubes. U.S. Geological Survey Professional Paper 700-C, pp. 237-241.

Technos, Inc. 1992. Application Guide to Borehole Geophysical Logging. Technos, Miami, FL, 15 pp.

Telford, W.M.N., L.P. Geldart, R.E. Sheriff, and D.A. Keys. 1990. Applied Geophysics, 2nd ed. Cambridge University Press, New York, 770 pp. [lst ed. 1976, reprinted 1982] [Chapter 11 covers borehole geophysics: SP, resistivity, dipmeter, induction, IP, acoustic, nuclear, gravity, magnetic, temperature.]

Tellam, J.H. 1992. Reversed Flow Test: A Borehole Logging Method for Estimating Pore Water Quality and Inflow Rates Along an Uncased Borehole Profile. Ground Water Monitoring Review 12(2):146-154. [fluid conductivity log]

Testa, S.M. 1988. Benefits of Downhole Geophysical Methods in Low Permeability Hydrogeologic Environments. In: Proc. 2nd Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 969-985.

Theys, P.P. 1991. Log Data Acquisition and Quality Control. Editions Technip, Paris, 326 pp.

Thomas, M.D. and D.F. Dixon (eds.). 1989. Proceedings of a Workshop on Geophysical and Related Geoscientific Research at Chalk River, Ontario. AECL-9085, Atomic Energy of Canada Limited. [25 papers on surface (GR, S, MAG, EM, ER, GPR) and borehole (electric, television, acoustic televiewer, spectral gamma)]

Thornhill, J.T. and B.G. Benefield. 1990. Injection-Well Mechanical Integrity. EPA/625/9-89/O07, 123 pp. Available from U.S. EPA Center for Environmental Research Information, Cincinnati, OH.

Thornhill, J.T. and B.G. Benefield. 1992. Detecting Water Flow Behind Pipe in Injection Wells. EPA/600/R-92/041, 82 pp. U.S. EPA R.S. Kerr Environmental Research Laboratory, Ada, OK. [neutron lifetime log]

Tittle, C.S. 1961. Theory of Neutron Logging I. Geophysics 26(1):27-39.

Tittman, J. 1986. Geophysical Well Logging. Academic Press, New York, 192 pp. [electrical, nuclear, sonic]

Tittman, J. and J.S. Wahl. 1965. The Physical Foundations of Formation Density Logging (Gamma-Gamma). Geophysics 30(2):284-294.

Tittman, J. et al. 1966. The Sidewall Epithermal Neutron Porosity Log. J. Petrol. Tech. 18(1):1351-1362.

Toksoz, M.N. and R.R. Stewart. 1984. Vertical Seismic Profiling, Part B: Advanced Concepts. Seismic Exploration Volume 14b, Geophysical Press, London, 419 pp.

Trainer, F.W. and J.E. Eddy. 1964. A Periscope for the Study of Borehole Walls and Its Use in Ground-Water Studies in Niagara County, New York. U.S. Geological Survey Professional Paper 501-D, pp. 203-206.

Tsang, C.F. and P. Hufschmied. 1988. A Borehole Fluid Conductivity Logging Method for the Determination of Fracture Inflow Parameters. LBL-23096. Lawrence Berekeley Laboratory, Berkeley, CA 19 pp.

Tsang, C., P. Hufschmied, and F.V. Hale. 1990. Determination of Fracture Inflow Parameters with a Borehole Fluid Conductivity Logging Method. Water Resources Research 26(4):561-578.

Tura, M.A.C., L.R. Johnson, E.L. Majer, and J.E. Peterson. 1992. Application of Diffraction Tomography to Fracture Detection. Geophysics 57(2):245-257.

Turcan, Jr., A.N. 1962. Estimating Water Quality from Electric Logs. U.S. Geological Survey Professional Paper 450-C, pp. 135-136.

Turcan, Jr., A.N. 1966. Calculation of Water Quality from Electrical Logs-Theory and Practice. Louisiana Geological Survey Water Resources Pamphlet 19,23 pp.

Turcan, Jr., A.N. and A.G. Winslow. 1970. Quantitative Mapping of Salinity, Volume and Yield of Saline Aquifers Using Borehole Geophysical Logs. Water Resources Research 6(5):1478-1481.

Turner, W.S. and J.H. Black. 1989. The Use of Geophysical Logs in the Characterization of a Structurally Complex Site. In: Proc. 3rd Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 909-919.

Tweeton, D.R. 1988. A Tomographic Computer Program with Constraints to Improve Reconstruction for Monitoring In Situ Mining Leachate. U.S. Bureau of Mines Report of Investigation 9159.

