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Locating Abandoned Wells: A Comprehensive Manual of Methods and Resources

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EXECUTIVE SUMMARY

Subsurface Technology, Inc. and their subcontractor, Zonge Engineering & Research Organization, Inc., were contracted by the Solution Mining Research Institute to conduct a Survey of Methods and Commercial Resources for Locating Abandoned Wells. The current volume is the result, presenting descriptions of methods that have been used, or have the potential for use, in detecting abandoned artificial penetrations. Included are descriptions of selected methods, explanations of the physical quantity being measured, discussions of procedures, cost estimates, and resources for procuring services to implement the methods.

The methods discussed are listed below in three phases:

Background Site Investigation

- Historical Research of State and Local Records, Site Interviews
- Surface and Aerial Reconnaissance
- Remote Sensing – Visible and Infrared Images

Geophysical Methods

- Magnetics
- Resistivity
- Self Potential
- Electrical Tomography
- Frequency Domain Electromagnetics
- Time Domain Electromagnetics
- Controlled Source Audio-Frequency Magnetotellurics
- Ground Penetrating Radar

Monitoring Wells

- Potentiometric Surface
- Fluid Sampling

The goal of this manual is to provide a resource to persons responsible for the safe operation of storage cavern facilities. No manual such as this can provide a prescriptive set of procedures to follow. Rather, the intent of this manual is to provide guidance for educated selection and supervision of service companies that provide the various methods.

1.0 INTRODUCTION

Abandoned, improperly plugged wells are potential conduits for migration of fluids from deep pressurized zones in the subsurface to lower pressured zones or to the surface. Operators of salt caverns where hydrocarbons are stored are seeking to assure the safety of these facilities by proactively investigating the area surrounding and overlying storage caverns to identify any such wells, and mitigate any potential risk. This manual of methods is a result of the Solution Mining Research Institute's efforts to assist operators of these facilities to procure resources and implement effective investigations to identify abandoned wells.

The primary challenges to locating previously undetected abandoned wellbores flow from the same reasons that they are previously undetected. They are usually concealed below the ground surface, or they are in remote areas. Direct excavation to find wellbores is impractical over large areas, so abandoned well searches depend heavily on non-invasive techniques. These include methods for locating wells by searching historical records and reconnaissance of the area, and methods that detect physical properties of wellbores and well materials. This manual presents descriptions of various methods considered to be appropriate for this purpose.

There have been remarkably few problems related to subsurface integrity of caverns over the history of cavern storage. However, one recent incident in Hutchinson, Kansas raised concern about potential leakage from abandoned wells in the vicinity of natural gas storage caverns. This incident, occurring on January 17, 2001 illustrates complex issues related to abandoned wells. Depressurization of a cavern in the Yaggy underground natural gas storage field was followed a few days later by explosions in the town. Extensive geological investigations found that the gas had migrated horizontally through porous and faulted zones, and eventually intercepted abandoned wells located approximately 8 miles from the point of origin, and underlying the town. While the problem in Hutchinson is isolated, the solution mining and cavern storage industry identified from this the need to address any possibility of a leak to the surface via an improperly plugged wellbore.

The concept of various paths of migration of leaking hydrocarbon is depicted in Figure 1-1.

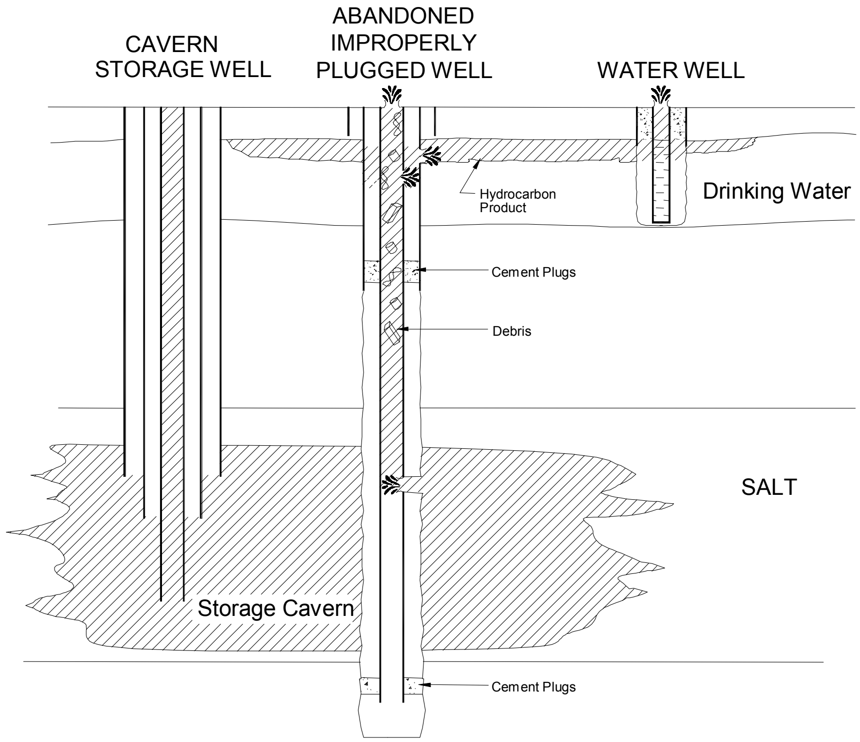

Figure 1-1. Hydrocarbon migration in an abandoned, improperly plugged well.

This figure depicts a well that is encountered by the expanding wall of a cavern in a bedded salt. A properly plugged well would provide an adequate seal against migration. However, the well depicted was not properly plugged, and the wellbore contains debris that may actually compromise the sealing qualities of drilling mud left in the tubing. Hydrocarbon is depicted entering the central tubing, and exiting at the surface, and at a break. The hydrocarbon then migrates up the annulus between the tubing and the outer casing to a shallow porous and permeable aquifer. It then moves laterally and exits to the surface via a shallow well. Some aspects of Figure 1-1 are worst-case, however, the figure depicts the concepts that hydrocarbon may migrate vertically by various paths within a single well, and laterally in porous zones to encounter another well.

This manual presents descriptions of methods, explanations of the physical quantity being measured, discussions of procedures, cost estimates, and resources for procuring services to implement the methods.

The methods discussed are listed below in three phases:

Background Site Investigation
- Historical Research of State and Local Records and Site Interviews
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- Frequency Domain Electromagnetics
- Time Domain Electromagnetics
- Controlled Source Audio-Frequency Magnetotellurics
- Ground Penetrating Radar

Monitoring Wells
- Potentiometric Surface
- Fluid Sampling

Initially, twenty-one methods were considered for inclusion in this manual. Appendix A lists these methods and discusses why they were not selected.

The goal of this manual is to provide a resource to persons responsible for the safe operation of storage cavern facilities. No manual such as this can provide a prescriptive set of procedures to follow. Rather, the intent of this manual is to provide guidance for educated selection and supervision of service companies that provide the various methods.

The following sections provide a short summary of background concepts and some guidance to the use of this manual and its contents.

2.0 BACKGROUND CONCEPTS

A storage cavern is developed by dissolving a cavity in a massive salt formation. Originally, these cavities formed as chemical companies solution-mined salt for feed stock to their processes. The potential for use of these cavities for storage was soon recognized. The requisite massive salt formations occur as either bedded salt or salt domes.

Bedded salt deposits underlie wide regions of mid-continental North America and other regions of the world. These formations are typically hundreds of feet thick. Salt is plastic at high temperatures and pressures, and this sealing property is one reason that hydrocarbons may be safely stored in the cavities formed by solution mining. Salt is also lower in density than most rock, and this has led to the formation of salt domes. Salt domes developed where massive bodies of salt were driven upward by density contrasts with the overlying rock. This massive migration of salt formed chimney-like "salt stocks" that are commonly hundreds of yards, to more than a mile across.

Successful oil exploration has long been associated with the same salt formations that are used for cavern storage. Salt domes and thick bedded salt form, by various geological processes, the traps against which hydrocarbons have accumulated in extractable quantities. This was recognized early in the history of drilling, and many wells were drilled in the vicinity of these formations. One result of this is the proximity of salt caverns and areas where many old oil and gas wells have been drilled.

2.1 History of Drilling

The history of deep drilling for oil and gas extends over approximately 150 years. In contrast to other of man's activities to extract wealth from the land, such as agriculture or mining, the period of oil drilling is relatively recent. During this 150-year period, much of what has occurred in a particular region has been documented to some degree, and this information may be used to assess the risk that abandoned wells are present.

Modern oil drilling dates back to 1859 when the first well for the purpose of oil extraction was drilled near Titusville, Pennsylvania. A steam engine was used to power the drill. Previous to this, oil had been extracted from seeps at the surface, or from seepage into mines. Drilling expanded rapidly, first in western Pennsylvania, then in Kentucky, Ohio, Illinois, and Indiana. During the 1890's and early 1900's, California, Oklahoma and Texas became the leading oil-producing states. In 1901, the first “gusher” was drilled at the Spindletop field in eastern Texas.

Oil production developed rapidly throughout the rest of the world. Production began in Italy in 1860, and soon followed in Canada, Poland, Peru, Germany, Russia, Venezuela, India, Indonesia, Japan, Trinidad, Mexico, and Argentina. Oil was discovered in the Middle East, in Iran in 1908, in Iraq in 1927 and in Saudi Arabia in 1938.

The correctness of these historical generalizations should be checked as part of investigating a particular locality. However, this general time line provides guidance as to the regions that were drilled most intensively during the earliest periods of oil exploration. Knowledge of the starting point for drilling in a given locality will guide subsequent detailed investigation of historical records (Section 6) to locate abandoned wells.

2.2 Drilling Methods

The first wells for oil production were drilled with “cable tool” methods. Cable tool drilling consisted of penetrating rock with a heavy chisel-like bit. The bit was suspended from a cable to a lever at the surface. Up and down motion was driven by steam in the earliest drilling. Broken rock was removed from the hole periodically with a basket-like device suspended on the cable.

Cable tool holes were successful where the hole could be maintained essentially dry and stable through most of its depth. Casing to stabilize the hole was often limited to the surface and unconsolidated horizons, and was not deep. Accordingly, the remaining and major portion of cable-tool holes were left uncased.

Mud-rotary drilling became wide-spread after 1900. For this type of drilling, a bit is rotated on the end of a long “drill-string” of pipe. Heavy sections of pipe, drill collars, are included in the drill-string just above the bit to provide downward force and maintain the hole straight. Drilling mud is pumped down the interior of the drill string and out through the bit. Mud is continuously circulated out through the bit and up the annulus between the drill string and the wall of the hole. The flowing mud cools the bit and carries rock debris or cuttings to the surface. Cuttings are removed from the mud at the surface, and the mud is recirculated.

2.3 Configurations of Abandoned Wells

The configuration of wellbores is determined primarily by the drilling and casing practices current at the time of drilling. The earliest water wells were excavated by shovel, and wood, stone or masonry were used to support the walls of the wellbore and maintain the opening. These wells cannot extend to depths of concern for directly penetrating storage caverns, and are not directly addressed in this manual. However, openings of this sort, and other shallow wells associated with septic systems and old "dry wells" may form conduits to the surface for gasses that have migrated upward via another path such as a wellbore, then migrated laterally in a shallow subsurface horizon.

Cable-tool drilled wells are possibly the greatest concern in regions where this method was practiced because they were drilled early in the history of oil exploration, before standards were adopted. These wells often consist of an open wellbore over a large portion of their length. This provides a ready conduit for migration among intervals and to the surface. Prior to the adoption of standards and regulations governing plugging, drillers used any convenient material to plug these wells. This included debris and trash from the drilling operation, and in some cases, a convenient tree trunk.

Wells that were drilled using mud-rotary techniques typically consist of the drilled hole, and one or more concentric sets of casing. Casing is usually carbon steel pipe. The presence of the pipe creates an annular space between the wall of the wellbore and the surface of the pipe, or between concentric "strings" of casing. The annulus is commonly filled with cement over at least a portion of its length. The remainder of the uncemented annulus typically contains drilling mud, although it may contain fluids or gas that have invaded the wellbore from surrounding formations. The presence of concentric "strings" of casing creates the possibility that concentric annuli may not be cemented in the same locations.

If the casing ruptures due to corrosion or physical forces, then staggered annular spaces may form a conduit for migration. These concepts are depicted for the well illustrated in Figure 1-1 of the Introduction. Hydrocarbon is migrating up the interior casing of the abandoned, improperly plugged well, then out to the annulus, prior to exiting the wellbore into a shallow zone.

Casing material, drilling mud and cement in the wellbore, have materials properties that contrast with those of the surrounding rock or soil. These properties include: density, compressive strength, electrical conductivities, magnetic properties and salt concentrations. This contrast in physical and chemical properties, between the wellbore and the surroundings is what may be detected by many of the techniques discussed in this manual.

Drilled wellbores display variation diameter, depth, and shape. Typical surface holes range from approximately 5 inches to 24 inches in diameter. Larger surface holes are necessary for deeper wells to accommodate the installation of progressively deeper, concentric strings of casing. Depths range from hundreds of feet to over 20,000 feet for exploration and production wells. While the basic shape of the wellbore is cylindrical, there is often variation due to shifting of the drill bit, and due to washout of weaker or less consolidated formations. Washouts may extend to more than twice the bit diameter, although this situation is avoided to the extent possible.

Drilling fluids may also migrate from the wellbore. Pressure of the drilling mud in the wellbore is usually adjusted by varying the density or mud weight. The goal is to maintain pressures in the wellbore slightly greater than in the surrounding formation to prevent the wellbore from closing on the drill string. This overpressure causes the drilling mud to migrate laterally out of the wellbore. Additionally, the fluid portion of the drilling mud may infiltrate the surrounding formations. Mud and fluid migration out of the wellbore may provide a region of contrasting conductivity and physical properties that can be detected by the methods described in this manual.

2.4 Detection and Location of Abandoned Wells

Site investigations for abandoned wells depend heavily on non-invasive techniques that sense physical properties of wellbores, casing materials, and impacts of fluids migrating from the wellbore. Table 2-1 categorizes some different types of well-related materials that may be targeted in a site investigation or geophysical survey for abandoned wells.

The primary objective is, of course, to detect and locate the actual wellbore. All well construction and abandonment materials could be considered direct targets for well detection (Type I targets, Table 2-1). This would include casings, well head or joints, and concrete abandonment plugs. This type of target is fairly easily located using geophysical methods such as ground magnetics or electromagnetics (EM), depending on casing material, depth, and surrounding material properties.

The second class of targets that might indicate the presence of a wellbore could be loosely termed 'Anomalous Conditions' (Type II targets). These conditions are anomalous in the sense that they create a contrast in physical or electrochemical properties that is beyond natural variation in the subsurface. This type of target may be the only indication left of the presence of an artificial penetration, if part or all of the well casing has been removed, and the borehole was improperly plugged. Targets of this nature would include anomalous fill in the borehole itself such as drilling mud, water, brine, or air; brine plumes which emanate from the borehole laterally into the surrounding formations; wash-outs or solution cavities in the vicinity of the borehole; or anomalous surface or soil conditions near the wellbore due to hydrocarbon contamination or brine disposal pits, for example. These would be considered indirect targets that are a direct consequence of the presence of a well.

Detection of anomalous conditions (Type II targets) related to wells will depend upon subtle contrasts in subsurface properties of the material in or near the wellbore versus surrounding material. For brine plumes and other anomalous conditions in this category, a geophysical survey will most often look at contrasts in the material property known as conductivity (ability to conduct an electric current). A highly saline plume, for example, will be more conductive than fresh groundwater. Figure 2-1 illustrates some possible origins of anomalous brines in the near-surface, including the upward movement of brine through an oil, gas, or deep, unplugged water well. Brines are highly conductive compared to fresh groundwater. The various salinity sources shown in Figure 2-1 may all be detected using electrical or EM geophysical methods; distinguishing natural sources from well-related sources may be accomplished by analyzing the patterns of conductivity, and by comparing conductivity anomalies with known information or other geophysical data such as magnetic signatures. Anomalous conditions that are confined to the borehole itself, and where no well-construction materials are left, will be the most difficult to image with surface geophysics.

A last class of targets that might indicate the nearby presence of abandoned wells is drilling or well-related structures and debris (Type III targets). This would include surface or buried evidence of infrastructure such as concrete pads or rebar, product lines, pumps heads, barrels, or other debris. Site investigations that detect these types of targets would be considered strong evidence that there may be a well or wells in the area. Detection and identification of these types of targets could serve to narrow the focus of an initial search area for further investigation.

TABLE 2-1

Classification of Abandoned Well Related Targets for Geophysical Surveys

Target Class	Example Targets
I. Well Construction Materials	• Well casings • Well head or joints • Concrete abandonment plugs
II. Anomalous Conditions	• Anomalous fill material in the wellbore or annulus (drilling mud, water, brine, clay, air) • Contamination plume (brine plume in freshwater aquifer, fluid leakage into the unsaturated zone, etc.) • Wash-outs or cavities in vicinity of the wellbore • Small voids or cavities due to wash-outs near the wellbore, or larger voids or solution caverns in soluble formations.
III. Well Related Structures and Debris	• Concrete pads • Pipes or production lines • Pump heads • Barrels or tanks • Other infrastructure or debris

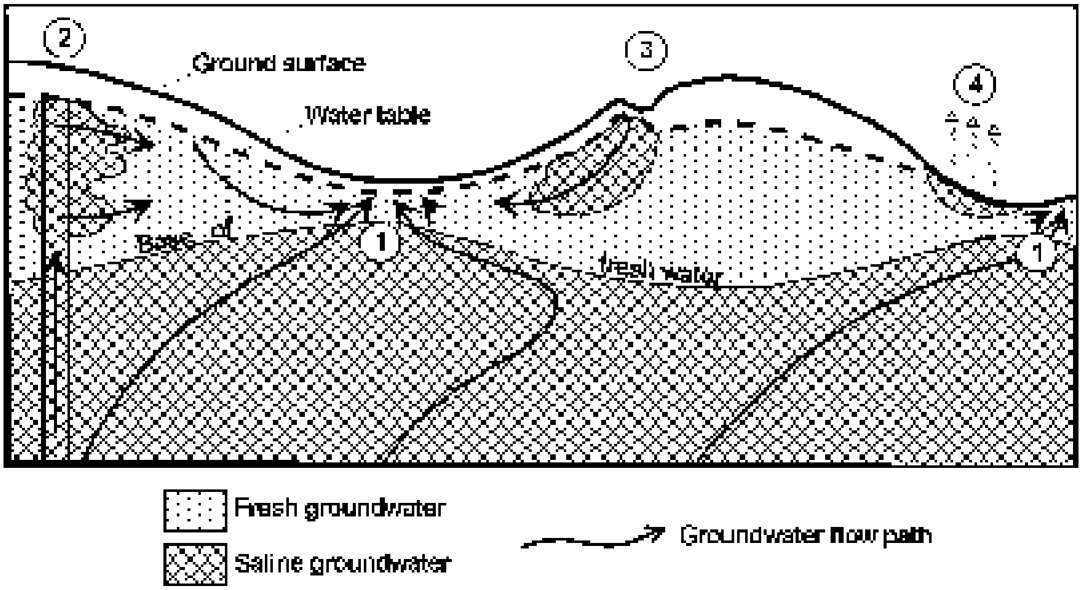

Figure 2-1. Conceptual model of salinity sources in the vicinity of oil-field operations. (1) natural discharge of brine through permeable stratigraphic units, fractures, and joints; (2) upward flow of brine through inadequately plugged and leaky boreholes; (3) infiltration of saline water beneath brine disposal pits; and (4) evaporative concentration of salts in shallow groundwater. (After Paine et al., 1997).

3.0 DESCRIPTION OF THE STUDY

The Solution Mining Research Institute contracted Subsurface Technology, Inc. of Houston, Texas to develop this manual of methods for detecting abandoned wellbores as an aid to operators of cavern storage facilities that are tasked with mitigating risks from these operations. Subsurface partnered with Zonge Engineering and Research Organization, Inc. to draw on the expertise of this firm in geophysical investigations.

Subsurface and Zonge conducted the study in phases: 1) research of the relevant literature and compilation of in-house knowledge, 2) development of lists of vendors and other information sources, and 3) description of methods as applied to cavern storage facilities or closely analogous sites.

4.0 HOW TO USE THIS MANUAL

The intended users of this manual are individuals that are responsible for safety and environmental and health concerns for storage cavern facilities. The goal of the manual is to provide usable information to guide supervision of the conduct of abandoned well searches in the vicinity of storage caverns.

Users may approach this manual as a quick reference, or for more in-depth reading. The following section contains a decision tree to assist the reader to understand and compare candidate methods. The reader may then read the detailed method descriptions to further evaluate their applicability. For readers that wish to browse the manual, each method description begins with a “bullet-list” overview that highlights features of the method.

The description of each candidate method should be read in detail to further understand applicability and limitations. The manual stresses that each of the detection and location methods described is sensitive to particular “signals” that result from materials left in a wellbore such as ferrous metal casing, physical properties of wellbores that are anomalous, relative to surrounding rock or soil, or impacts of the well on the immediate surroundings such as brine contamination.

5.0 HOW TO BEGIN AN ABANDONED WELL INVESTIGATION

An investigation of abandoned wells begins with determining the possible paths of migration that hydrocarbon might take, and the land area that might be reached by migrating hydrocarbon via these paths. Paths of migration might be through a well that directly intersects a cavern, or (more likely) through a well that intersects a porous and permeable zone where migrating hydrocarbon moves laterally. The spatial distribution of the area at-risk, the area of investigation, may then be delineated using the description of potential paths, and detailed geological knowledge of the actual locations and aerial size of these paths.

Delineation of the area of investigation is critical for effectively mitigating risk, and efficiently utilizing scarce resources. This process requires the input of qualified geologists, reservoir engineers, and engineers familiar with the physical properties of stored hydrocarbons and the operational parameters of the cavern.

The material above implies that early stages (and indeed all stages) of investigation cannot be prescribed precisely in a manual. This is because so much depends on a thorough site-specific analysis by qualified geologists and engineers of all potential distances and directions for hydrocarbon migration. Notwithstanding, the list of phases that follows constitutes a broad program for mitigating the risk of undetected, abandoned wells. This will help put the subject of this manual in the proper order and context.

Phase 1. Geological Investigation: A qualified geologist should compile information from well logs and other sources to develop a thorough description of potential routes of migration by stored hydrocarbons. This should include (but not be limited to) descriptions of the following:

- Porous and permeable zones above, lateral to and below the cavern: Depths, thickness, structure (description of slope, and presence of high and low spots), and lateral extent of porous and permeable zones that could receive hydrocarbon migrating from a cavern should be described and mapped.

- Confining units: These units should be described and mapped similarly to the porous and permeable units. These intervals may form traps for migrating hydrocarbon.

- Faults: These should be mapped and their displacement described. Faults of sufficient displacement ("throw") may block lateral migration of hydrocarbon, or may direct migration to another porous and permeable unit. Faults may also form conduits for vertical migration.

- Unconformities: An unconformity is a discontinuity of a stratum created by geological processes happening subsequent to its original deposition. One example would be a stratum that was tipped up, a portion eroded away, and subsequent deposition "capped" the eroded surface. Like faults, unconformities may form traps for migrating hydrocarbon, or they may redirect migration to other intervals.

- Outcrops: Locations where any of the porous and permeable units described above intercept the surface should be determined.

Phase 2. Delineation of an Area of Investigation: The geological description should be integrated with engineering knowledge of the physical properties of stored hydrocarbons and operational parameters for the cavern to determine worst-case migration distances and directions. This information will then guide the delineation of an area of investigation that encompasses all possible horizontal and vertical migration of leaking hydrocarbons.

Phase 3. Historical Research: Compile known, recorded information from sources such as state and county records for the site, conduct interviews with residents, etc. Identify known wellbores within the area of investigation that are inadequately plugged. Compile a history of drilling and casing practices in the local area. Earliest records provide guidance regarding drilling prior to the start of record keeping.

Phase 4. Wide-Area Survey: Depending on the size of the study area, this might be an aerial survey, or it might be conducted from a land vehicle. The objective of this phase is to eliminate from further consideration portions of the study area that are of very low risk.

Phase 5. Detailed Survey and Location of Wellbores: Wells that are known to be of concern are located by site inspection and/or high resolution geophysical techniques. The high resolution search is also extended to areas of greater than acceptable risk for the presence of undetected and unrecorded wellbores. The survey utilizes techniques of sufficient resolution and sensitivity that the residual risk of the presence of an undetected wellbore is reduced to an acceptably low level.

Phase 6. Corrective Action: Abandoned wells that are improperly plugged should be re-entered and plugged properly, or monitored intensively for signs of migration.

Phase 7. Monitoring for Future Signs of Migration from Storage Caverns: Monitoring well methods are presented in this manual.

This manual provides guidance addressing phases 3 through 6. Phase 3 and portions of Phase 4 are addressed in Section 6 (Historical Research and Reconnaissance Survey Methods), Phases 4 and 5 are addressed in Section 7 (Geophysical Survey Methods), and Phase 7 is partially addressed in Section 8 (Well Monitoring Methods). Section 8 is specific to monitoring for migration in the subsurface. It does not cover the many surface-based monitoring methods such as atmospheric gas monitoring.

The following sections provide a rapid overview of the various geophysical and other methods that are the main subject matter of this manual.

5.1 Summary Charts

The various geophysical methods presented in this manual can only be compared based on the type of targets, or survey objectives, defined for an abandoned well search. As discussed in Section 2.4, numerous targets exist that might constitute evidence of an abandoned well or evidence of the likely existence of abandoned wells at a site. In this section, the two most prominent and obvious types of target are presented: 1) casings and well-related structures, and 2) well-related brine plumes. The benefits, limitations, and relative survey costs are compared for each of the relevant geophysical methods in Table 5-1 and Table 5-2.

TABLE 5-1

Comparison of Applicable Geophysical Methods for Locating Casings and Well-Related Structures

Criterion	Magnetic	Time & Frequency Domain Electromagnetics	Ground Penetrating Radar	Self-Potential
Targets:	• steel casing • steel well heads, joints • steel pipes, product lines, pumps, barrels, tanks, rebar	• steel and other metallic casing (aluminum, stainless steel) • well heads, joints • pipes, product lines, pumps, barrels, tanks, rebar	• any type casing or plug material (steel, PVC, concrete) • almost any shallow infrastructure or debris	• oxidizing steel casing
Benefits:	• fast data acquisition • very fast airborne data acquisition • proven track record for detecting steel casing	• fast data acquisition • very fast airborne data acquisition • any metallic casings/ materials detectable • possibly to detect both casing and conductivity anomalies	• any type casing or abandonment plug materials detectable	• simple survey procedures • inexpensive equipment
Limitations:	• only ferrous (iron-bearing) casings / materials detectable • sensitive to cultural noise	• limited DOI in highly conductive ground	• slow/moderate data acquisition • limited DOI to very near-surface-very limited DOI in conductive ground	• slow data acquisition • ambiguous interpretation of anomaly sources
Relative Cost:	• low, but depends on scope (ground *vs.* airborne MAG	• low, but depends on scope (ground *vs.* airborne EM)	• moderate	• moderate

MAG:	The Magnetic Method (Section 7.1 of this manual)
TDEM & FDEM:	Time and Frequency Domain Electromagnetics (Section 7.2.3 of this manual)
GPR:	Ground Penetrating Radar (Section 7.3 of this manual)
SP:	The Self-Potential Method (Section 7.2.2 of this manual)
DOI:	Depth of Investigation

TABLE 5-2

Comparison of Applicable Geophysical Methods for Locating Well-Related Brine Plumes

Criterion	Resistivity	Time & Frequency Domain Electromagnetics	Controlled Source Audio-Frequency Magnetotellurics	Self-Potential
Targets:	• surface plumes / alteration • moderately deep plumes • well-bore fluid	• surface plumes / alteration • moderately deep plumes	• moderately deep plumes • very deep plumes	• surface plumes / alteration • moderately deep plumes • well-bore fluid
Benefits:	• flexibility in survey arrays including tomography • insensitivity to cultural noise	• greater DOI	• greater DOI • insensitivity to cultural noise	• simple survey procedures • inexpensive equipment
Limitations:	• difficult logistics for greater DOI • requires contact with ground surface	• difficult logistics for greater DOI	• moderately complex survey logistics • cannot image very near-surface	• ambiguous interpretation of anomaly sources
Relative Cost:	• low (for continuous, shallow, non-contact type RES) • moderate (deeper RES) • high (ERT)	• low (shallow EM) • moderate (deeper EM)	• moderate	• low

RES:	The Resistivity Method (Section 7.2.1 of this manual)
TDEM & FDEM:	Time and Frequency Domain Electromagnetics (Section 7.2.3 of this manual)
CSAMT:	The Controlled Source Audio-frequency Magnetotelluric Method (Section 7.2.4 of this manual)
SP:	The Self-Potential Method (Section 7.2.2 of this manual)
DOI:	Depth of Investigation
ERT:	Electrical Resistance Tomography
EM:	Electromagnetic

5.2 Decision Tree

Phases 1 through 4, described in the introduction to Section 5, including geological and historical investigations, should always be conducted as a prerequisite to physical surveys for abandoned wells. If a geophysical survey is warranted at a site, based on records research and site reconnaissance, then the investigator should consider the following general guidance to the selection of methods.

The type of geophysical survey best suited for an abandoned well search, and the efficacy of the method to detect abandoned wells, will hinge on one primary factor. This factor is whether or not the wells are likely to have steel casings. If some or all of the steel casing is left, a well can likely be found with magnetic or electromagnetic methods, depending primarily on depth, geological, and cultural conditions (refer to Section 5.1, Table 5-1).

If steel-cased wells are NOT likely, then the problem is extremely difficult, especially if the area to be searched is large. However, because uncased and improperly abandoned wells are a likely location for fluid accumulation in the borehole, and a likely source for subsurface brine plumes, several geophysical methods exist that could successfully delineate these fluids, and locate the likely source (refer to Section 5.1, Table 5-2).

The following is a very general guide for decision-making regarding the possible geophysical methods to consider for an abandoned well search. Note that a list of acronyms is provided at the end of this section.

IF abandoned wells with steel-casing are likely to exist in the area, THEN:

A. If the area to be searched is small (several square miles or less), consider ground MAG or combined ground MAG and EM.

B. If the area to be searched is very small (several acres or so), consider ground MAG or ground MAG and EM first. If these fail to locate any wells, then consider GPR or SP.

C. If there is evidence of a brine plume in the subsurface or near-surface, and MAG and EM fail to locate a well as the likely source of the plume, then consider an alternate, deep-sounding EM method, Resistivity, CSAMT, or SP to delineate the plume and locate the source.

If abandoned wells with steel-casing are NOT likely to exist in the area, THEN:

A. First, consider a MAG or combined MAG and EM survey to assure all steel-casings or related metallic material associate with wells that can be found, are found.

B. If the area to be searched is larger than a few acres or so, consider any means available to narrow the search area, including records search, ground and aerial site reconnaissance, or a geophysical survey to locate drilling-related debris or infrastructure.

C. If the area to be searched is very small (a few acres or less), consider GPR or SP.

D. If there is evidence of a brine plume in the subsurface or near-surface, then consider EM, Resistivity, CSAMT, or SP to delineate the plume and locate the source.

The reader should note that there are many caveats to these suggestions. Experienced personnel and multiple methods are strongly recommended for these risk-critical investigations.

MAG: The Magnetic Method (Section 7.1 of this manual)
Resistivity: The Resistivity Method (Section 7.2.1 of this manual)
SP: The Self-Potential Method (Section 7.2.2 of this manual)
EM: Time and Frequency Domain Electromagnetics (Section 7.2.3 of this manual)
CSAMT: Controlled Source Audio-Frequency Magnetotellurics (Section 7.2.4 of this manual)
GPR: Ground Penetrating Radar (Section 7.3 of this manual)

6.0 HISTORICAL RESEARCH AND RECONNAISSANCE SURVEY METHODS

Historical research and reconnaissance are necessary to characterize the degree of risk associated with abandoned wellbores, and to describe the range of wellbore configurations that are most likely to occur in a locality. This is necessary for the selection of appropriate methods. This section describes research and reconnaissance methods that characterize types of wells in an area, and identify areas of risk for the presence of wells. Section 6.1 describes methods of background research. Section 6.2 describes methods of aerial surveillance and remote sensing.

6.1 Historical Research, Oil and Gas Records, Site Reconnaissance

METHOD OVERVIEW
Targets: all wells.
Objective(s): Identify: 1) drilling and completion methods used in a given area 2) known wells that are improperly plugged.
Methodology: State/county/municipal records search, interviews with long-time residents, interviews with local oilfield workers and oilfield service providers.
Primary cost items: Personnel effort, travel.

6.1.1 Historical Records Research

A search of historical records is a necessary first step to identifying the types of abandoned wells that are likely to be encountered in a study area. The configuration of the recorded wells in an area is the best guide to configuration of those that were abandoned and not recorded. Within most regions, a relatively small number of geological formations have been identified as productive for oil and gas. As a result, total depths of wells and their completion zones are often closely grouped. Additionally, drilling practices such as the choice of depths, hole diameters, and casing depths are guided by previous experience in a region so that these characteristics are also relatively similar.

The history of widespread deep drilling extends only back to 1870's. Each state or locality can mark the beginning of local oil and gas exploration. From this information, and knowledge of the techniques used from that time on, the investigator may characterize the range of likely well configurations, and identify the appropriate techniques for detection of unidentified and abandoned wells.

It should be noted that there are many known abandoned wells for which records are inadequate, or for which inadequate plugging is a recorded fact. Correction of these known problems will mitigate much of the risk associated with a site. In many cases, locations of known wells are not marked at the surface, and the methods described in this manual will be useful in physically locating the actual wells.

State Records

Currently, states require that operators apply for a permit to drill. This is through a state agency such as a Department of Natural Resources, Department of Environmental Quality or a state geological survey. Current regulations require that operators file standard forms that record location, total depth, depths at which the major geological features are encountered, types of casing or plugs, and test records. Required attachments include a survey plat for more precise location of the well at the surface, and deviation surveys that describe the location of the wellbore at various depths. Records of the final or current condition of each well are maintained, and operators are required to file with the state certain operating data such as completion intervals and amounts produced, test results, and information on the plugging and abandonment of wells.

Regulation of drilling, operating, and plug and abandonment practices began in most states during the 1920's. However, compliance with early regulations would not insure adequate casing or plugging and abandonment by today's standards. The intent of many early regulations was to establish legal mechanisms to grant and protect rights to extract resources. Regulations governing drilling, casing, and plugging and abandonment practices were adopted at various times during the 1930's through 1980's. Research of historical records should take into account the phased-in nature of oil and gas regulations in order to judge the adequacy of casing and plugging for wells in the area of concern.

Many states now have computerized oil and gas databases that are accessible via the Internet. Many are in transition to a computer-based system, and the most recent records are being entered first. Consequently, records of the older wells that are of the greatest concern are less likely to be available via this medium. Additionally, many states have maintained separate filing systems for wells drilled during various periods of history.

Because of this complexity, it is often more efficient to contract research with a commercial service that is familiar with the structure of files in a particular state.

County Records

Local tax assessors and county clerks maintain survey maps, ownership records, chain-of-title and lease history for properties. This is important information for describing historical land use. There are many private abstracting or title-search companies that will conduct this research.

Private Information Services

Private information services compile well data, primarily for the use of the oil and gas industry. These services often maintain extensive libraries and databases of geological information and records of wells. Records include scout tickets, casing and plugging reports, results of formation testing and occurrence of hydrocarbons. Many services provide maps of a client's area of concern with all the known wells located and classified according to their use and current status. This information is often compiled from records of exploration and production companies and is more detailed than the information that was provided to state agencies.

One of the most valuable tools provided by these services is a map of known well locations. These maps aid in identifying areas that have been drilled most intensively, and list the uses and depths of these wells. The standard scale for these maps is 1 inch to 2000 feet, similar to USGS topographic maps. Maps plotted at other scales are available for an additional fee. Map information is typically updated on a standard schedule that varies from company to company, so that information may be as much as 2 to 3 years out-of-date. Most companies will bring specific maps current to the most recent records for an additional fee.

6.1.2 Local Sources of Information

People that live and work in the locality of a cavern storage facility may be valuable sources of information regarding locations and drilling methods for wells. Long-time residents may recall drilling activities for which there is no longer any surface evidence, and for which there may not be any formal records. Information from residents is often useful at different phases of a well search. Early in the process, residents may recall less specific information such as names of owners and general locations of drilling. As more information is gathered, residents may be able to recall locations of specific wells, in response to specific questions.

Work with local residents requires that good relations be maintained. The purpose and importance of the interview should be presented and the interviewer should convey sincere interest in the response. Often, an introduction by another local resident can facilitate this process.

Local individuals that have had experience with local oil and gas exploration may be especially informative. These include:

1. Oilfield workers such as drillers and individuals that worked to operate and maintain oil wells may remain in the locality and be able to provide valuable information. These individuals may have worked for oil companies, or one of the many companies that provide services to the oil and gas industry. Service companies include drillers, casing service companies, pumpers, and logging companies. Oilfield workers may know the families or companies that have owned or leased land for many years. They may also recall locations of wells that they worked, and those that they might have encountered as they traveled in the local area.

2. "Land men" are professionals that facilitate the acquisition of rights to drill on local properties. Often, local land men have excellent detailed knowledge of the history of ownership and drilling in a locality.

3. Oil and gas consultants provide professional expertise and recommendations to companies that are drilling and producing from a local area. These individuals will be familiar with the companies that have drilled in an area, and can also provide valuable information regarding drilling and casing practices in their local service area.

6.1.3 Site Reconnaissance

A physical search of the study area will often reveal evidence of abandoned wellbores. This may be feasible for relatively small sites, and may be necessary for sites with heavy vegetation where an aerial survey would be ineffective. Surface evidence of abandoned wells may have been partially obliterated over time, and trained personnel may be required to interpret residual evidence such as topography or stressed vegetation. Personnel should be trained to recognize evidence by visiting known sites that have been identified by other means such as local interviews or state records. This is important because the process of deterioration of these sites will vary depending on geographic location, land use, topography, and other factors.

An excellent review of this subject in the context of detecting abandoned wells in the vicinity of brine and industrial waste disposal wells is presented in Aller (1984).

6.1.4 Costs

The primary costs for historical research and site reconnaissance are for personnel time, and travel and subsistence. Thorough historical research of state records for regions of active oil and gas exploration costs from $3000 to $8000 per square mile. For site reconnaissance, the amount of time needed to search for evidence of wells will vary widely, depending on terrain, vegetation and season. In general, a qualified firm may place a person in the field for approximately $500 per day, plus travel. An individual can complete a thorough walkover of 1 to 10 acres in a day, depending on conditions.