Tweeton, D.R., C.L. Cumerlato, J.C. Hanson, and H.L. Kuhlman. 1991. Field Tests of Geophysical Techniques for Predicting and Monitoring Leach Solution Flow During In Situ Mining. Geoexploration 28:251-268. [seismic tomography, CSAMT]

University of Tulsa. 1985. Index to Well Logging Literature, 1965 -1984. Tulsa, OK 399 pp.

Upp, J.E. 1966. The Use of the Cement Bond Log in Well Rehabilitation. In: Trans. SPWLA 7th Annual Logging Symp., Society of Professional WeII Log Analysts, Tulsa, OK, pp. X1-X11.

U.S. Army Corps of Engineers. 1979. Geophysical Exploration. Engineer Manual EM 1110-1-1802, Department of the Army, Washington, DC, 313 pp. [Section II of Chapter 3 covers borehole seismic, SP, resistivity, acoustic, gamma, gamma-gamma, neutron, temperature, caliper and fluid resistivity.]

U.S. Environmental Protection Agency (EPA). 1987. A Compendium of Superfund Field Operations Methods, Part 2. EPA/540/P-87/001 (OSWER Directive 9355.0-14) (NTIS PB88-181557/AS). [Section 8.3.4 covers borehole methods.]

U.S. Environmental Protection Agency (EPA). 1993. Subsurface Field Characterization and Monitoring Techniques: A Desk Reference Guide, Volume I: Solids and Ground Water. EPA/625/R-93/O03a. Available from EPA Center for Environmental Research Information, Cincinnati, OH. [Section 3 covers borehole geophysical methods.]

U.S. Nuclear Regulatory Commission. 1985. Rules and Regulations, Title 10, Chap. 1, Code of Federal Regulations, Part 20, Standards for Protection Against Radiation.

van der Leeden, F. 1991. Geraghty & Miller's Groundwater Bibliography, 5th ed Water Information Center, Plainview, NY, 507 pp.

Vonhof, J.A. 1966. Water Quality Determination from Spontaneous-Potential Electrical Log Curves. J. Hydrology 4(4):341-347.

Voytek, J. 1982. Applications of Downhole Geophysical Methods in Ground Water Monitoring. In: Proc. Second Nat. Symp. on Aquifer Restoration and Ground Water Monitoring, National Water Well Association, Dublin, OH, pp. 276-278.

Wahl, J.S. 1983. Gamma-Ray Logging. Geophysics 48(11):1536-1550.

Walstrom, J.E. 1952. The Quantitative Aspects of Electric Log Interpretation. Trans. Am. Inst. Min. and Met. Engineers, Petroleum Division 195:47-58.

West, R.C. and S.H. Ward. 1988. The Borehole Controlled-Source Audiomagnetotelluric Response of a Three-Dimensional Fracture Zone. Geophysics 53(2):215-230.

Westphalen, O. 1991. The Application of Borehole Geophysics to Identify Fracture Zones and Define Geology at Two New England Sites. In: Ground Water Management 7:535-546. (8th NWWA Eastern GW Conference). [VOC contamination caliper, SP, SP resistance, temperature, gamma, gamma-gamma, neutron, acoustic televiewer]

Wheatcraft, S.W., K.C. Taylor, J.W. Hess, and T.M. Morris. 1986. Borehole Sensing Methods for Ground-Water Investigations at Hazardous Waste Sites. EPA/600/2-86/111 (NTIS PB87-132783).

Wiebenga, W.A., W.R. Ellis, B.W. Seatonberry, and J.T.G. Andrew. 1967. Radioisotopes as Ground Water Tracers. J. Geophysical Research 72:4081-4091.

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]

Williams, J.H., L.D. Carswell,, O.B. Lloyd and W.C. Roth. 1984. Borehole Temperature and Flow Logging in Selected Fractured Rock Aquifer in East Central Pennsylvania. In: NWWA/EPA Conf. on Surface and Borehole Geophysical Methods in Ground Water Investigations (1st, San Antonio, TX), National Water Well Association, Dublin, OH, pp. 842-852.

Wilt, M.J. and C.F. Tsang. 1985a. Monitoring of Subsurface Contaminants with Borehole/Surface Resistivity Measurements. Lawrence Berkeley Laboratory Report No. LBL-19106.