6.1.5 Information Sources

Oil and Gas Records
Cambe, Houston, Texas (713-659-8363)
Riley's Electric Log Service, Houston, Texas and Oklahoma City, Oklahoma (713-957-0490, 800-592-1424),
Kansas Blue Print, Wichita (316-264-9344/888-457-2583)
Kansas Geological Survey (316-943-2343)

Maps
Eby Engineering, El Dorado, Arkansas (870-863-5285)
Nixon Blueprint, Corpus Christi, Texas (800-882-2556)
IHS Energy (US-888-645-3282/713-840-8282; Canada-877-495-4473/403-770-4646)
Tobin (Denver-303-831-3555/Dallas-972-960-6104/Houston-713-334-2242)

6.2 Wide-Area Survey Methods – Aerial Photography and Remote Sensing

METHOD OVERVIEW
Targets: All wells.
Objective(s): Identify conditions on the surface that are associated with well sites and leaking wells.
Methodology: Procure and interpret existing images or obtain new images by aerial photography or satellite imaging techniques.
Primary cost items: Aerial or satellite images from existing governmental or commercial sources. Expertise to interpret images. Acquisition of photography from aircraft or satellites

Wide-area surveys are conducted for the purpose of describing the study area in detail and to note features that are correlated with drilling activity. The end product of such a survey is typically a detailed map of the study area, or images that display the study area at a resolution sufficient to address the goals of the study. Mapping and imagery can be quite useful in addressing other information needs for spatial information and inventories. These include land use studies, safety planning, community right-to-know requirements, infrastructure access routes, etc.

This section discusses aerial photography and remote sensing as separate topics. However, this traditional distinction is becoming increasingly arbitrary, as remote sensing concepts and methods that were developed in support of satellite imaging have been applied to aerial photography.

6.2.1 Aerial Photography

A historical record consisting of aerial photographic images is available for many developed regions, including agricultural areas. These images were made for various reasons over the period from the 1930's to the present. Many are available in the archives of Federal, State and county agencies, and private companies. As noted in the introduction, widespread oil exploration predates wide use of aircraft by at least 30 years. However in many areas, the evidence of the earliest drilling may have persisted up to the time that the earliest photographs were taken. This is especially true since the impacts of oilfield sites were not routinely remediated in the early days.

The first systematic programs to accumulate aerial photographic surveys were in the 1930's. This work was performed by the Agricultural Adjustment Administration and its successor agency the Agricultural Stabilization and Conservation Service. Much more widespread use of aerial surveys occurred after World War II as a spin-off of technologies developed during that period.

Private firms often contract for aerial surveys and retain the resulting aerial photographs. A firm that is utilizing land resources for agriculture, forestry, quarries, mining, oil exploration, etc. may wish to inventory their own land, identify prospects for acquisition, or monitor the activities of competitors. Historical aerial photographs may be acquired from these firms, or from the aerial photography service company.

6.2.1.1 Methods

Aerial photographs are typically taken from an airplane, rather than from a helicopter because of the cost of operation and ability of airplanes to cover a wide area rapidly. Often, companies that do aerial photography will schedule systematic flights over a wide area, and clients may then purchase the images. For less developed areas, a special flight may be required.

Photographs are taken as the aircraft flies in as straight a line as possible. Planning of flight lines must take into account topography and potential obstructions. The Federal Aviation Administration must approve low altitude flights and flights in the vicinity of airports, military installations, and other busy or sensitive areas. Flight lines are spaced so that there is approximately 60% overlap of adjacent swaths. This permits stereoscopic viewing of pairs of photographs from adjacent flight lines.

Photographs may be viewed as contact prints of large-format negatives, enlargements, or as transparencies. The transparencies offer greater definition for viewing. Many photographic images have been digitized and may be viewed on a computer.

There are four commonly available types of aerial imagery. These are described below:

- Black and white – This is the conventional panchromatic black and white image. Panchromatic film is sensitive to a slightly wider spectrum than the human eye.

- Color – Color images facilitate identification of a wide variety of features.

- Black and white infrared – This type of photograph is shot with infrared sensitive film and is printed in black and white. Vegetation is relatively reflective in the near infrared, while water is dark. This type of photograph is particularly useful for identifying surface water and wet areas.

- False-color visible and near infrared – This type of photograph translates bands of the spectrum in the visible and near infrared into visible colors for the final image. Bands are essentially shifted so that they are represented as colors of shorter wavelengths (refer to explanation of the electromagnetic spectrum in Section 6.2.2.1). This type of image is particularly useful in differentiating vegetation type and condition. In heavily vegetated areas, vegetation condition may be the only visible evidence of former drilling sites.

Detection of well sites in aerial photographs requires some practice and expertise in local drilling methods, in order to recognize the "signature" (Aller, 1984) of these sites. Elements of a site signature include the derrick, rig platform, brine pits, sources of power, roads for equipment access, and the sizes and shapes of each of these. Also, the level of deterioration of evidence of each of these elements must be accounted for in forming an expectation of the appearance of a site at the time of the photograph.

To "calibrate" and train the analyst who is studying the photographs, known sites should be included in the area covered. Information about the location of known sites is accumulated as part of the records review discussed in a previous section.

6.2.1.2 Sources of Aerial Photography

The process of acquiring aerial photographic images and delivering them to users involves the design of the flight paths, operation of aircraft, use of appropriate cameras, processing of images, archiving of images, indexing and making the information about the images available to potential users, printing, and interpretation. Companies that provide aerial photography will usually specialize in a segment of this process. For instance, companies that take aerial photographs are often quite localized geographically, and have specific capabilities that are governed by the aircraft and cameras that they operate. Mapping companies often acquire extensive libraries of existing images for use in studies of land-use, infrastructure, etc.

For an investigation of potential well sites, historical photography is often the most valuable. A mapping company that maintains a library of images of the study area may be the appropriate source. If there are no existing images, and the area of study cannot be surveyed easily using ground-based methods, then a local aerial photography service should be contacted.

Commercial firms archive most or all of their images. However, the clients that have commissioned the photographs may have the right to approve release of these images, particularly if they are of their own property.

The Federal USGS, states, and counties often maintain extensive collections of aerial photographs and maps. Contact information for the USGS program that serves as a central information source is given below:

Agency: United States Geological Survey (USGS)
Product: USGS National Aerial Photography Program (NAPP) Photos
Website: edc.usgs.gov/Webglis/glisbin/finder_main.pl?dataset_name=NAPP
Costs: $10 – $200, plus $5 handling, plus shipping.

6.2.1.3 Costs

Costs for implementing aerial photography as a method of detecting abandoned wells include procurement of the images and interpretation.

Commercial firms that market existing images typically charge approximately $100 per image. The investigator should consult with the image provider regarding requirements for area of coverage and resolution. Often, discounts are available for volume of work, and contiguous images.

The cost to commission a flight varies widely, depending on required altitude, distance from the base airport, and type of photography (black and white, color, infrared). Set-up of a low altitude flight may involve special permitting by the FAA.

Costs for a single flight include a base fee of approximately $1000, with each image increasing the cost by about $100. This cost is for a black and white image; color or "false color" (see Remote Sensing, below) images may double the per-image cost.

Local professionals familiar with drilling practices in an area should be consulted for assistance in designating well sites. Additionally, experts familiar with local vegetation types should be consulted to identify signs of vegetation stress associated with brine leaks. Mapping services often partner with consultants that have the appropriate expertise. Interpretation of a single image usually requires less than an hour, however, reporting and additional research will increase the cost of the final report.

6.2.2 Remote Sensing-Visible and Infrared Imaging

Remote sensing refers to the detection of surface characteristics without direct contact. Remote sensing data are usually presented by means of an image that represents that spatial distribution of reflected visible, ultraviolet, or infrared radiation. Specific to the context of detecting abandoned wells, remote sensing aids in the detection of spatial patterns of reflectance or emission from the earth's surface that might be associated with sites, or influences of, abandoned wells.

Abandoned well sites may have one or more of the following characteristics that are discernible in remote sensing images:

1. Spatial pattern of the well site, roads, pits, pipelines, etc.
2. Size of the above-surface features is characteristic of well sites. This is determined by local practice in a region, and by the size of equipment used in drilling and servicing wells.
3. Modified topography associated with the above features of well sites.
4. Vegetation age, coverage, or species composition that is different from the surroundings.
5. Vegetation stress associated with leaking brine.

Operationally, these characteristics are reflected in spatial pattern and changes in coloration of remote sensing images.

This section will present background that will aid in developing expectations for the results of remote sensing, and list commercial sources of these images.

6.2.2.1 Basis of Remote Sensing

Remote sensing detects, analyzes and presents reflected or emitted electromagnetic radiation from the earth's surface. The end product is often an image, where a pattern of energy reflection or emission is reproduced as a spatial image of the landscape or other remotely sensed surface.

It is necessary that radiation from an external source - usually the sun – be intercepted by the surface and either reflected or absorbed and reemitted. During this process, the atmosphere, the surface to be visualized, and the receiver change the intensity and quality of radiation. The human eye cannot actually see much of the radiation that is available to be recorded by remote sensing. Hence, the spatial pattern of reflected radiation is translated into visible colors or shades of gray for presentation as an image.

Solar and Terrestrial Radiation

The distribution of wavelengths in solar radiation is depicted in Figure 6-1. This spectrum is conveniently divided into visible light between 0.4 and 0.7 μm, and wavelengths greater or less than the visible band. Lower-wavelength radiation is in the ultraviolet and beyond, and higher wavelengths are in the infrared, thermal, microwave and longer wavelength regions.

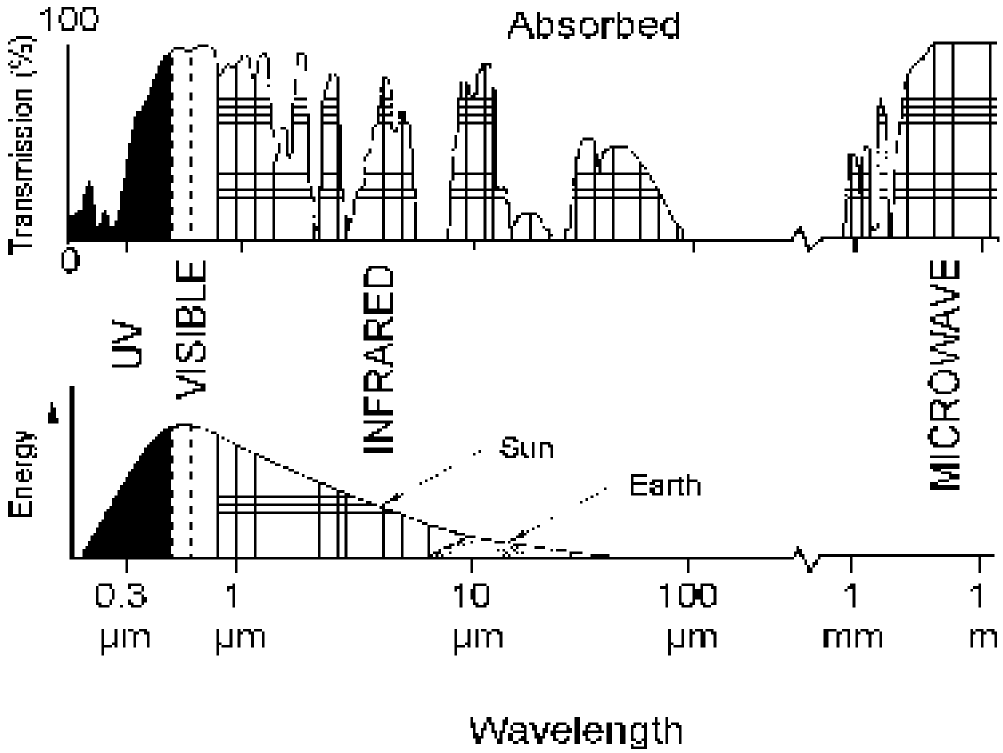

Figure 6-1. Electromagnetic Spectrum.
* Redrawn from CCRS, 2001.

Radiation exists in discrete packets known as photons. Higher energy photons are distributed in the ultraviolet end of the spectrum, and lower energy photons in the infrared and higher-wavelength regions. All objects emit radiation in a distribution that is a function of energetic state of their surface. The peak in the distribution of energy from the surface of the sun at 5800 ºK is in the range of the spectrum between 0.4 μm and 0.7 μm. The human eye is, fortunately, adapted to sense radiation in that range. The earth's surface, at temperatures within our normal experience, emits low energy "thermal" photons, with most of this energy emitted in wavelengths around 10 μm.

Atmospheric Scattering and Absorption

The earth's atmosphere is not uniformly transparent to all wavelengths. Radiation at each wavelength is reduced in intensity by atmospheric scattering and absorption. Three types of scattering are termed Rayleigh, Mie, and nonselective. Both Rayleigh and Mie scattering are broadly selective, favoring different regions of the spectrum. Absorption (to be discussed later in this section) is highly specific.

Rayleigh scattering is caused by particles that are much smaller than the wavelengths of electromagnetic radiation passing through the atmosphere. Shorter wavelengths, toward the blue and violet end of the visible spectrum, plus the ultraviolet, are affected more by this type of scattering. The blue of the sky is due to Rayleigh scattered light that is thrown toward the viewer (actually in all directions) by the atmosphere. At sunset, light from the sun traverses a long path through the atmosphere and is depleted in the shorter wavelengths. This makes sunset appear more red and orange.

Mie scattering is caused by particles of sizes similar to the wavelengths of visible electromagnetic radiation. This mode of scattering is more effective in longer wavelength regions than Rayleigh scattering. It is the dominant mode of scattering under overcast conditions in the lower atmosphere. Nonselective scattering is caused by large particles and droplets. Clouds scatter nonselectively, causing them to appear white.

As indicated in the upper panel of Figure 6-1, the atmosphere is not uniformly transparent to all wavelengths. This is due to selective absorption of specific wavelength radiation by the molecules that make up the atmosphere. Figure 6-1 shows that the atmosphere absorbs most radiation below 0.3 µm, due to ozone, broad bands between 0.7 and 3 µm (near-infrared) due to oxygen and water vapor, and thermal radiation due to carbon dioxide. These regions of high absorption are not useful for remote sensing of the surface, hence, satellite and aircraft-based sensors are made to sense radiation in the “atmospheric windows” of high atmospheric transmission (Figure 6-1).

6.2.2.2 Methods of Acquiring Images

We think of image acquisition in terms of photography, where radiation from each point within the field of view is focused on a corresponding point on a film, and the entire image is acquired at one time. However, much of the electromagnetic spectrum cannot be gathered and focused through a lens in the way that a conventional camera gathers an image. Sensors that measure this type of radiation receive radiation from a very narrow field of view that scans across the surface, recording intensity sequentially. This is similar to the way that a television picture is "drawn" on the screen as horizontal lines that vary in intensity across the screen.

Sensed radiation is recorded digitally, which means that the continuous range of intensity is simplified into a limited number of discrete ranges of values. Radiometric resolution of remote sensing data is determined by sensor characteristics and the recording format and describes the capability of the system to measure and record differences among levels of energy. Number of bits is a term used to describe radiometric resolution recorded digitally. The number 2, raised to the power of the number of bits, indicates the number of levels that may be recorded. For instance, one-bit storage means that 2^1 or 2 levels (on or off) are recorded. For eight-bit storage, 2^8 or 256 levels are of intensity distinguished. Common digital resolution formats are 4, 8 and 16 bit.

Satellites orbit the earth over predictable paths, or a satellite may be in a geostationary orbit. Most remote sensing satellites, that are not geostationary, orbit the earth from pole to pole. The relative timing of the satellite's orbit and the earth's rotation results in a different portion of the earth being scanned with each orbit. Through the selection of orbit and angle of view for the satellite's instruments, the satellite can scan almost every part of the earth's surface every few days. The physics of orbiting objects, and the earth's rotation constrain the altitude of geostationary satellites to approximately 22,000 miles. Orbital altitudes of pole-to-pole orbiting satellites are approximately 600 miles. Consequently, the resolution of images is much greater for pole-to-pole satellites.

Sensors mounted on these satellites scan rapidly from side-to-side across the surface below the orbital path. The signal from the sensors is then relayed, and a continuous image of the swath formed. Most modern aircraft and satellite-based sensors incorporate a line of CCDs (charge-coupled devices), where each CCD views a single narrow angle with respect to the orbital or flight path. The fields of view of these linearly arrayed CCDs may be visualized as a broom sweeping the surface being scanned. Output of each sensor is recorded sequentially. A strength of CCDs is that combinations of sensor characteristics and filters afford high wavelength selectivity in specific bands.

Wavelengths Measured

Remote sensing primarily records radiation in three bands: visible (0.4 µm – 0.7 µm) near infrared (0.7 µm – 1.0 µm), shortwave infrared (1.0 µm – 7 µm), and thermal infrared (10 µm – 13 µm). Most remote sensing equipment is designed to record narrow bands within these ranges. These bands have been selected to discriminate among features on the earth's surface that are of scientific and commercial interest, and to respond to wavelengths that are not strongly affected by atmospheric scattering and absorption.

The remainder of this section lists some of the satellite image types that are commercially available and potentially applicable for detecting surface impacts of abandoned wells. Potential for applicability is based on spatial resolution and sensors that record visual and near- to shortwave-infrared bands.

Landsat Thematic Mapper

These are among the oldest and most widely available images. The relatively long history of this satellite program makes these images valuable for assessment of changes in vegetation and land use. Resolution is 90 meters, which is not applicable for detecting specific well sites. The spectral bands recorded by these satellites are listed in Table 6-1. Those in the near IR are useful for identifying vegetation and moisture. Landsat false color images visualize the near IR as red, red as green, and green as blue, essentially compressing the spectrum of the visible and near IR to colors in the lower, visible wavelengths.

TABLE 6-1
Landsat Thematic Mapper
Remote Sensing Data and Wavelength Bands Utilized

Channel	Wavelength Range (μm)	Application
TM 1	0.45 - 0.52 (blue)	soil/vegetation discrimination; bathymetry/ coastal mapping; cultural/urban feature identification
TM 2	0.52 - 0.60 (green)	green vegetation mapping (measures reflectance peak); cultural/urban feature identification
TM 3	0.63 - 0.69 (red)	vegetated vs. non-vegetated and plant species discrimination (plant chlorophyll absorption); cultural/urban feature identification
TM 4	0.76 - 0.90 (near IR)	identification of plant/vegetation types, health, and biomass content; water body delineation; soil moisture
TM 5	1.55 - 1.75 (short wave IR)	sensitive to moisture in soil and vegetation; discriminating snow and cloud-covered areas
TM 6	10.4 - 12.5 (thermal IR)	vegetation stress and soil moisture discrimination related to thermal radiation; thermal mapping (urban, water)
TM 7	2.08 - 2.35 (short wave IR)	discrimination of mineral and rock types; sensitive to vegetation moisture content

SPOT (Système Pour l'Observation de la Terre)

Table 6-2 lists the spectral bands recorded by the SPOT series of satellites. The resolution of SPOT images is 10 meters in the panchromatic (PLA) band, and 20 meters in the multispectral (MLA) bands. Overlay of images in the PLA and MLA bands effectively provides the higher resolution for all channels. These satellites were specifically designed for commercial use, and there are numerous agents that distribute SPOT images.

TABLE 6-2
SPOT (Système Pour l'Observation de la Terre)
Remote Sensing Data and Wavelength Bands Utilized

Mode/Band	Wavelength Range (μm)
Panchromatic / PLA	0.51 - 0.73 (blue-green-red)
Multispectral / MLA Band 1	0.50 - 0.59 (green)
Multispectral / MLA Band 2	0.61 - 0.68 (red)
Multispectral / MLA Band 3	0.79 - 0.89 (near infrared)

Like the Landsat images, the green, red and near infrared bands permit assessment of the density and condition of vegetation, and the normal repeat frequency for any portion of the earth is approximately 26 days.

Indian Remote Sensing (IRS) Satellite Series

This series of satellites provides image data from three sensors (Table 6-3), a panchromatic high resolution camera (PAN), a medium resolution four-channel linear array (Linear Imaging Self-Scanning Sensor; LISS-II), and a low resolution two-channel sensor (Wide Field Sensor; WiFS). Similar to the SPOT satellite series, IRS information would be most effectively used by overlaying the high resolution PAN and LISS-II channels.

TABLE 6-3
Indian Remote Sensing (IRS) Satellite Series
Remote Sensing Data and Wavelength Bands Utilized

Sensor / Band	Wavelength Range (μm)	Spatial Resolution
PAN	0.5 - 0.75	5.8 m
LISS-II / Green	0.52 – 0.59	23 m
LISS-II / Red	0.62 – 0.68	23 m
LISS-II / Near IR	0.77 – 0.86	23 m
LISS-II / Shortwave IR	1.55 – 1.70	70 m
WiFS / Red	0.62 – 0.68	188 m
WiFS / Near IR	0.77 – 0.86	188 m

Compact Airborne Spectrographic Imager (CASI)

The CASI was developed for imaging from aircraft. This is a hyperspectral sensor that detects 288 channels between 0.4 μm and 0.9 μm. Each narrow band is 0.018 μm wide. Because this sensor is mounted on an aircraft, spatial resolution is very high, relative to satellite imagery, and only limited by the altitude of the aircraft. The array of wavelength channels allows for research and detection of special targets that do not conform to the preselected bands measured by the satellites listed above.

Image Processing

Digital processing of remotely sensed data permits the observer to enhance image sensitivity to the surface characteristics of interest. Image processing operates on the intensity values recorded for each pixel (picture element, the smallest element of image resolution) and applies various mathematical transformations. Two of the more common image transformations employed are described here:

Image Subtraction

Image subtraction is used to emphasize changes from one image to another. It is useful for delineating areas that have changed during the period between images. The intensity value of each pixel in one image is subtracted from that value in the corresponding pixel of the other image. This process requires careful registration between the images so that the pixels to be subtracted correspond to the same points on the surface. The process of registration involves identification of features on the two images, and spatial adjustments, by means of a computer, to line these features up.

Spectral Ratioing

For this type of image, the intensity or color of each pixel represents the ratio of intensity in two bands of the spectrum. This is particularly useful for delineating vegetation because foliar pigments absorb strongly in the red and reflect in the near infrared. Hence, the spectral ratio of near infrared to red is high for healthy vegetation with high contents of foliar pigment. Foliar pigments such as chlorophyll turn over rapidly in leaves due primarily to damage by high energy solar photons. Healthy plants maintain this high turnover of foliar pigments, while stressed plants will often change pigmentation before other signs of stress are visible. Stress due to brine contamination is one factor that leads to physiological stress of plants.

Because ratios are represented, the absolute intensity of reflected radiation influences the final values of each pixel. As a result, differences in illumination such as between sides of a mountain are de-emphasized.

6.2.2.3 Applicability

Remote sensing technology is used in many applications where a wide-scale survey is required, and the subjects of the survey are distinguishable in one or more of the wavelength bands that are measured. Spatial resolution is limited so that direct observation of an object, such as a wellhead, would not be possible. However, any well that is leaking close to the surface is likely to have an influence on surface moisture, and temperature and brine contamination will affect the physiological status of vegetation. These influences often spread over tens to hundreds of feet. The direction and shape of this spread is strongly influenced by soil conditions and topography. Hence, the effect of a brine leak may be evident along the course of a stream or swale.

6.2.2.4 Commercial Resources

SPOT Image Corporation
1897 Preston White Drive
Reston, VA
USA 20191-4368

(800) ASK-SPOT
(703) 715-3100

InfoTerra
Delta House
Southwood Crescent
Farnborough, Hampshire
GU14 0NL

6.2.2.5 Costs

The cost of a single, high resolution image can range from $1000 to $3000. Additional images are usually about one-half that price.

6.2.2.6 References

Aller, L., 1984, "Methods for Determining the Location of Abandoned Wells," EPA-600/2-83-123. January, 1984.

CCRS, 2001, "CCRS Remote Sensing Tutorial," Canada Centre for Remote Sensing. www.ccrs. nrcan.gc.ca/ccrs/eduref/tutorial/indexe.html

7.0 INTRODUCTION TO GEOPHYSICAL SURVEY METHODS

Surface geophysical methods for investigating the composition, structure, and nature of the subsurface have reached a high degree of sophistication in recent years. The impetus for technological improvements has been the realization that shallow geophysics can aid in addressing societal problems related to the environment and engineering, in addition to the more traditional problems in petroleum and minerals exploration for which many of the methods were initially developed.

Improvements in both instrument precision and computational efficiency have made electrical, seismic, gravity, magnetic, and other techniques quite successful at delineating the shallow subsurface to a resolution necessary to address engineering and environmental problems. Some of the methods discussed in this manual, such as the magnetic, ground penetrating radar (GPR), and some electromagnetic (EM) techniques, have been used successfully to directly detect buried or abandoned wells. Other methods, such as the resistivity, self-potential (SP), controlled source audio-frequency magnetotellurics (CSAMT), and transient electromagnetic (TEM) sounding techniques, are capable of delineating subsurface brine plumes or other borehole leakage which may be the only remaining evidence of a borehole penetration.

What is a Geophysical Survey?

The practice of geophysics uses either measurements of the earth's natural potential fields, such as the gravity or magnetic field, or measurements of the earth's response to an applied energy source, such as acoustic energy, electric currents, or radar pulses. In general, variations in these measurements at the surface of the earth reflect changes in the geometry and material properties of the subsurface. In geophysics, the measurements are referred to as 'data', and the calculated subsurface properties are often referred to as the 'model' or 'model parameters'. The concept of a model is key to understanding the strengths and limitations of modern geophysical methods. The model is the best description of the subsurface that optimizes conformance to the data with feasibility constraints. The objective of most geophysical surveys is to estimate the subsurface model that best fits the observed data at the surface, subject to certain constraints. This is known as an inverse problem, and the solution (model) is generally not unique. Hence, models, or subsurface images, must be interpreted by a geophysicist in terms of likely causative bodies (i.e., what is in the ground).

Signal Versus Noise in Geophysical Data

The best interpretation of geophysical data is intimately related to what the geophysicist interprets as signal versus that which is considered noise. In every geophysical survey, it is important to understand that "noise" is a relative term. All geophysical anomalies have a source; variations in the measured survey parameter which are caused by the source of interest are considered signal (for example, an anomaly due to a buried well), all other sources of variation may be considered noise. The signal of interest in one method, or for one particular abandoned well-related target may constitute noise in another.

Most geophysical surveys conducted for abandoned wells will be 2-D, or surface surveys, in which data are gathered on a grid or multiple traverse-line pattern. In these types of surveys, noise may be characterized as either spatially coherent or spatially incoherent. These two types of noise have quite different properties that must be understood to conduct a survey with the best possible quality-control procedures, and to interpret data with the proper consideration of noise sources. It is important to remember that although the geophysical response of a particular target may be predictable, noise, including local background conditions, also determines the detectability of targets.

Spatially coherent noise may have spectral characteristics that cause it to look like signal from the source of interest. Natural, random processes in the earth often generate spatially coherent patterns (for example, clouds, topography, etc.). Instruments whose readings drift with time can also generate spatially coherent noise (due to the regular manner in which data are acquired), as can cultural features at a survey site. Spatially coherent noise is difficult to distinguish from signal when processing and analyzing geophysical data, and so it is very important to understand all identifiable sources of coherent noise that exist at a particular survey site. This involves consideration of all available information about the soil cover, groundwater, sediments, lithology, geologic structure, topography, and vegetation characteristics, as well as location and characteristics of cultural features such as pipelines, powerlines, structures, and debris at the site.

Spatially incoherent, sometimes called "white" noise, is easier to identify and simple filtering can often suppress this type of noise. Incoherent noise is like static noise on a television screen; it has no apparent pattern to it. Instrument noise, measurement precision errors, and survey positioning errors often generate spatially incoherent noise, or chatter, in geophysical data. Careful quality-control checks of instrument function and of survey procedures should be implemented in any geophysical survey in order to help identify incoherent noise in the data.

The Importance of Integrated Interpretation of Geophysical Data

Because of the inherent ambiguity in earth models obtained from geophysical data, the importance of an integrated approach to geophysical investigation cannot be overemphasized. All known information regarding the surface and subsurface properties at a site should be used to guide selection of parameter constraints, models, and range of possible interpretations. Also, two or more independent geophysical data sets, which are sensitive to different earth properties and noise factors, can greatly increase the accuracy of an earth model. For an abandoned well search, joint interpretation of two independent geophysical datasets would greatly increase the chance for successful identification of buried wells. Paine et al. (1997) and Takata et al. (2001) provide excellent examples of how an integrated geophysical approach might be utilized to best meet the goals of a large area survey for abandoned wells or similar targets.

The following section of the manual comprises technical overviews of the various geophysical methods identified as potentially useful for abandoned well search. The methods are divided into the magnetic method, electrical and electromagnetic (EM) methods, and the ground-penetrating radar (GPR) method. The electrical and EM methods are further divided into the resistivity, self-potential (SP), time and frequency domain EM (TDEM and FDEM), and controlled source audio-frequency magnetotelluric (CSAMT) methods. All of the methods presented in this manual are potentially useful for abandoned well search.

In each of the geophysical method descriptions, an initial brief overview statement describes the primary objective, in terms of abandoned well search. The physical basis and survey methodology of the method are discussed. The specific applicability to abandoned well search and related case histories is presented next. Finally, time and cost estimates are given followed by selected reference lists applicable for each specific method. While this manual presents the various methods individually for ease of reference, the reader should keep in mind that an approach that integrates more than a single geophysical method may more effectively meet the survey goals of an abandoned well search.

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7.1 The Magnetic Method

METHOD OVERVIEW
Primary Objectives: location of steel well casings, pipelines, or other metallic debris associated with wells
Measured Parameter: Magnetic field intensity
Property of Interest: Magnetic susceptibility

7.1.1 Introduction

The magnetic method is one of the oldest geophysical survey methods. It has been used for many decades in the mineral and petroleum industries for mapping geologic basement trends, faults, and mineral or petroleum prospects. The magnetic method has been used in recent years for various engineering and environmental applications including locating abandoned wells, buried tanks, pipelines, and unexploded ordnance; delineating pits, trenches and landfills containing metallic debris; and mapping archaeological sites, shallow geology, and soils.

The magnetic method is relatively fast and cost-effective compared to other geophysical methods, and it has a proven track record for locating abandoned wells. In most cases, it should be considered the primary tool to be employed before other methods are implemented, especially if competent, steel-cased wells are suspected.

7.1.2 Physical Basis

Magnetic Field of the Earth

The earth's magnetic field is thought to be derived from fluid motions in the conductive outer core which are possibly coupled to thermally driven convection cells in the mantle. The field is manifested as a smoothly varying dipolar field with south and north magnetic poles roughly aligned with the earth's geographic north and south poles, respectively. The earth's magnetic field is a vector field, specified at a given location by the magnitude of the magnetic force (total field intensity) and its direction. Declination (the angle between geographic north and magnetic north) and inclination (the angle of dip) describe the direction of the field at a given point (Figure 7-1). The total field intensity is typically given in units of nanoTeslas (nT) or Gammas (Table 7-1). Over the conterminous U. S., the total field intensity varies from about 48,000 to 60,000 nT, the declination varies from about 20 degrees east of geographic north to about 20 degrees west of north, and the inclination varies from about 52 to 72 degrees from the horizontal plane.

The magnetic field of the earth is not constant in time. Movement of ionized particles high in the atmosphere create irregular electrical currents that induce secondary magnetic fields. These daily changes are called the diurnal variation. The amplitude of the diurnal variation ranges from about 20 nT to 50 nT on a daily cycle. Magnetic storms due to sunspot activity often cause extreme disturbances in the magnetic field over periods of days to weeks. Further, secular (long-term) variation of the field occurs over periods of years to thousands of years. For reasons not entirely clear, the magnetic field has changed polarity, as well, many times throughout earth's history.

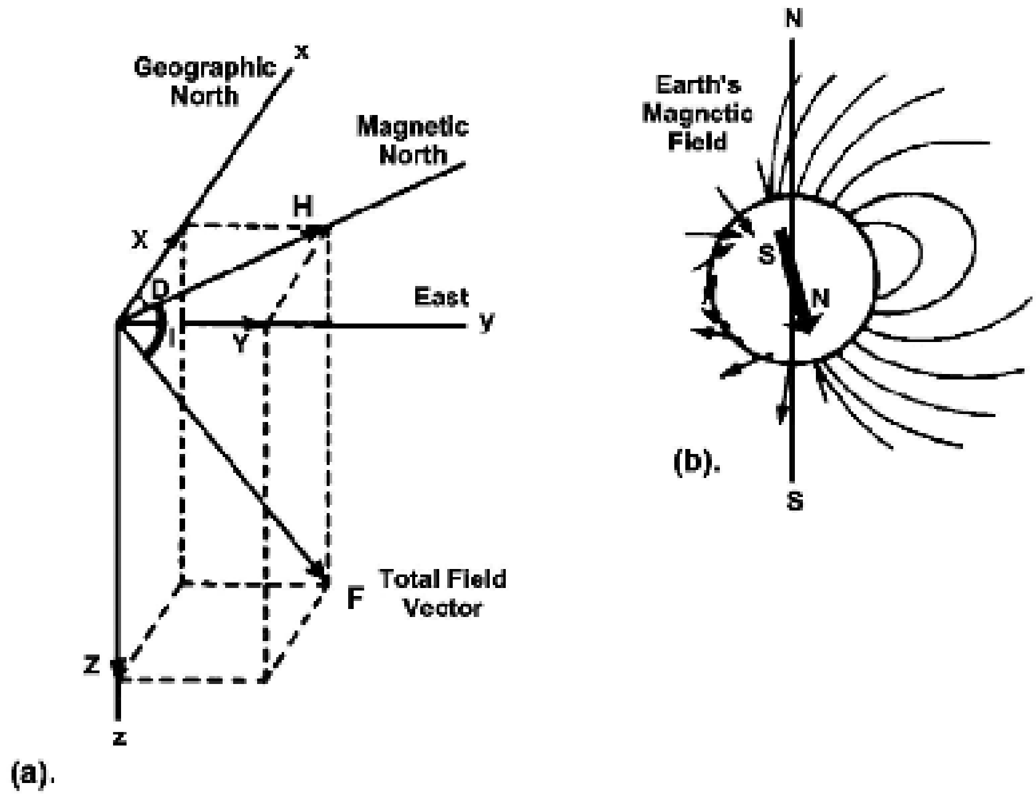

Figure 7-1. **(a). Schematic diagram of the components of the earth's magnetic field vector at the surface in northern, midlatitudes: D, declination; I, inclination; H, horizontal component; Z, vertical component; F, total field vector. (b). Schematic diagram of the Earth's dipolar field (modified after Hinze, 1990).**

TABLE 7-1
EQUIVALENT UNITS OF MAGNETIC INTENSITY

1 Nanotesla (nT)	= 10-9 Tesla
	= 1 Gamma
	= 10-9 Weber/m2
	= 10-5 Gauss
	= 10-5 Oersted

Magnetic Properties of Materials

Natural earth and man-made materials may be non-magnetic, or may exhibit variable amounts of magnetization. There are two basic types of magnetization: induced and permanent, sometimes referred to as remnant. The total magnetization of an object is the sum of the induced and permanent components. Induced magnetization in a material is caused by preferential alignment of magnetic minerals as a result of placement of the material in the Earth's magnetic field. A material property called magnetic susceptibility is responsible for the degree to which a material may be magnetized by the inducing magnetic field. Permanent, or remnant, magnetization is the property of some materials to retain magnetization in the absence of a magnetic field (an example is a common bar magnet).

The magnetic susceptibility of rocks and soils is primarily dependent on the amount of the iron-bearing mineral magnetite that is present. Magnetite is a common accessory mineral in igneous and metamorphic rocks, and is found in trace amounts in sediments and sedimentary rocks. Iron-bearing manmade objects, such as most modern well casings, generally have magnetic susceptibilities several orders of magnitude greater than natural materials. Magnetic susceptibility, k, is a dimensionless number in centimeter-gram-second (cgs) units. Magnetic susceptibility is extremely variable and can range over many orders of magnitude for similar materials. Common ranges of susceptibility for various rocks, sediments, and man-made materials are given in Table 7-2.

TABLE 7-2
Common Ranges of Magnetic Susceptibility for Various Materials

Material	Magnetic Susceptibility, *k* (in cgs units)
Most iron and steel object	~1 to 10
Most steel pipes (e.g., well casing)	~10 to 50+
Pure magnetite	~1
Pure hematite	~10^{-3}
Mafic igneous rocks (e.g., basalt, gabbro)	~10^{-3} to 10^{-1}
Acidic igneous rocks (e.g., granites)	~10^{-5} to 10^{-3}
Metamorphic rocks	~10^{-4} to 10^{-2}
Sediments and sedimentary rocks	~10^{-5} to 10^{-3}

Magnetic Anomalies

The magnetic method involves measuring some component of the magnetic field near the surface of the earth. Small spatial variations in the shape of the field near the earth's surface reflect conditions in the subsurface. These local variations, with respect to a smoothly varying regional component, are referred to as magnetic anomalies. Delineation and interpretation of the source of magnetic anomalies is the primary objective of most magnetic surveys.

Magnetic anomalies are caused by both induced and permanent magnetism of subsurface materials. The shape, dimensions, and amplitude of an induced magnetic anomaly is a function of the orientation, geometry, size, depth, and magnetic susceptibility of the body as well as the intensity and inclination of the earth's field at the survey site.

A magnetic anomaly is generated only when there are lateral variations in magnetic susceptibility, i.e. it is a susceptibility contrast that causes an anomaly. Because the earth's field is dipolar, the shape of a magnetic anomaly due to a particular source will vary with latitude. In mid-northern latitudes such as the conterminous U.S., local magnetic anomalies generally have a minor negative northern lobe and a larger positive southern lobe (Figure 7-2). The shape of an anomaly will also vary depending on depth (or distance from the measurement point). The amplitude of an anomaly will decrease with increasing depth to the source, and the wavelength of an anomaly will increase with increasing depth to the source. The amplitude of a magnetic anomaly falls off rapidly with depth, or distance from the magnetometer to the object:

Total intensity, T, due to a dipolar source: $T \propto 2M/r^3$

Total intensity, T, due to a monopolar source: $T \propto M/r^2$

where T is the total field intensity, r is the distance to the pole or dipole, and M is the magnetic moment (magnetic moment is proportional to the magnetic susceptibility and the inducing field intensity).