Wilt, M.J. and C.F. Tsang. 1985b. Monitoring Subsurface Contaminants with Borehole/Surface Resistivity Measurements. In: Conference on Surface and Borehole Geophysical Methods and Ground Water Investigations (2nd, Fort Worth, TX), National Water Well Association, Dublin, OH, pp. 167-177.

Wong, J. 1991. Seismic Transmission Tomography. In: Proc. (4th) Symp. on the Application of Geophysics to Engineering and Environmental Problems, Soc. Eng. and Mineral Exploration Geophysicists, Golden, CO, pp. 97-116.

Woods, R.D. 1978. Measurement of Dynamic Soil Properties. In: Proc, of the ASCE Geotechnical Engineering Specialty Conference, Earthquake Engineering and Soil Dynamics (Pasadena, CA), Vol. 1, pp. 91-178.

Woods, R.D. and K.H. Stokoe, II. 1985. Shallow Seismic Exploration in Soil Dynamics. In: Richart Commemorative Lectures, R.D. Woods (ed.), ASCE, Detroit MI, pp. 120-156.

Woodyard, D.G. 1984. Lithologic Changes in Aquifer in Southeastern Minnesota as Determined from Natural Gamma Borehole Logs. In: NWWA/EPA Conf. on Surface and Borehole Geophysical Methods in Ground Water Investigations (1st, San Antonio, TX), National Water Well Association, Dublin, OH, pp. 762-787.

Worthington, P.F. 1976. Hydrogeophysical Equivalence of Water Salinity, Porosity, and Matrix Conduction in Arenaceous Aquifers. Ground Water 14(4):224-232.

Wrege, B.M. 1986. Surface- and Borehole-Geophysical Surveys Used to Define Hydrogeologic Units in South-Central Arizona. In: Proc. Conf. on Southwestern Ground Water Issues (Tempe, AZ), National Water Well Association, Dublin, OH, pp. 485-499.

Wright,, D.L., R.D. Watts, and E. Bramsoe. 1984. A Short-Pulse Electromagnetic Transponder for Hole-to-Hole Use. IEEE Trans. on Geoscience and Remote Sensing GE-22(6):720-725. [cross-hole radar]

Wu, R. and M.N. Toksoz. 1987. Diffraction Tomography and Multisource Holography Applied to Seismic Imaging. Geophysics 52:11-25.

Wyllie, M.R.J. 1960. Log Interpretation in Sandstone Reservoirs. Geophysics 25(4):748-778. [induction and others]

Wyllie, M.R.J. 1963. The Fundamentals of Well Log Interpretation, 3rd ed Academic Press, New York, 238 pp. [Earlier editions 1954, 1957] [SP, resistivity, neutron, gamma-gamma, acoustic velocity, gamma, gamma-spectrometry, nuclear magnetic resonance, cement bond]

Yearsley, E.N., R.E. Crowder, and L.A. Irons. 1990a. Monitor Well Completion Evaluation with Geophysical Density Logging. In: Proc. (3rd) Symp. on the Application of Geophysics to Engineering and Environmental Problems, Soc. Eng. and Mineral Exploration Geophysicists, Golden, CO, pp. 349-364.

Yearsley, E.N., J.J. LoCoco, and R.E. Crowder. 1990b. Borehole Geophysics Applied to Fracture Hydrology. In: Ground Water Management 3:255-267 (7th NWWA Eastern Ground Water Conference). [acoustic waveform, temperature, resistivity, brine tracing]

Yearsley, E. N., R.E. Crowder, and L.A. Irons. 1991. Monitoring Well Completion Evaluation with Borehole Geophysical Density Logging. Ground Water Monitoring Review 11(1):103-118. [acoustic cement bond, gamma-gamma]

Young, S.C. and J.S. Pearson. 1990. Characterization of Three-Dimensional Hydraulic Conductivity Field with an Electromagnetic Borehole Flowmeter. In: Proc. Fourth Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods. Ground Water Management 2:83-97.

Young, S.C. and W.R. Waldrop. 1989. An Electromagnetic Borehole Flowmeter for Measuring Hydraulic Conductivity Variability. In: Proc. Conf. on New Field Techniques for Quantifying the Physical and Chemical Properties of Heterogeneous Aquifers (Dallas, TX), National Water Well Association, Dublin, OH, pp. 463-475.

Zemanak, J., R.L. Caldwell, E.E. Glenn, Jr., S.V. Holcomb, L.J. Norton and A.J.R. Strange. 1969. The Borehole Televiewer: A New Logging Concept for Fracture Location and Other Types of Borehole Inspection. J. Petroleum Technology 21(6):762-774.