For the purposes of magnetic searches, many objects may be approximated as either a magnetic dipole or, in the case of a steel well casing extending to depth, a magnetic monopole. For ease of modeling, geophysicists usually assume that an anomaly is due entirely to induced magnetism. For a well casing however, there is likely to exist a significant component of permanent magnetism that may complicate modeling of the source. However, anomalies due to well casings are generally quite sharp and large in amplitude, and since detection, rather than quantitative modeling, is of primary concern for magnetic searches, this is not a problem.

In practice, the total field intensity measured by a magnetometer is the sum of the earth's magnetic field and that due to other sources. Magnetic anomalies represent the cumulative effect from many sources at variable depths. Geophysicists use various signal processing procedures to analyze magnetic data and separate the anomalies of interest.

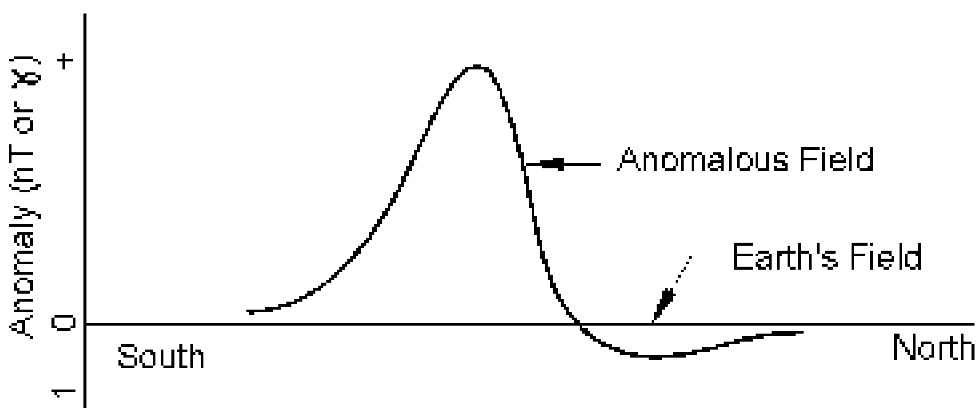

Figure 7-2. Schematic total field anomaly curve over a magnetic dipole source in northern, midlatitudes (after Hinze, 1990).

7.1.3 Survey Methods

Magnetometers

A magnetometer is used to measure the total intensity of the magnetic field, or some component of the field. Most magnetometers used today are of three basic types: proton precession, flux-gate, and alkali-vapor, sometimes called optically-pumped magnetometers. The most commonly used magnetometers employed for ground and airborne magnetic surveys are proton-precession magnetometers and alkali-vapor magnetometers.

Proton precession magnetometers measure only the total field intensity and are independent of orientation. The sensitivity of modern instruments is on the order of 0.1 nT. Proton precession magnetometers do not provide true continuous measurements with time, but many can operate at sample rates as high as 10 Hz. Proton precession magnetometers are especially sensitive to the interfering influence of AC power sources and large magnetic gradients.

Alkali-vapor, or optically-pumped, magnetometers are generally the most sensitive, able to achieve a precision of one or more orders of magnitude less than 1 nT. They are commonly employed for airborne measurements of the total magnetic field. Optically-pumped magnetometers are generally the most expensive type of magnetic sensor.

Less commonly used for geophysical surveys are the flux-gate magnetometers. Flux-gate magnetometers are directionally dependent, that is they must be oriented in the direction of the magnetic field vector. This is both a disadvantage, due to the added requirement for sensor orientation, as well as an advantage because the horizontal and vertical components, as well as the total intensity, of the magnetic field can be resolved. The sensitivity of flux-gate magnetometers is generally on the order of 1 nT.

Survey Procedures

Magnetic surveys may be conducted either as ground surveys or from fixed-wing aircraft or helicopters. Ground surveys are usually made with a portable, hand carried instrument along straight parallel lines so that the operator covers the survey area systematically (Figure 7-3). Aeromagnetic surveys are conducted from an aircraft at either fixed altitude or fixed distance above the ground (Figure 7-4).

Many of the latest model ground magnetometers automatically acquire data at rates between 1 and 10 Hz, and may integrate automatically acquired RTK (Real Time Kinematic) GPS (Global Positioning System) location data with the magnetic data in real-time. Along-line spacing (or sample rate) and between-line station spacing is based on the survey goals and size of anomalies expected.

For abandoned well searches using the ground magnetic method, line or transect spacing should be no more than about 20 to 30 ft, and oriented north-south in the absence of any information dictating otherwise. With current state-of-the-art magnetometers and GPS instruments, the station, or in-line, spacing can be easily accomplished at an interval of 1 ft or less using automatic sampling and positioning capabilities. A reconnaissance aeromagnetic survey looking for localized, short-wavelength anomalies due to well casings, may use a flight line spacing on the order of 50 to 100 ft.

Magnetic survey data may be acquired in either total field, vertical gradient, or horizontal gradient mode. For gradient measurements, two magnetometers are placed either horizontally adjacent, or vertically adjacent to each other, with a separation distance of several feet or more. Gradient measurements can provide better resolution of very shallow, localized sources. They are insensitive to time variations in the magnetic field and to regional geologic variations in magnetic properties. Gradient measurements taken near ground level, however, are usually more prone to noise contamination than total field measurements. Most successful magnetic surveys for locating abandoned wells to date have employed the total field intensity measurement, rather than gradient measurements.

The most important procedural controls that help to insure good quality magnetic data include avoidance of magnetic materials on or near the magnetometer (including clothing or personal items on the operator), periodic reoccupation of a local base station in order to insure repeatability of measurements, continuous monitoring of the diurnal variation, and, in some environments, careful positioning of the magnetometer sufficiently elevated to avoid high-magnetic gradients near the ground. In a ground magnetic survey that uses a GPS receiver for positioning, it is also necessary to insure that the GPS receiver instrumentation does not adversely affect magnetic readings.

Figure 7-3. **A Geometrics 858 Mag Mapper portable ground magnetometer with integrated Trimble GPS positioning system (courtesy of Geometrics).**

Figure 7-4. **Fugro Airborne Survey's helicopter-borne stinger mounted magnetic sensor system (courtesy of Fugro Airborne Surveys).**

Data Processing and Interpretation

Data processing steps generally include integration with positioning data, correcting for the diurnal variation, filtering, and preparation of contour maps for presentation and interpretation. Quality control is performed at various stages of the data processing and includes checking for data dropouts, repeatability, and survey line ties (agreement of data at line intersections). For ground magnetic surveys, the diurnal correction is usually accomplished by monitoring a magnetic base station in the area either continuously or periodically throughout the survey. For airborne surveys, the diurnal and other time-dependent drift factors are removed from the data by adjusting the flight path line ties, usually with a best-fit, least-squares method. Corrections for aircraft altitude, orientation, and low-pass filtering the time-domain signal are usually necessary in processing aeromagnetic data.

Once the preliminary data processing steps are complete, various 2-D filtering techniques may be applied to enhance the data's interpretability. Regional removal, spatial band-pass filtering, derivative and gradient filtering, and reduction-to-the-pole are some types of signal processing commonly applied to magnetic data. The data are then displayed as plan view, color contour maps showing areas of constant total intensity. Very often the final product will be a ‘residual’ map which is a map of magnetic intensity which has been spatially filtered to remove the regional trend so that local anomalies are illuminated. The maps are interpreted along with any control information such as known cultural features for trends and possible sources of anomalies.

7.1.4 Applicability

Sensitivity

The three most important factors affecting the detectability of abandoned wells using the magnetic method are the depth (or distance between the magnetometer and top of well casing, the mass of ferromagnetic material associated with the well (i.e. how much of the casing is left), and the level of background magnetic noise due to geology and cultural features. Sediments, soils, sedimentary rocks, brines, freshwater and air have usually have insignificant magnetic signatures when compared to that expected from a steel-cased well or well cap; however, there are notable exceptions, especially in the vicinity of very magnetic near-surface sediments.

Maximum anomalies expected from typical well casings and well heads from a ground magnetic survey are commonly in the range given in Table 7-3. Note that these are representative estimates only and actual anomaly amplitudes will depend on many factors such as magnetic latitude; background noise; size, orientation, metallurgy, permanent magnetization, and degree of degradation of the well casing.

TABLE 7-3
Common Range of Ground Magnetic Anomalies For Typical Well Casings*

Depth	Maximum Total Field Intensity
5 ft	2000 to 5000+ nT
50 ft	200 to 500 nT
500 ft	2 to 5 nT

*modified after Breiner (1973)

A recent magnetic survey of abandoned wells in eastern Kansas by Hecker et al. (2001) found anomalies of 500 nT to 5000 nT above background level for 25 buried, abandoned wells which were later confirmed by backhoe excavation. An extensive study by Frischknecht (1984) found ground magnetic anomalies ranging from about 1,000 to 6,000 nT for many confirmed wells in several test areas in Colorado and Oklahoma. Low-altitude aeromagnetic anomalies (100 and 200 ft flight altitudes) for these same wells ranged from about 1 nT to 100 nT (1 nT being near the limit of detectability). Frischknecht (1984) concluded that most wells containing on the order of 200 ft or more of 8 inch casing could be detected with airborne measurements.

For abandoned well searches of large areas, a high-resolution aeromagnetic survey using a low-altitude (100 ft or less), slow-flying, helicopter-borne magnetometer system should provide excellent data for this application. Airborne, multisensor configurations are best as they provide gradiometer as well total field measurements. For most abandoned well searches, however, where the survey areas are on the order of tens or hundreds of acres, the aeromagnetic method may be cost-prohibitive.

Well-Related Targets

Well construction materials which could be detected using the magnetic method include only steel well-casings or joints. Because magnetometers detect only ferrous metal sources, uncased abandoned wells, or older wells with other casing material, such as wood, would not be detected. Very degraded, oxidized steel or iron is usually not detected with the magnetic method either, depending on the degree of degradation. Targets comprised of iron or steel are the only practical targets for the method (with the minor exception of cavity search discussed briefly below). Other materials, including stainless steel (300 series) (Breiner, 1973), can usually be considered non-magnetic for this application.

Subsurface cavities in the vicinity of a wellbore might be detected with a high-resolution ground magnetic survey given particular geologic conditions. The first condition requires that cavities are fairly large and shallow in depth (for example, cavity size on the order of tens to hundreds of feet in dimension; depths in the range of tens to a few hundred feet, depending on cavity size). The second condition requires that surrounding country rock has moderate or high magnetic susceptibility, so that a significant susceptibility contrast exists between it and the air-filled cavern which has zero to negligible susceptibility.

In some cases, the detection of well-related structures and debris may help direct or refine search efforts for the actual boreholes. In most magnetic surveys, however, signals due to cultural features are problematic, and can lead to a high rate of false anomalies. Such cultural noise might include power lines, buildings, fences, pipelines, rebar reinforced concrete, pipelines, or steel and iron debris either on or in the ground. In areas with a large amount of cultural noise, well casing anomalies may be contaminated by a significant amount of interference, and the probability of false detections increases. The surrounding geological conditions must also be considered when interpreting magnetic anomalies in a search area. Variations in the magnetization of near surface rocks may cause anomalies similar in appearance to those caused by well casings.

Advantages and Disadvantages

The advantages and disadvantages of the magnetic method for abandoned well search are summarized below.

Advantages:
The method can locate buried well casings which no longer have any surface evidence.

Aeromagnetic methods can provide rapid, large area coverage for reconnaissance using low-altitude fixed wing systems, or low-altitude terrain following helicopter systems.

Data acquisition and results can be obtained relatively fast using the ground magnetic method.

Modern, automatically recording ground magnetometers with real-time GPS for positioning can cover local areas with sufficient resolution to locate well casings to within a few feet.

The method is among the lower cost geophysical survey techniques.

Disadvantages**:**
Only ferrous metallic well casings, such as steel, can be detected.

Small amounts of casing or joints, or deeply buried casings, cannot be detected.

In some areas, cultural magnetic noise due to buildings, pipelines, and debris, or anomalies due to naturally occurring magnetic minerals in near-surface rocks, sediments, or soils, may cause false detections or otherwise interfere with the recognition of buried casing anomalies.

Most commercial and public institutions will require technical assistance to conduct, process, and successfully interpret the data from a magnetic survey.

7.1.5 Case Histories and Literature

Magnetic anomalies due to buried well casings are first described in the literature by Barret (1931). An extensive sensitivity study was conducted by Frischknecht and Raab (1984) where they compared ground and airborne magnetic survey results from several test areas with many wells in Colorado and Oklahoma. For both of the survey methods, greater than 95% of the wells were detected. Where airborne anomalies were difficult to interpret, follow-up local ground surveys were utilized to clarify the results. Paine et al. (1997) describe a survey in which airborne electromagnetic and magnetic data were utilized in an investigation of the source of saline water leaking into the shallow section from unknown wells. Hecker (2001) describes a successful ground magnetic survey of a 130 acre site in eastern Kansas where more than two dozen abandoned wells were found, many of which had no surface ground expression, could not be located on historical aerial photographs, and were found to be unplugged and/or leaking gas to the surface. Other case histories describing the use of the magnetic method for abandoned well search may be found in Johnston et al. (1973), Fairchild et al. (1983, 1984), Frischknecht et al. (1983), Van Ee (1984), Martinek (1988), and Phillips et al. (1995).

Applications which have similar objectives to abandoned well search include airborne or ground magnetic surveys for metallic debris, unexploded ordnance, underground storage tanks, and pipelines. Case histories describing use of high-resolution airborne magnetic surveys for UXO and buried tanks may be found in Doll et al. (2001), Lahti et al. (2001), and Takata et al. (2001), for example. Other useful literature and case histories regarding the use of the magnetic method for these applications may be found in Gilkeson et al. (1992), Brown and Poulton (1996), Gamey and Mahler (1999), Holt and Daniels (2000), LeBlanc et al. (1997), McConnell et al. (1999), Pearson (1996), Phillips et al. (1995), Phillips (2001), Pierce and DeReamer (1993), and Tyagi et al. (1983).

An excellent review of environmental and engineering applications using the magnetic method, as well as summary of the principles of the technique, may be found in Hinze (1990). Breiner (1973) is an excellent, hands-on manual covering many practical aspects of ground magnetic surveying. Other good references on the theory and practice of the magnetic method include Blakely (1996), Dobrin (1976), Nettleton (1971), Nettleton (1976), and Telford (1976).

7.1.6 Time and Cost Estimates

Ground magnetic surveys require very little in the way of setup or equipment preparation and data acquisition is relatively fast. A walking magnetic survey may cover about 5 line-miles per day, depending on terrain and vegetation. The time required for a magnetic survey is comparable to that for small-loop, electromagnetic methods, and generally faster than the grounded electric methods where electrodes must be planted at each station. An aeromagnetic survey, of course, can acquire a large amount of data very quickly; however, for small search areas may be cost prohibitive.

The requesting client and magnetic survey contractor must consult regarding particular objectives, site characteristics, and required survey parameters in order to obtain a cost estimate. A magnetic survey usually consists of the following basic cost factors (the costs shown are general estimates only, based on typical survey prices applicable at present):

Mobilization and demobilization: variable cost

Production (data acquisition):
high-resolution ground magnetic survey: ~ $ 100 to 200 per line-mile (one operator could cover on the order of 5 line-miles per day on foot)

high-resolution airborne magnetic survey: ~ $ 2000 to 5000 per day (This would be for low-altitude, high-resolution work, using a helicopter stinger-mounted or towed system, for example. Line coverage per day depends on many factors such as required airspeed, locations of areas to be covered, distance/stand-time for refueling, helicopter endurance, etc. Helicopter survey costs are usually comprised of a daily rental rate (~ $1500/day), installation/magnetometer equipment setup (several hours, or ~ $500), and additional hourly operating costs.

Downtime (due to inclement weather, magnetic storms, etc.):
typically 0.5 to 1.0 times the production rate.

Expenses (per diem, lodging, fuel, incidentals): Variable cost.

Basic data processing (includes data compilation, processing, logistic reports, etc.): this is usually included in the production rate.

Extra processing, interpretation, interpretive report: often priced at typical technical consulting rates of ~ $ 50 to 150 per hour.

Many companies also rent or sell magnetometers. Typical rental rates for ground magnetometers are about $20 to $100 per day, with digital-recoding, high-resolution vapor magnetometers in the upper price range. There is usually a setup and equipment fee of approximately $100 to $ 300.

A comprehensive list of service and equipment vendors is given in Appendix D of this manual.

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Pierce, D., and DeReamer, J., 1993, “Geophysical Investigation for Buried Drums: A Case Study,” Proceedings of the Symposium on the Applications of Geophysics for Environmental and Engineering Problems (SAGEEP), April 18-22, 1993, San Diego, California, p. 229-244.

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Tyagi, S., Lord, A. E., Jr., and Koerner, R. M., 1983, "Use of Proton Precession Magnetometer to Detect Buried Drums in Sandy Soil," J. Hazardous Materials, 8, p. 11- 23.

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Dobrin, M. B., 1976, "Introduction to Geophysical Prospecting," New York, McGraw-Hill, Inc., 446 p.

Hinze, W. J., 1990, "The Role of Gravity and Magnetic Methods in Engineering and Environmental Studies," Geotechnical and Environmental Geophysics, S. Ward, ed., Society of Exploration Geophysicists, Tulsa, OK, p. 75-126.

Nettleton, L., 1971, "Elementary Gravity and Magnetics for Geologists and Seismologists," Society of Exploration Geophysicists, Tulsa, OK, 121 p.

Nettleton, L., 1976, “Gravity and Magnetics in Oil Prospecting,” New York, McGraw-Hill, 464 p.

Telford, W. M., Geldart, L. P., Sheriff, R. E., and Keys, D. A., 1976, “Applied Geophysics” New York, Cambridge University Press, 860 p.

7.1.8 Selected Web Resources

National Geophysical Data Center:
www.ngdc.noaa.gov

United States Geological Survey’s Geomagnetism Page:
www.geomag.usgs.gov

Society of Exploration Geophysics Gravity and Magnetics Committee Page:
www.seg.org/comm-info/grav_mag

University of British Columbia’s Geophysical Inversion Facility:
www.geop.ubc.ca/ubsgif/tutorials

Colorado School of Mines Introduction to Geophysics Modules:
www.mines.edu/fs_home/tboyd/GP311

7.2 Introduction to Electrical and Electromagnetic Methods

The basis for all electrical and electromagnetic (EM) methods is the earth’s response to applied or natural electromagnetic fields. The electrical methods discussed in this manual include the resistivity and self-potential (SP) methods. These electrical methods are based on the measurement of potentials at the surface of the earth in response to applied or natural electric currents in the ground. In the resistivity and most other electrical methods (excluding the SP method), the energizing source is direct or low-frequency alternating current that is transmitted into the ground via dipoles. Dipoles, in electrical surveying, are pairs of electrodes connected by insulated conducting wire which are used to either generate or detect electrical voltages.

The EM methods presented in this manual include time- and frequency-domain EM methods. (The controlled source audio-frequency magnetotelluric (CSAMT) method has been presented separately from the other EM methods because it is very different in the way the survey is implemented). With EM methods, the energizing source most commonly consists of a closed loop of wire in which alternating current flows (although in some cases, such as the CSAMT method, it can be a dipole source). In EM methods, current in the transmitter generates a magnetic field. The magnetic field is the energizer in electromagnetic methods, as opposed to the electric current in electrical methods.

There is a fundamental difference in the desired response of the earth with these two methods: in EM methods, the inductive response is desired (see "Electromagnetic induction" discussion, below), and in electrical methods the effects of EM induction are considered noise and it is the galvanic response that is desired.

Resistivity and Conductivity of Rocks

In most electrical and electromagnetic methods, the primary property of interest is the electrical conductivity of materials in the earth. Conductivity, σ, is the ability of a material to conduct an electric current. Rocks and soils are often described by a related property called resistivity, ρ, which is the reciprocal of conductivity. Resistivity is analogous to resistance in a simple electric circuit, except that resistivity is an inherent, bulk property of the material.

Resistivity: ρ, in units of (Ohm-meters)
Conductivity: σ, in units of (Mhos per meter)

Most rock-forming materials are not good conductors of electricity, with the exception of native metals, massive sulfides and graphite. The primary factors controlling resistivity of rocks and sediments are porosity, saturation, and pore-fluid content. Pure water is not a particularly good conductor of electricity; however, dissolved salts, even in small amounts, greatly enhance conductivity. Because most groundwater contains dissolved compounds, porosity and saturation tend to dominate electrical resistivity measurements. For these reasons, delineation of fluid saturated zones, or intrusion of highly conductive brines into fresher water areas are common targets of many electrical and electromagnetic surveys. Although not highly porous, clays are also highly conductive (low resistivity). The resistivity of earth materials is extremely variable and may range over several orders of magnitude, as illustrated by Figure 7-5. The general effect of various geological processes on resistivity is shown in Figure 7-6.

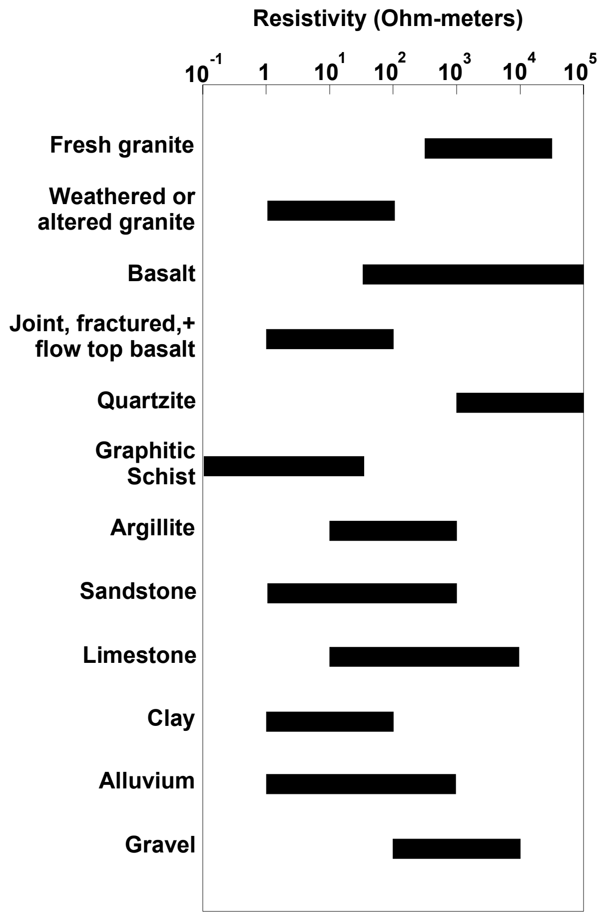

Figure 7-5. **Typical range of resistivity of rocks and sediments (modified after Ward, 1990). For comparison, the resistivity of sea water is about 0.2 Ohm-meters; the resistivity of groundwater ranges from about 0.5 – 300 Ohm-meters, commonly in the 10 – 100 Ohm-meter range**.

Process	Effect on Resistivity
Clay alteration	Decreases
Dissolution	Decreases
Faulting	Decreases
Salt water intrusion	Decreases
Shearing	Decreases
Weathering	Decreases
Induration	Increases
Carbonate precipitation	Increases
Silicification	Increases
Metamorphism	Increases or Decreases

Figure 7-6. Effect of various geological processes on resistivity (modified after Ward, 1990).

Electromagnetic Induction

Electromagnetic (EM) methods of exploration are based on the phenomenon of electromagnetic induction. Usually, an artificially generated electromagnetic field provides the source energy, and the methods are used to determine the conductivity properties of the subsurface. Electromagnetic induction is the process by which electrical currents are generated in conductive materials when placed in an electromagnetic field.

If a time-variable electric current is generated by a transmitter at the surface of the earth (either a loop of wire or grounded electric dipole), a corresponding primary magnetic field of the same frequency and phase is set up. The primary magnetic field may penetrate conductive materials or objects in the subsurface of the earth. When this happens, secondary, or eddy, currents will flow in the subsurface conductor. The eddy currents in turn set up a secondary magnetic field whose lines of force oppose the primary magnetic field. The site of the conductive body is therefore energized by two fields: a primary field from the transmitter and a secondary field due to the induced eddy currents. When characteristics of the transmitted field are known (such as the orientation, frequency, amplitude, and phase), then changes in the characteristics of the field measured at a receiver site can indicate that induced currents are flowing in the ground (after certain corrections are made for geometry, attenuation, etc.). This is the basis by which the conductivity structure (or resistivity structure) of the subsurface is estimated.

Note that like all models calculated from geophysical data, the conductivity structure determined by EM methods is not uniquely determined; it is a best-fit estimate of a possible subsurface model which would generate the observed data at the surface. This is an important concept to keep in mind for techniques such as CSAMT or other techniques in which the final product is a model of the subsurface resistivity structure. For EM techniques which are used simply for detection of subsurface conductors (e.g., fast, small-loop systems such as EM-61, GEM-3, or NanoTEM systems), and not characterization of them, this point is less significant.

7.2.1 The Resistivity Method

METHOD OVERVIEW:
Primary Objectives: delineation of brine plumes or fluid leakage from boreholes.
Measured Parameter: electrical impedance.
Property of Interest: resistivity structure of the subsurface.

7.2.1.1 Introduction

The resistivity method is an electrical technique that is well suited for identifying brine plumes or other fluid leakage that may emanate from an abandoned well. The objective of the survey in this case would be to locate the source of the plume, which might emanate from an unknown improperly plugged or leaking borehole. Because it is a depth profiling method, it is not appropriate for wide-area searches for specific well construction materials such as casings or pipelines, although both of these may cause anomalies in resistivity data.

The resistivity method has been used for many decades for petroleum, mining, and geothermal exploration. In recent years, it has been used for numerous geotechnical and environmental applications. Many of these relate to groundwater: groundwater delineation, evaluation, protection, contamination and tracer studies are all common applications of the resistivity method. It has also been used for mapping shallow geology, tunnels, cavities, buried materials, landfills, archaeology, salt water incursion, and for studies of soil salination, site evaluation, dam integrity, and landslides.

7.2.1.2 Physical Basis

The primary goal of an electrical resistivity survey is to determine the apparent resistivity of soils and rock as a function of depth and position. In the resistivity method, either direct current or low-frequency alternating current is applied to the earth through a pair of electrodes and the potential difference is measured across two receiver electrodes (Figure 7-7). Either direct current or low-frequency AC current is used in order to avoid effects from electromagnetic induction which, unlike electromagnetic methods, are not desired in this case. Pairs of electrodes in a resistivity survey are referred to as dipoles (a dipole, in electrical surveying, is a pair of electrodes connected by insulated conducting wire which is used to either generate or detect an electrical voltage).

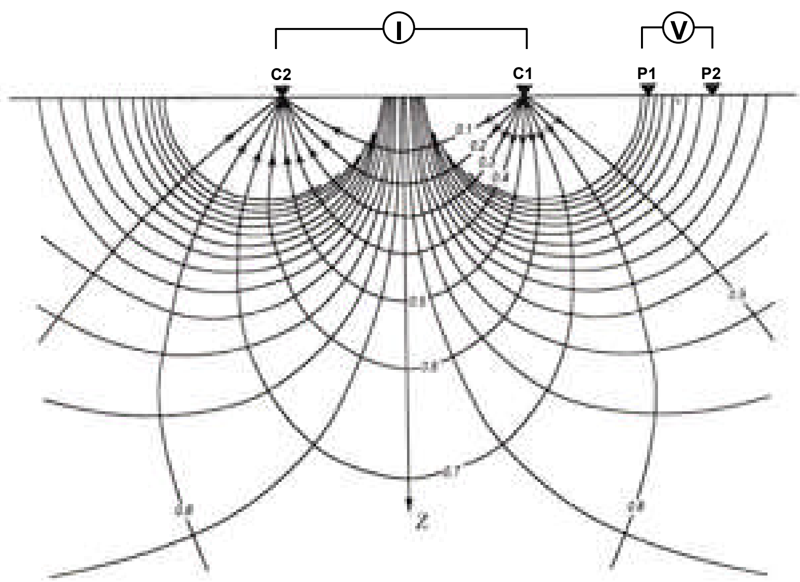

Figure 7-7. Distribution of current and potential lines for two current electrodes at the surface of a simple, homogeneous earth. Current lines represent the surface of tubes each of which carries one tenth of the current. Note that about 50% of the current is carried in the depth range about equal to the separation distance between current electrodes. As the current and potential dipoles are moved apart farther, the current paths would extend deeper; however, more input current is required to get a measurable signal. (Figure modified after Ward, 1990).

The ratio of the voltage output at a receiving dipole to the current input at a transmitting dipole is referred to as the electrical impedance. The apparent resistivity of the ground is then calculated from the impedance by scaling by a correction factor which accounts for the geometry of the survey (specific to the electrode spacing and type of array being used). Apparent resistivity is the average resistivity of all soils and rock influencing the flow of current along a particular path, and thus is somewhat different than the true resistivity of materials. The calculated apparent resistivity of the earth, at a location determined by the geometry and separation of the transmitting and receiving electric dipoles, is related to the amplitude, or real component, of the impedance.

Another measurement that can be made simultaneously using more sophisticated equipment than that used for resistivity-only surveying, is related to the phase, or imaginary component, of the impedance. This measurement relates to the induced polarization (IP) effect, a measure of the earth's ability to polarize at interfaces and thus retain a charge for a short while after the current is turned off (see Appendix A). Resistivity and IP data are very often acquired together, as IP can yield additional information about subsurface materials. With respect to abandoned well search, however, IP data may not yield any more diagnostic information than resistivity alone, especially if the primary target is brine plumes (see Appendix A).

7.2.1.3 Survey Methods

Survey Procedures and Instruments

Resistivity surveys may be conducted using a variety of logistical techniques including those for depth sounding, lateral profiling, or a combination. In resistivity sounding, the distance between the current (transmitting) and potential (receiving) dipoles is expanded in a regular manner between readings, thus 'sounding' to increasing depths with increasing dipole separation. The entire array can then be moved laterally along a line (or different channels utilized in multichannel systems) in order to get a combination depth sounding and profiling image of the subsurface (a resistivity cross-section model). The resistivity method in general comprises a suite of different survey arrays and methodologies. Some of these include the pole-dipole, dipole-dipole, Schlumberger, and Wenner arrays.

Electrical resistance tomography (ERT) is a type of resistivity survey in which an entire array of transmitting and receiving dipoles is employed to yield a high-resolution image of the surface between the two arrays. This is typically done either between two dipole arrays on the surface, between an array of borehole dipoles and an array on the ground, or between dipole arrays in two separate boreholes. While ERT is fairly expensive due to more complex survey logistics and data processing procedures, use of the ERT method would be justified when finding the source of, or monitoring the progress of a well-related plume is critical. In recent years, the use of time-lapse resistivity and ERT surveys has become fairly common, especially for monitoring the development of brine or other contaminant plumes.

Resistivity Instruments

The basic components required for a resistivity survey include a current source, ammeter, potential measuring device analogous to a voltmeter, electrodes, insulated conducting wire cable, and positioning instrument for recording the location of electrodes. Complete resistivity surveying systems are sold commercially. Although not complex, they generally require experienced geophysical technicians or geophysicists to operate properly. Large scale surveys where depth of investigation is greater than about 5 meters require equipment with dipoles of several meters to several hundred meters in length. These are laid out along long, linear spreads. A central geophysical receiver controls where current is directed and records both the current and potentials on the receiving dipoles. Other systems are available in which a portable, pull-along system is dragged along the ground behind a vehicle or cart, and some newer systems employ small portable array systems (e.g., Panissod et al., 1998). Because the depth of penetration depends, in part, on the dipole lengths, these compact, portable systems are only applicable to imaging resistivity in the upper few meters of the subsurface.

Noise Sources

Sources of noise in resistivity measurements include unwanted polarization of electrodes, current induction in cables, high ground-contact resistance, and cultural noise. Cultural noise sources in resistivity measurements can be due to pipelines, powerlines or other infrastructure. Topography can also affect resistivity measurements and must be corrected for. The presence of nearby, off-line conductors can introduce geologic noise into the data, as the source of such cannot be adequately modeled on a 2-D depth model of resistivity along the line. Also, as with all electrical or EM techniques, a highly conductive near-surface zone can limit the depth of penetration for the resistivity method.

7.2.1.4 Applicability

Well-Related Targets

The primary targets for which the resistivity method would be applicable for abandoned well search are brine plumes or other borehole leakage. The objective of the survey in this case would be to locate the source of the plume, which might emanate from an improperly plugged or leaking borehole. Delineation and time-lapse monitoring of a plume is also possible with the resistivity method. Because it is a depth profiling method, it is not appropriate for wide-area searches for specific well construction materials such as casings or pipelines, although both of these may cause anomalies in resistivity data.

The resistivity method yields an estimate of the subsurface resistivity structure. There are several cases in which a resistivity anomaly might occur which is related to an abandoned well. First, an un-cased or improperly plugged borehole might provide a conduit for deeper, more saline groundwater to migrate upwards and laterally in a porous zone containing less saline groundwater. Another situation might arise if a borehole is providing a conduit for water from below the water table to leak upwards into the unsaturated, or vadose zone. Lastly, fluids leaking from the borehole may contain a significant amount of either hydrocarbon contamination or drilling fluid residue. Drilling fluids, although widely variable in composition, are generally conductive, and would generally increase the conductivity of fresh groundwater they came in contact with. The resistivity method has proven very effective for mapping conductivity contrasts in groundwater due to contaminant and brine plumes, and for related investigations (e.g., Barker, 1990; Butler and Llopis, 1990; Ward, 1990; Ardau et al., 2000). In fact, the resistivity method is the most common geophysical method used for these types of investigations.

Sensitivity and Limitations

Whether or not a borehole-related plume can be seen as a resistivity anomaly will depend on the contrast in the resistivity of the plume versus that of the surrounding rock pore fluids, and the size and depth of the plume. In most of the cases discussed above, a low resistivity (high conductivity) anomaly would be expected in the geophysical data. The shallower, thicker, and more laterally extensive the plume, the better the chance for detecting and resolving the plume using resistivity data measured on the surface. In general, lateral resolution of resistivity models depends on the dipole length. Both lateral and vertical resolution decrease with increasing depth. Depth of penetration depends on dipole length, as well as the conductivity of the subsurface. A general rule-of-thumb for effective depth of penetration is about 2 to 3 dipole lengths: 10 meter dipoles could image up to 20 or 30 meters depth; 200 meter dipoles could image up to 400 to 600 meters depth. Increasing the dipole length in order to image deeper decreases the lateral resolution. To alleviate this inherent limitation, in many surveys, data will be acquired using a small dipole length for shallow, high-resolution imaging of the near-surface zone, and then more data will be acquired over the same line using longer dipoles, in order to obtain deeper resistivity information.

For the resistivity method, and all other geophysical methods discussed in this manual, the most difficult situation to detect is when anomalous fluid is confined to an uncased borehole, has very little lateral extent, and does not reach surface. While difficult, the resistivity method may be able to image this situation if the borehole is in line with the potential electrodes (or less than about ½ a dipole length off-line). The nearer the fluid-filled borehole is to an electrode, the better the chance of its causing an anomaly. (Other methods which could possibly detect this situation are the SP or GPR methods).

7.2.1.5 Time and Cost Estimates

The time required for a resistivity survey depends on overall coverage area, number of separate lines, and dipole length required. Survey setup is moderately time consuming, as it involves laying out cables and connecting and burying electrodes. Difficult terrain and vegetation can impede progress. Generally, a field crew of 2 to 4 people is required for an extensive, deep resistivity survey; shallow imaging, pull-along systems may be operated by 1 or 2 crew people.

The requesting client and resistivity survey contractor must consult regarding particular objectives, site characteristics, and required survey parameters in order to obtain a cost estimate. A resistivity survey usually consists of the following basic cost factors (the costs shown are general estimates only, based on typical survey prices applicable at present):

- Mobilization and demobilization: Variable cost. Include travel to and from the site, and costs of shipping equipment.
- Production (data acquisition): ~ $1,600 to $1,800 per day for a typical resistivity survey crew. A crew may acquire from ~ 25 to 100 stations per day, depending on dipole length, terrain, etc. Shallow imaging, pull-along resistivity surveying may cost significantly less and be able to acquire more data faster than deep-imaging surveys.

- Downtime (for example, due to inclement weather): Typically 0.5 to 1.0 times the production rate.

- Expenses (per diem, lodging, fuel, incidentals): Variable cost.

- Basic data processing (includes data compilation, processing, logistic reports, etc.): this is usually included in the production rate

- Extra processing, interpretation, interpretive report: Often priced at typical technical consulting rates of ~ $ 50 to $ 150 per hour.

A comprehensive list of vendors who provide resistivity and other geophysical survey services is given in Appendix D of this manual.

7.2.1.6 References

Case histories and Methodology Studies:

Ardau, F., Balia, R., Barbieri, G., Barrocu, G., Gavaudo, E., Ghiglieri, G., and Vernier, A., 2000, "Geophysical and Hydrogeological Studies in a Coastal Plain Affected by Saltwater Intrusion," Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems (SAGEEP), February 20-24, 2000, Arlington, Virginia, p. 223-231.

Barker, R. D., 1990, "Investigation of Groundwater Salinity by Geophysical Methods," Geotechnical and Environmental Geophysics, Vol.II, S. Ward, Society of Exploration Geophysicists, Tulsa, OK, p. 201-211.

Butler, D. K., and Llopis, J. L., 1990, "Assessment of Anomalous Seepage Conditions," Geotechnical and Environmental Geophysics, Vol.II, S. Ward, ed., Society of Exploration Geophysicists, Tulsa, OK, p. 153-199.

Panissod, C., Michel, D., Hesse, A., Joivet, A., Tabbagh, J. and Tabbagh, A., 1998, "Recent Developments in Shallow-Depth Electrical and Electrostatic Prospecting Using Mobile Arrays," Geophysics, 63, p. 1542-1550.

Ward, S. H., 1990, "Resistivity and Induced Polarization Methods," in Geotechnical and Environmental Geophysics, S. Ward, ed., Society of Exploration Geophysicists, Tulsa, OK, p. 147-189.

General References on Theory and Practice of the Resistivity Method:

Hallof, P. G., 1992, "Grounded Electrical Methods in Geophysical Exploration," Practical Geophysics II for the Exploration Geologist, R. Blaricom, ed., Northwest Mining Association, Spokane, Washington, p. 39-138.

Keller, G. V., and Frischknecht, F. C., 1966, "Electrical Methods in Geophysical Prospecting," Pergamon, New York, 519 p.

Telford, W. M., Geldart, L. P., Sheriff, R. E., and Keys, D. A., 1976, "Applied Geophysics" New York, Cambridge University Press, 860 p.

Ward, S. H., 1990, "Resistivity and Induced Polarization Methods," Geotechnical and Environmental Geophysics, S. Ward, ed., Society of Exploration Geophysicists, Tulsa, OK, p. 147-189.