Zemanak, J., E.E. Glenn, L.J. Norton, and R.L. Caldwell. 1970. Formation Evaluation by Inspection with the Borehole Televiewer. Geophysics 35(2):254-269.

# 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 | | | | | | Reference |
|---|---|---|---|---|---|---|---|---|---|
| | | | SR | ER | EMI | GPR | M | G | |
| 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 | Thermal | | | | 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 | | | | | | | Reference |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | SR | ER | EM | I | GPR | M | G | |
| 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 polari-zation, 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 resis-tance, 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 contami-nation 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 polari-zation, 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 resis-tance, 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 contami-nation 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) |

**References for Table A-1**


Adams, M.L., M.S. Turner, and M.T. Morrow. 1988. The Use of Surface and Downhole Geophysical Techniques to Characterize Flow in a Fracture Bedrock Aquifer System. In: Proc. 2nd Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 825-847.

Allen, R.P. and B.A. Rogers. 1989. Geophysical Surveys in Support of a Remedial Investigation/Feasibility Study at the Municipal Landfill in Metamora, Michigan. In: Proc. 3rd Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 1007-1020.

Berk, W.J. and B.S. Yare. 1977. An Integrated Approach to Delineating Contaminated Ground Water. Ground Water 15(2):138-145.

Blackey, M. and D.A. Stoner. 1988. Application of Seismic Refraction Analysis to Siting a Waste Disposal Facility over Carbonate Bedrock. In: Proc. 2nd Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 697-706.

Cartwright, K., and M.R. McComas. 1968. Geophysical Surveys in the Vicinity of Sanitary Landfills in Northeastern Illinois. Ground Water 6(5):23-30.

Cosgrave, T.M., J.P. Greenhouse, and J.F. Barker. 1987. Shallow Stratigraphic Reflections from Ground Penetrating Radar. In: Proc. 1st Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 555-569.

Emilsson, G.R. and R.T. Wroblewski. 1988. Resolving Conductive Contaminant Plumes in the Presence of Irregular Topography. In: Proc. 2nd Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 617-635.

Evans, R.B. and G.E. Schweitzer. 1984. Assessing Hazardous Waste Problems. Environ. Sci. Technol. 18(11):330A-339A.

Gilkeson, R.H., P.C. Heigold and D.E. Layman. 1986. Practical Application of Theoretical Models to Magnetometer Surveys on Hazardous Waste Disposal Sites-A Case History. Ground Water Monitoring Review 6(1):54-61.

Glaccum, R., M. Noel, R. Evans, and L. McMillion. 1983. Correlation of Geophysical and Organic Vapor Analyzer Data over a Conductive Plume Containing Volatile Organies. In: Proc. 3rd Nat. Symp. on Aquifer Restoration and Ground Water Monitoring, National Water Well Association, Dublin, OH, pp. 421-427.

Greenhouse, J.P. and R.D. Harris. 1983. Migration of Contaminants in Groundwater at a Landfill: A Case Study 7. DC, VLF, and Inductive Resistivity Surveys. J. Hydrology 63:177-197.

Hall, D.W. and D.L. Pasicznyk. 1987. Application of Seismic Refraction and Terrain Conductivity Methods at a Ground Water Pollution Site in North-Central New Jersey. In: Proc. 1st Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 505-524.

Kelly, W.E. 1976. Geoelectric Sounding for Delineating Ground-Water Contamination. Ground Water 14:6-10.

Knuth, M. 1988. Complementary Use of EM-31 and Dipole-Dipole Resistivity to Locate the Source of Oil Brine Contamination. In: Proc. 2nd Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 583-595.

Ladwig, K.J. 1983. Electromagnetic Induction Methods for Monitoring Acid Mine Drainage. Ground Water Monitoring Review 3(1):46-57.

Lyverse, M.A. 1989. Surface Geophysical Techniques and Test Drilling Used to Assess Ground-Water Contamination by Chloride in an Alluvial Aquifer. In: Proc. 3rd Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 993-1006.

Mills, T., L. Evans, and M. Blohm. 1987. The Use of Time Domain Electromagnetic Soundings for Mapping Sea Water Intrusion in Monterey, Co., Ca.: A Case History. In: Proc. 1st Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Asociation, Dublin, OH, pp. 601-622.

Morgenstern, K.A. and T.L. Syverson. 1988. Determination of Contaminant Migration in Vertical Faults and Basalt Flows with Electromagnetic Conductivity Techniques. In: Proc. 2nd Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 597-615

Ringstad, C.A. and D.C. Bugenig. 1984. Electrical Resistivity Studies to Delimit Zones of Acceptable Ground Water Quality. Ground Water Monitoring Review 4(4):66-69.