7.2.1.7 Selected Web Resources

University of British Columbia's Geophysical Inversion Facility:
www.geop.ubc.ca/ubsgif/tutorials

Colorado School of Mines Introduction to Geophysics Modules:
www.mines.edu/fs_home/tboyd/GP311

7.2.2 The Self-Potential Method

METHOD OVERVIEW
Primary Objectives: location of corroding steel well casing, delineation of brine plumes or fluid leakage from a borehole
Measured Parameter: potential (ground voltage)
Property of Interest: electrochemical polarization or ionic flow in the ground

7.2.2.1 Introduction

The Self-Potential (SP) method is a passive electrical survey method which is relatively simple and inexpensive to implement, although it would be rather labor intensive for abandoned well search. SP anomalies have been noted in the past near well casings which are undergoing corrosive processes. In addition, brines or other ionic fluids leaking through a borehole could possibly be detected with the SP method. For various reasons, the method would be less reliable than electromagnetic or magnetic methods for locating well casings; however, it may be useful and cost-effective in some cases for locating brine plumes or other fluid leakage from boreholes.

The Self-Potential (SP) method has been used for many decades in the petroleum and geothermal exploration industries and has been used since the early 1800's for mineral exploration. In the environmental and engineering industries, the SP method has been primarily used to investigate subsurface water movement. Recent applications include delineating flow patterns near faults, landslides, and engineering structures; investigating groundwater flow patterns; and mapping leaks or seepage from containment structures such as dams, dikes, waste contaminant ponds, and underground storage tanks.

7.2.2.2 Physical Basis

Electrochemical reactions between metallic objects or ionic fluids and the surrounding rocks or soil cause electrical potentials which drive naturally occurring DC currents in the earth. Self-potential (sometimes called spontaneous polarization) is the naturally occurring, electrical potential of the earth resulting from these geologic, geochemical, and hydrologic interactions.

Electrical Potential

The voltage, or potential difference, between two points is a measure of the amount of work done in moving a charged particle from one point to the other, in the presence of an electric field. Electrical potential is expressed in units of Volts (V), or more commonly in geophysical work, milliVolts (mV). The strength or intensity of the electric field is the gradient of the potential.

The origins of self potentials in the earth are not entirely understood, but they comprise two basic components: mineral potential and background potential. Mineral potential arises from electrochemical processes within conductive minerals in the ground. Background potential varies with time and is primarily related to groundwater flowing in the ground as an electrolyte. The various types of potentials commonly dealt with in surface geophysics are listed below:

- A streaming potential results from the actual flow of an electrolyte (fluid containing ions) in the ground, such as brine or salt water.

- An adsorption potential results when an electrolyte is in contact with a solid and a potential difference occurs across a diffuse layer near the interface where the ions are relatively mobile.

- A liquid-junction, or diffusion, potential is produced at the contact between fluids with different ionic concentrations. Here, mobile, negatively charged anions tend to cross the contact surface more readily than the larger, positively charged cations, resulting in a potential difference across the boundary.

- The shale potential, usually discussed relative to SP wireline logs in boreholes, results because shale acts as a cationic membrane permitting sodium cations to flow through it, but not chloride anions.

- An electrolytic contact potential is developed between dissimilar metals when in contact with an electrolyte.

- A polarization potential results from the polarization of bodies containing primarily metallic minerals in the ground. Natural polarization of interfaces in the ground can occur due to processes of ionic conduction in metallic bodies, or induced polarization at interfaces may occur due to electronic conduction which is excited by artificially generated electric fields.

Sources of SP Anomalies

Groundwater is the common factor in most processes that generates self potentials. Ore bodies, especially massive sulfides, which are in contact with groundwater often have large SP anomalies associated with them. Sources of SP anomalies can also be due to flowing groundwater, differences in groundwater ionic concentration, various mineral/groundwater interactions, oxidizing metallic objects in the ground (such as pipes or well casings), and variable near-surface conditions in soil properties, saturation, and vegetation. Negative SP anomalies are sometimes observed over the tops of well casings, where an oxidation-reduction mechanism similar to that observed in buried ore bodies may be occurring. If a well casing penetrates the water table, then differences in the amount of available free oxygen above and below the water table cause a galvanic cell to develop in the ground (DC current cell, similar to a battery), and a negative potential is measured over the cell relative to the surrounding area (Figure 7-8). Figure 7-9 shows some actual SP anomalies observed over a buried pipeline and steel well casing.

SP anomalies are often observed to be correlated with topography. They are usually negative over topographic highs and are thought to be due to the downslope movement of subsurface water. These potentials are not seen consistently, but when present may be as much as a few milliVolts per meter of elevation (Corwin, 1990). Topographic anomalies are most often observed in the vicinity of volcanic geology, porous near-surface rocks, large topographic changes, or abundant, near-surface groundwater.

Telluric currents (natural, low-frequency electric currents in the earth due to the interaction of the ionosphere and the earth's magnetic field) and artificially generated electric fields (such as those from power lines and cathodic pipe protection systems) can also cause SP anomalies, but these are considered noise for most geophysical surveys. In addition, anomalous noise can be generated from inadequate or improper SP surveying techniques. For example, the cumulative effect from electrode drift and polarization over time can introduce coherent noise into SP data.

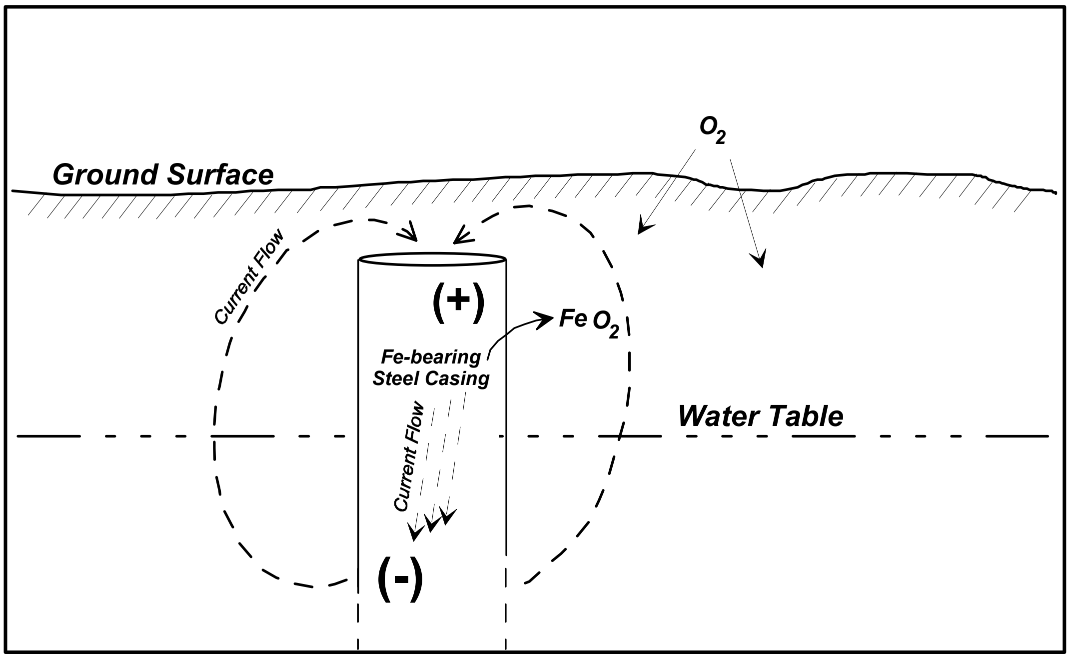

Figure 7-8. Schematic of a possible galvanic-cell mechanism for generating negative SP anomalies over a buried well casing.

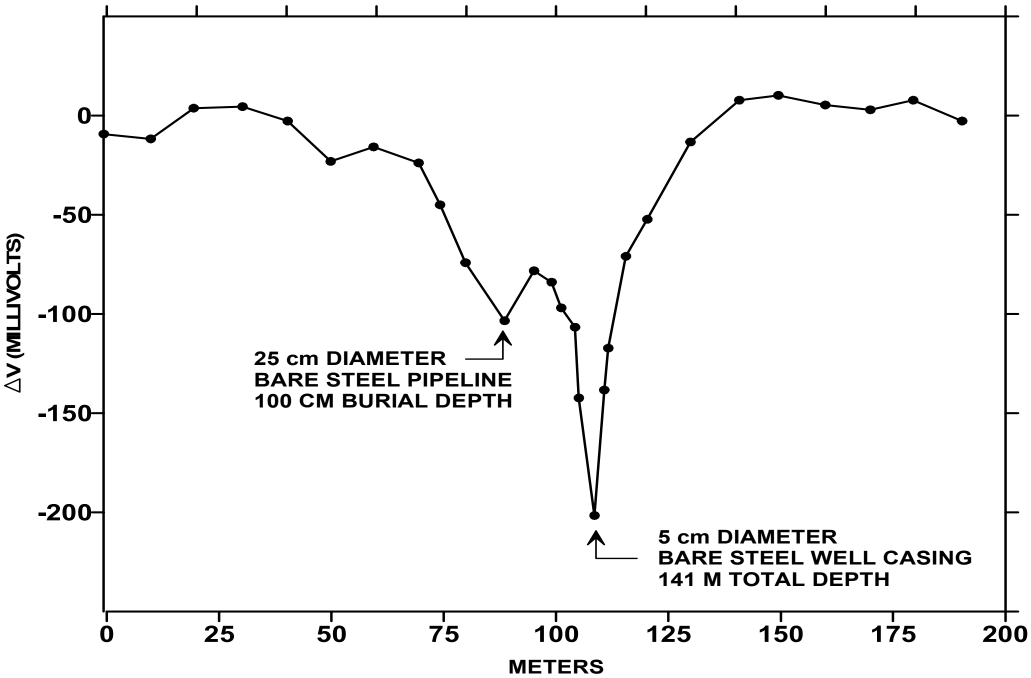

Figure 7-9. Self-potential anomalies generated by buried metal pipelines and well casings at East Mesa, California (after Corwin, 1990).

7.2.2.3 Survey Methods

The quality of SP data depends heavily on survey configuration and procedures, selection and maintenance of equipment, and the use of appropriate data reduction techniques. The SP method has been used successfully for many years; however, the method has a reputation for problems with repeatability and reproducibility. Very careful attention to field techniques and proper supervision by a responsible geophysicist can, however, yield excellent, high-quality SP data.

SP Instruments

Self potential survey equipment is relatively inexpensive and easily obtained, although complete 'systems' of SP survey equipment are less readily available than for other geophysical methods. SP survey equipment consists simply of two electrodes, a connecting wire, and a high-precision voltmeter. A digital voltmeter with high input impedance should be used with a measurement precision of 0.1 mV or better. The electrodes should consist of non-polarizing, porous-pot electrodes. These generally yield the best, most repeatable data for SP surveys and consist of a conductive piece of metal, such as copper, immersed in a saturated solution of its own salt, such as copper-sulfate solution. The electrodes are then in contact with the soil through a porous, ceramic vessel (pot). Survey stations may be positioned relative to local landmarks using tape and chain, or by more rapid and efficient means such as real-time GPS surveying (see Appendix B).

Survey Procedures

The SP method measures electrical potential, or voltage, between electrodes placed in the ground in order to delineate subsurface sources which are creating the potential difference. The potential levels measured in an SP survey are always arbitrary; that is, they are measured relative to a base station which is usually outside the area of interest. The value at the base station is arbitrarily assigned a value of 0 mV. The second potential electrode is placed at various measurement stations within the area of interest, and the voltages measured are then either positive or negative values relative to the base station (the base pot is always attached to the negative lead of the voltmeter). For an abandoned well search, station spacing on the order of 5 to 10 ft would be required.

SP surveying is relatively simple and may be conducted either with a single person, or with a field crew of two. When using GPS for station positioning, two people will be required, one to carry the wire reel and GPS antenna, and the other to take the station voltage and location measurement readings.

Procedural controls which help to insure good quality SP data should include:

- No spurious potentials should be introduced by the measurement technique or equipment.
- The reference electrode should be placed outside the system in dry ground (above the water table and not in a reducing environment such as a bog or swamp).
- The survey design should minimize movement of the reference electrode to the extent possible.
- A telluric current monitor should be deployed which allows monitoring of the longer period, greater than 1 sec, telluric currents.

- Time should be recorded at for all station readings for comparison to the telluric current monitoring data.

- Stations should not be placed in the immediate vicinity of possible cultural noise sources such as power lines, telephone lines, pipelines, power plants, substations, etc. Base station electrodes should be located at least 500 meters away from any of the above.

Data Processing and Interpretation

SP data requires little in the way of basic data reduction if careful survey procedures have been followed. Time profiles of the data may be compared qualitatively to the telluric monitoring data to identify possible noisy areas and check repeatability in these areas. Quantitative correction can also be applied for telluric variations. On 1-D profiles, or 2-D maps, SP data are often examined for regional trends, and residual maps or profiles are generated to emphasize the local anomalies of interest. Trends in the spatial pattern of vegetation, topography, soil variation or saturation should be noted in field data for comparison.

Interpretation techniques for SP data can be either qualitative or based on complex, analytical modeling programs. Another commonly used and quite useful interpretive technique is the comparison of observed anomalies with standard curves or contours calculated for simple source models.

7.2.2.4 Applicability

Well-Related Targets

There are two specific well related targets which could be successfully identified using the SP method. These are:

1. A borehole which is providing a conduit for ionic fluid leakage. In particular, an improperly plugged borehole may provide a conduit for brine from deeper aquifers to migrate up toward the surface. Leakage may be confined to the borehole itself in some depth range, may leak all the way to the surface, or may leak laterally from a borehole into a confined porous subsurface layer.

2. A well casing in which iron or other oxidizable constituents are in contact with groundwater, and corrosive processes are taking place.

Sensitivity and Limitations

Modern multimeters can easily measure potential differences of 0.1 milliVolts. The SP response expected over a well casing may range from no response to anomalous amplitudes on the order of 100 mV or more, usually negative. The environmental conditions around the well will determine if electrochemical potentials exist which are due to the well casing or fluid flow within the wellbore. The ability to detect an abandoned well using SP will be determined by the following two factors: 1), whether or not electrochemical reactions are occurring in the subsurface due to the presence of the well casing or wellbore fluids, and 2), if a potential anomaly is generated, is it distinguishable from interfering signals from other sources in the area. Table 7-4 shows some common ranges of SP anomaly amplitudes expected from various naturally occurring sources.

An example of an actual SP anomaly from a 5 cm diameter, steel casing (shown in Figure 7-9 above) is on the order of -100 mV in amplitude (Corwin, 1990). In a test of the SP and other geophysical methods for abandoned well search, Frischknecht (1983, 1984) found similar large, distinct SP anomalies for 4 out of 11 known wells. The remaining 7 wells had small, clearly distinguishable anomalies on the order of -20 mV; however, Frischknecht points out that there were other similar anomalies of unknown origin in the data which may have complicated interpretation had the survey been an abandoned well search, rather than a test study.

The biggest limitation of the SP technique is its sensitivity to naturally occurring, time-variable background potentials, the sources of which are numerous and not well understood. SP anomalies are often observed for the targets of interest in a survey; but, the abundance of similar anomalies from other unknown sources may lead to high rates of 'false detection' of the survey objective targets (Frischknecht, 1984; Mmann et al., 1997). Nevertheless, SP has been used successfully and quite often for identifying sources of subsurface leakage and flows (e. g., Perry et al., 1996; Sirles, 1997).

Used alone, the SP method may have only moderate reliability for abandoned well detection. Metallic well casings would best be identified using magnetic or electromagnetic methods, and these methods would also be somewhat more cost-effective due to the speed and efficiency of ground coverage. The SP method may be useful and cost-effective tool for delineation of near-surface brine or hydrocarbon contaminant plumes related to abandoned wells (e.g., Corwin, 1990; Vichabian, 1999; Zonge et al., 1985). Taken together, SP data could provide an independent data set which is sensitive to different noise factors than magnetic or electromagnetic data. Joint interpretation of two independent geophysical datasets would greatly increase the chance for successful identification of abandoned wells.

TABLE 7-4
Common Sources of SP Anomalies and Typical Range of Amplitudes

Source	Sign of Anomaly	Approximate Amplitude Range
Mineral Potentials		
Ore bodies (conductive minerals)	Negative	100 to 1000 mV
Quartz veins, pegmatites (resistive minerals)	Positive	10 to 100 mV
Background Potentials		
Fluid streaming, geochemical reactions	Positive or Negative	<100 mV
Bioelectric effects from vegetation (plants, trees)	Negative	<300 mV
Groundwater movement	Positive or Negative	100 to 1000 mV
Topography	Negative	up to 2000 mV (or up to few mV per meter elevation change)
Well Casings (geochemical/corrosive processes)	Negative	20 to 100 + mV

7.2.2.5 Time and Cost Estimates

SP surveying is relatively fast and inexpensive when compared to most other grounded electrical surveys. Equipment is simple and readily available. Probably the most expensive item in an SP survey for abandoned well search would be rental or purchase of a GPS system for station positioning. A sub-meter accuracy system, such as a DGPS would be adequate (Appendix B) for this method and application. An SP survey would consist of the following basic cost factors (the costs shown are general estimates only, based on typical survey and equipment prices applicable at present):

- Mobilization and demobilization: variable cost

- Production (data acquisition): ~ $ 500 to 1000/day (~ $100-$300/day for GPS rental; 1 to 2 field operators for 8 hrs @ $50/hr, $20-$100/day SP equipment rental- multimeter, wire and reels, electrodes)

- Downtime (due to inclement weather, etc.): typically 0.5 to 1.0 times the production rate

- Expenses (per diem, lodging, fuel, incidentals): Variable cost.

- Basic data processing (includes data compilation, processing, logistic reports, etc.): this is usually included in the production rate

- Extra processing, interpretation, interpretive report: often priced at typical technical consulting rates of ~ $ 50 to 150 per hour

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7.2.3 Time and Frequency Domain Electromagnetic Methods

METHOD OVERVIEW
Primary Objectives: detection of metallic casing, or delineation of brine plumes or fluid leakage from boreholes.
Measured Parameter: variable, depending upon particular implementation of the method.
Property of Interest: response from metallic casing, or resistivity structure of the subsurface.

7.2.3.1 Introduction

The electromagnetic methods, both time and frequency domain, allow information concerning the subsurface conductivity (and to a lesser degree magnetic permeability) to be measured from surface measurements.

Anomalous materials associated with abandoned wells are generally conductive in comparison to background earth resistivities. Two distinct targets are available for detection of abandoned wells using the electromagnetic methods. The first of these is direct detection of metallic materials within and surrounding the well. These metallic materials would include well casing, product lines, and water lines that may have led to the well. Steel pipe, of which most of these materials are constructed, is up to 10,000 times more conductive than normal earth materials, making this an ideal inductive target. In addition, the high magnetic permeability of steel adds to the electromagnetic response.

A second possible target often associated with abandoned wells is conductive soils created by brines leaking from the wells and increasing both the salinity and water saturation of the near surface (Sandberg, et. al. 2002). In areas in which the surface casing has been removed, this methodology can be successful when no direct target, such as metallic casing, is available.

In addition to mapping both metallic materials and conductive plumes, the electromagnetic methods are non-invasive – no electrodes need be installed into the earth. Both the transmitter and receiver are carried, towed or flown across the earth's surface without the sensors having to be in direct contact with the earth. This can be particularly important in environmentally and culturally sensitive areas as well as areas covered with asphalt or concrete.