Roberts, R. G., W.J. Hinze, and D.I. Leap. 1989. A Multi-Technique Geophysical Approach to Landfill Investigations. In: Proc. 3rd Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 797-811.

Rodrigues, E.B. 1987. Application of Gravity and Seismic Methods in Hydrogeological Mapping at a Landfill Site in Ontario. In: Proc. 1st Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 487-504.

Rogers, R.B. and W.F. Kean. 1980. Monitoring Groundwater Contamination at a Fly-Ash Disposal Site Using Surface Electrical Resistivity Methods. Ground Water 18:472-478.

Rudy, R.J. and J.A. Caoile. 1984. Utilization of Shallow Geophysical Sensing at Two Abandoned Municipal/Industrial Waste Landfills on the Missouri River Floodplain. Ground Water Monitoring Review (Fall) pp. 57-65.

Saunders, W.R. and S.A. Cox. 1987. Use of an Electromagnetic Induction Technique in Subsurface Hydrocarbon Investigations. In: Proc. 1st Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 585-600.

Saunders, W.R. and R.M. Germeroth. 1985. Electromagnetic Measurements for Subsurface Hydrocarbon Investigations. In: Proc. NWWA/API Conf. Petroleum Hydrocarbons and Organic Chemicals in

Ground Water—Prevention, Detection and Restoration, 1985, National Water Well Association, Dublin, OH, pp. 310-321.

Stewart, M.T. 1982. Evaluation of Electromagnetic Methods for Rapid Mapping of Salt-Water Interfaces in Coastal Aquifers. Ground Water 20:538-545.

Stewart, M. and R. Bretnall. 1986. Interpretation of VLF Resistivity Data for Ground Water Contamination Surveys. Ground Water Monitoring Review 6(.1):71-75.

Stollar, R.L. and P. Roux. 1975. Earth Resistivity Surveys-A Method for Defining Ground-Water Contamination. Ground Water 13:145-150.

Sweeney, J.J. 1984. Comparison of Electrical Resistivity Methods for Investigation of Ground Water Conditions at a Landfill Site. Ground Water Monitoring Review 4(1):52-59.

Walsh, D.C. 1988. Integration of Surface Geophysical Techniques for Landfill Investigation: A Case Study. In: Proc. 2nd Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 753-778.

White, R.B. and R.B. Gainer. 1985. Control of Ground Water Contamination at an Active Uranium Mill. Ground Water Monitoring Review 5(2):75-82.

References for Table A-2

**See glossary for meaning of method abbreviations.**

Adams, M.L., M.S. Turner, and M.T. Morrow. 1988. The Use of Surface and Downhole Geophysical Techniques to Characterize Flow in a Fracture Bedrock Aquifer System. In: Proc. 2nd Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 825-847.

Crowder, R.E., L. Brouillard, and L. Irons. 1987. Utilizing A Borehole Geophysical Logging Program in Poorly Consolidated Sediments for a Hazardous Waste Investigation: A Case History. In: Proc. 2nd Int. Symp. on Borehole Geophysics for Minerals, Geotechnical and Groundwater Applications. pp. 65-75.

Dearborn, L.L. 1988. Borehole Geophysical Investigations of Fractured Rock at an EPA Superfund Site in Massachusetts. In: Proc. 2nd Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 875-895.

Foster, J.B. and D.A. Goolsby. 1972. Construction of Waste-Injection Monitor Wells Near Pensaeola, Florida. Florida Bureau of Geology Information Circular 74.

Ring, G.T. and T.C. Sale. 1987. Evaluation of Well Field Contamination Using Downhole Geophysical Logs and Depth-Specific Samples. In: Superfund ’87, Proceedings of the 8th Annual Conference, Hazardous Material Control Research Institute, Silver Spring, MD, pp. 320-325.

Testa, S.M. 1988. Benefits of Downhole Geophysical Methods in Low Permeability Hydrogeologic Environments. In: Proc. 2nd Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 969-985.

Turner, W.S. and J.H. Black. 1989. The Use of Geophysical Logs in the Characterization of a Structurally Complex Site. In: Proc. 3rd Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 909-919.

Westphalen, O. 1991. The Application of Borehole Geophysics to Identify Fracture Zones and Define Geology at Two New England Sites. In: Ground Water Management 7:535-546. (8th NWWA Eastern GW Conference). [VOC contamination; caliper, SP, SP resistance, temperature, gamma, gamma-gamma, neutron, acoustic televiewer]

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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