7.2.3.2 Physical Basis

Basics of the Electromagnetic Methods

The time and frequency domain electromagnetic methods are based upon the same fundamental physical processes. A transmitter, effectively a loop of wire, is driven by a time varying current. The change in current, and resulting EM field, establishes an image current within the earth equal in magnitude but opposite in sign to that of the transmitter. This image current then interacts with conductive materials, setting up secondary magnetic fields that are measured at the surface of the earth.

Time-Domain Electromagnetics (TDEM)

The transient electromagnetic or TEM technique, which is sometimes called time-domain EM (TDEM) or pulse EM (PEM), has been traditionally used for vertical depth sounding or profiling, as well as deep sounding metal detection. In the TEM method, a transmitter emits nearly square-wave current pulses of alternating sign and the transient, or decaying field, is measured when the transmitter is off. With this method, the depth, total conductivity, and magnetic permeability of a buried conductor are reflected primarily by the magnitude of the secondary field, as well as the rate of decay and spatial extent of the anomalous response. As Figure 7-10 illustrates, the TDEM method relies on the different rates of decay of the secondary field to distinguish between a normal conducting earth response and a response from a buried metallic conductor.

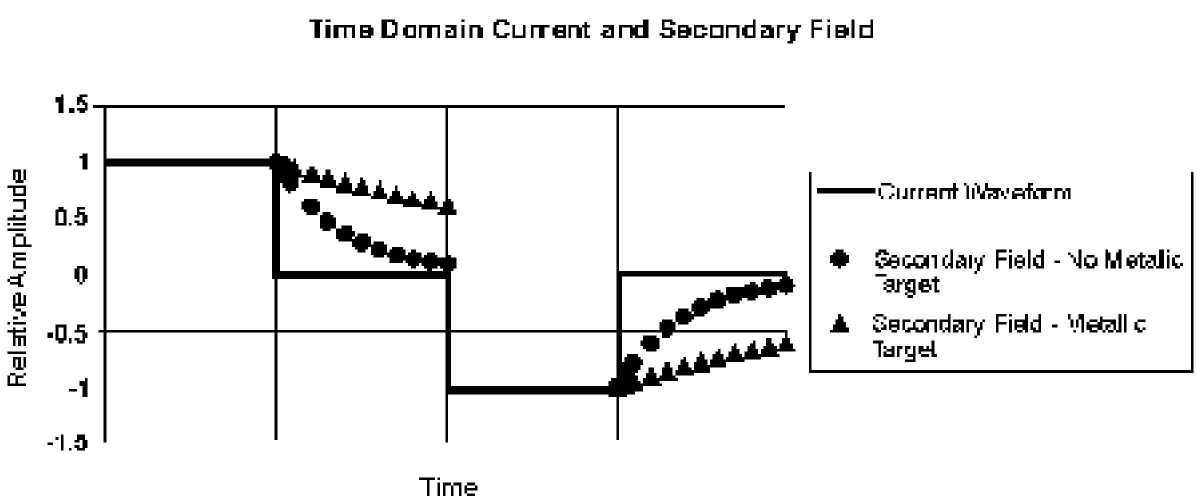

Figure 7-10. Secondary field decay curve schematic for TDEM data.

The equipment consists of a transmitter/receiver system that can be arranged in different geometries depending upon target of interest and the survey design. The sending and receiving antennas loops consist of wire near the ground, with the size depending upon the depth of exploration desired and the size of the target. The depth of exploration attained in a vertical sounding configuration can vary from a few meters to more than 1,000 meters, depending upon transmitter loop size and geometry, available power from the transmitter, and ambient noise levels.

The large TEM vertical sounding arrays used for mapping large-scale resistivity variations produce similar types of data as the CSAMT method discussed in Section 7.2.4 of this manual, however lateral variations in resistivity are smoothed and the logistics are distinctly different. At each sounding location the transmitter is laid out, with a sensor at the center of this loop. Measurements of the vertical magnetic field are made as a function of time after turnoff of the transmitter. Multiple measurements, sometimes several thousand, are averaged together to increase the resolution of these measurements. The depth of investigation (Figure 7-11) using the TDEM method is a function of the electrical resistivity of the subsurface, the time of the measurement after turnoff of the transmitter, and the total transmitter moment (the product of transmitter size times the current injected into the loop.) Systems such as the Geonics ProTEM and Zonge ZEROTem systems are specifically designed to meet the demanding resolution requirements of these systems.

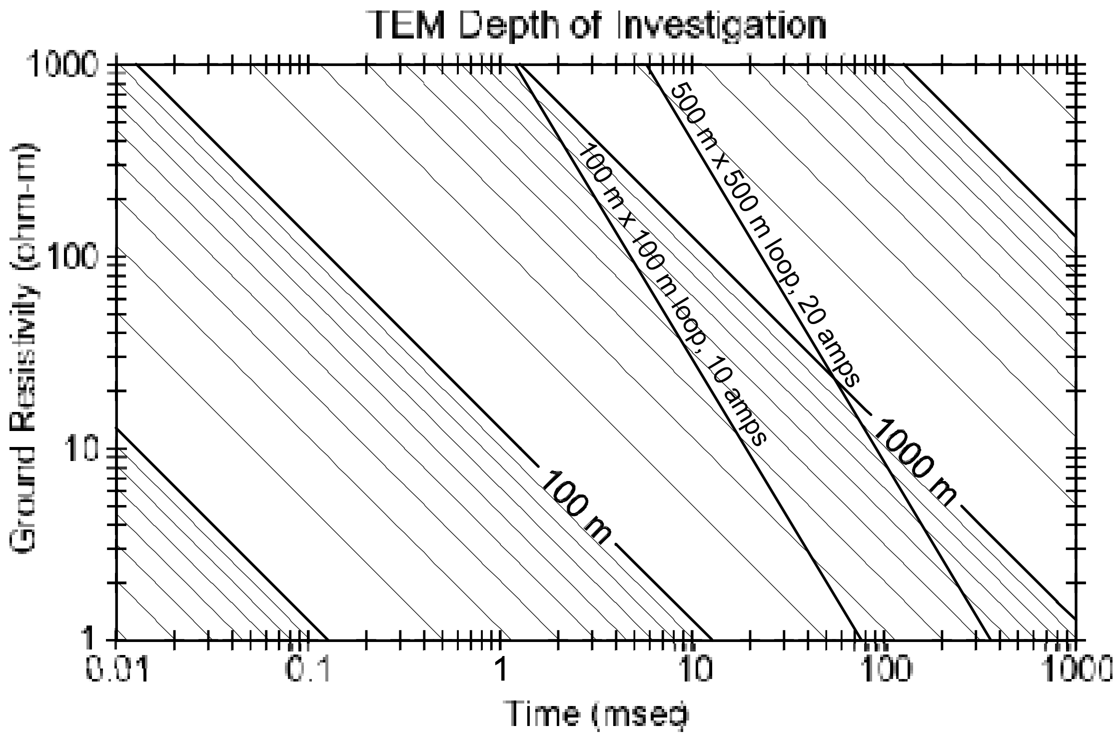

Figure 7-11. Depth of investigation for time-domain EM (TDEM).

Small loop TDEM has been successfully used to locate abandoned wells, unexploded ordnance (UXO), underground storage tanks (USTs), and other buried metallic objects. Small array TEM configurations usually consist of transmitter and receiver loops of one meter or less in size. These systems are portable and efficient, and some can cover ground in a continuous mode allowing the survey area to be covered with similar efficiency to a ground magnetics survey. However, the depth of investigation for small array TEM systems is limited to approximately 3 meters. (Three dimensional targets must be approximately 10% of the depth of burial for detection For instance: A 1 meter x 1 meter sheet of steel will be detectable if buried up to about 10 meters.)

Frequency-Domain Electromagnetics (FEM)

In the frequency-domain electromagnetic (FEM) method, a transmitter emits a periodically varying current at a specific frequency or set of frequencies. In the receiver coil, a secondary field generated by induced currents in a buried conductive body is measured. The physics of the process is identical to the TEM method; the difference being that in the time-domain method, a transient wave-form is measured when the transmitter is off, and in FEM the combined fields from the transmitter and secondary induced field are measured while the transmitter is on. FEM measurements require some sort of phase-lock or reference between the transmitted and received waveforms in order to measure the in-phase and out-of-phase components of the received signal. The depth and size of a conductor primarily affect the amplitude of the secondary field, while the quality of the conductor generally affects the ratio of in-phase to out-of-phase components (good conductors having higher ratios and poor conductors having lower ratios). The received voltage is usually reported in parts per million (ppm) of the primary field.

Similar to TEM, a wide-range of instrument types and designs are available for FEM ranging from small, inexpensive metal-detectors, to much more sophisticated instruments. (Simple, low power metal-detector systems will not be discussed in this report.) Transmitter loop sizes vary, depending on the depth of penetration desired. Single frequencies or a narrow-band of frequencies may be used. Broad-band FEM instruments which employ multiple frequencies in order to penetrate to different depths (depth sounding) are also available.

7.2.3.3 Survey Methods

There are several vendors for both time and frequency domain instruments in North America. Among the frequency domain instruments, two general classes of instruments are available. The first of these utilize some variation of an electromagnetic "dipole-dipole" array, with the transmitter and receiver separated by some fixed distance and coplanar transmitter and receiver loops. The most commonly used shallow sounding systems with this configuration are the Geophex GEM-2, and Geonics EM-31. While these instruments differ in specifics, they are similar in overall functionality.

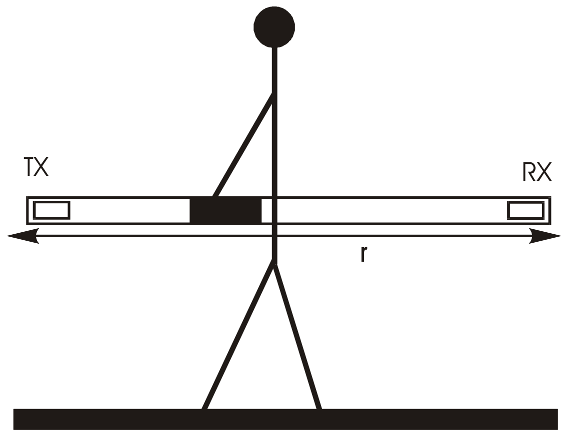

Figure 7-12. General Schematic of Dipole-Dipole EM Systems (Diagram from www.geophex.com)

The depth of investigation for frequency domain EM systems depends on frequency, subsurface resistivity, and the intercoil spacing ("r" in Figure 7-12). In general, the lower the frequency the greater the depth of investigation; and the higher the ground resistivity, the greater the depth of investigation. However, for ground based systems the primary control on the depth of investigation is the intercoil distance, as pointed out in Geonics' technical note TN-31. For these systems the majority of any electromagnetic response is from a depth of 40% of the intercoil distance with the transmitter coils vertical. Lateral resolution is controlled primarily by the station spacing, which is a critical component in the survey design.

A second style of frequency domain system utilizes a central loop orientation, with the transmitter and receiver loops both within a single sensor head. The only system available within North America with this configuration is the Geophex GEM-3 system, shown in Figure 7-13. This system uses a specialized transmitter geometry that creates a zone in the center of the that has no primary field. In this area the receiver loop can measure secondary fields, without the effect of the primary field interfering. This system has been developed primarily as a high-resolution metal detector system for use in locating UXO and land mines and is not designed to map the electrical resistivity of the subsurface.

Figure 7-13. GEM-3 (Photo from www.geophex.com)

The frequency domain instruments utilized in helicopter surveys (Figure 7-14) also use the Dipole-Dipole array geometry and operate over a broad range of frequencies. Airborne systems have significantly higher production rates, with coverage ranging from 400 to 800 line-kilometers and depths of investigation of up to 100 meters. For covering large areas, helicopter electromagnetic surveys could be an important tool. However, with respect to abandoned search, helicopter systems are not designed for detecting small metallic targets and are instead more applicable to measuring variations in resistivity created by brine plumes.

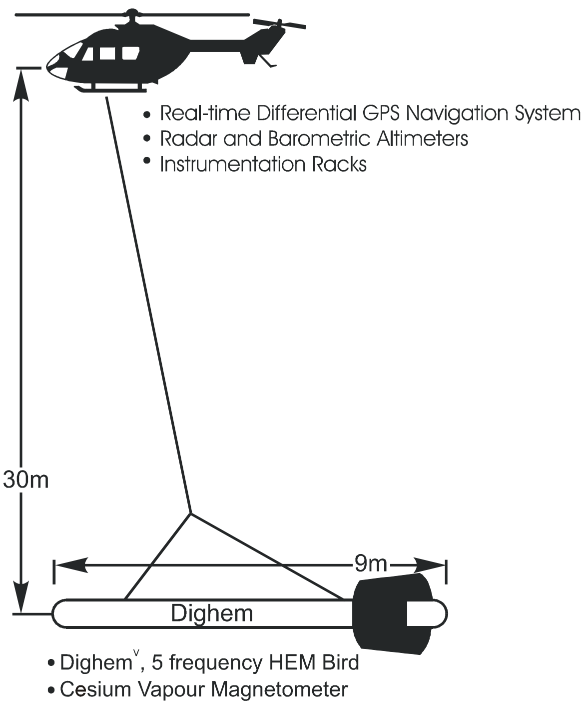

Figure 7-14. Example Airborne EM System (Redrawn from www.fugroairborne.com) (Further information on frequency domain EM instruments can be found in Geonics TN-31; McNeil, 1980;Won et al., 1996 and Won et al., 1998).

As discussed above, time domain instruments utilize some variation of a central loop geometry to collect information describing the electrical conductivity of materials in the subsurface. Two variant styles of TDEM data can be collected depending upon the target. The first method utilizes small transmitter and receiver loops and is designed to directly detect the response from discrete metallic items. These systems do not collect information concerning the earth resistivity and instead are effectively deep sounding metal detection systems. An anomalous signal in the late-time received transient waveform is, however, indicative of buried metals or other extremely good conductors and magnetic permeability adds to this response. Systems such as the Geonics EM-61 are designed to record just this late time response, making them very effective metal detection systems.

Larger loop systems are used to detect variations in the overall conductivity structure. These tools, commonly used in the mining and groundwater industries, consist of measurements that can be made in lines, in a grid, or scattered into available areas away from cultural effects. Spacing between stations need only be close enough that two or more stations be located over any conductive zone. Therefore some estimate of the size of any conductive plume must be generated to assist in the design of the survey.

Intermediate between the large loop and small loop systems are systems such as the Zonge NanoTEM system. This system can be utilized both in a small transmitter loop configuration, as is illustrated in Figure 7-15, or as part of a large loop system with a moving receiver within the central portion of the transmitter.

Figure 7-15. Zonge NanoTEM system

This second system, referred to as "fast turn-off" system (in reference to the turnoff of the transmitter) allows the early-time receiver transient waveform to be sampled. If the transmitter loops are large enough to capture the earth response, the early time transient contains information which describes the earth's conductivity, and thus may be useful for mapping surface alteration or other shallow ground conditions indicative of brine leakage. Data presented in Figure 7-16 were collected from stations surrounding a buried well casing using a 10m by 10m transmitter loop. The early time data, from 0.0005 to .02 milliseconds is in this case the earth response. At later time, particularly 0.1 milliseconds and later, there is a clear separation in the response between background and the response over the well casing. This survey design, with an intermediate sized transmitter loop and small receiver loop allowed information to be collected describing the electrical resistivity structure of the earth while detecting the metallic conductive signature of the casing (Carlson, et al, 1996).

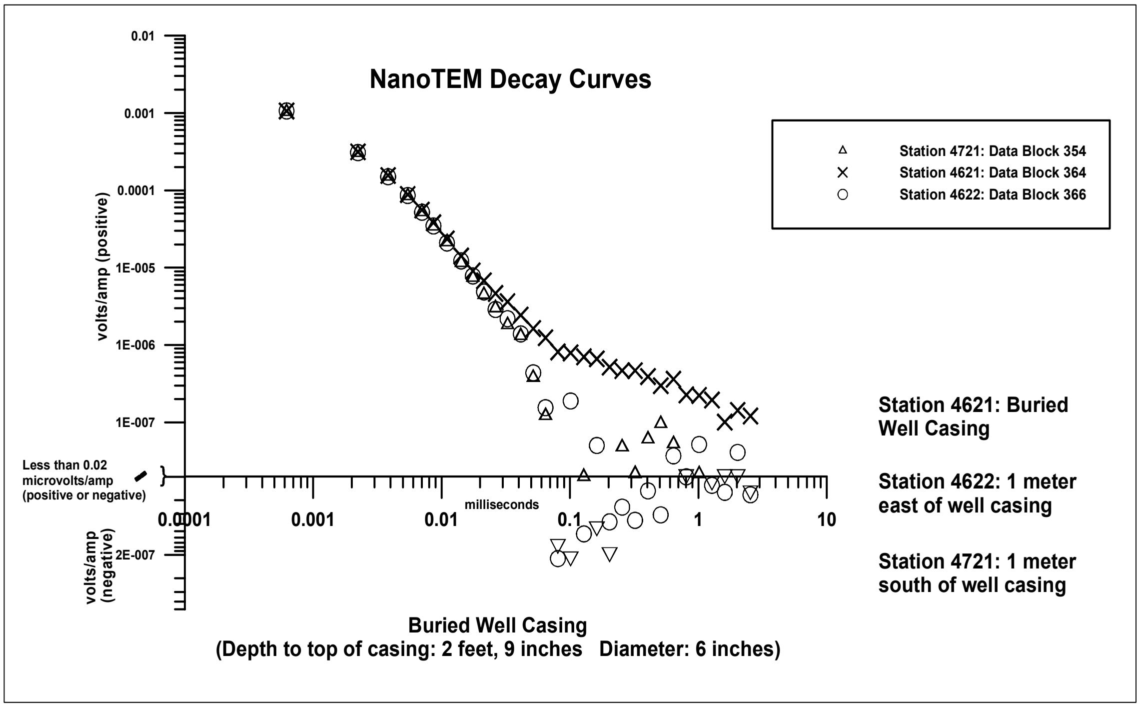

Figure 7-16. Zonge NanoTEM system decay curves over buried well casing.

Choices concerning the size of the transmitter loop, the location of the receiver loop, and time range measured all significantly affect the ability of the systems to detect specific targets. Smaller loops, less than a couple of meters in extent, are generally used for metal detection surveys while larger loops are used for mapping variations in the electrical resistivity of the earth.

Data Processing and Interpretation

There are several stages in the processing of electromagnetic data. The first step is to correct for any time dependant instrumentation drift. After correction for drift, the electromagnetic measurements are integrated with spatial information, either from surveys or GPS recordings. An examination of this integrated data set as profiles is then performed to identify any instrumentation problems. In addition to these basic processing steps, various types of spatial and time domain filters can be applied to the data sets in an attempt to reduce the effects of noise sources.

Finally, contour plots of the received secondary field voltages are generated and the contoured results are compared to known cultural sources, such as fences, water tanks, power lines, etc. which may have responses similar to that of the abandoned wells.

7.2.3.4 Applicability

Targets and Limitations

The controls on the detectability of abandoned wells are similar to those of the magnetic methods, discussed in Section 7.2. In the case of detection of the casing within the hole, these include the separation between the electromagnetic sensor and the top of the well casing, the total conductance of the metallic material (related to both the size and material type of the casing), and the background noise levels.

Noise sources for electromagnetic observations can be separated into two types, geological and cultural. Geological noise is the electromagnetic response from naturally occurring materials, such as highly magnetic rocks or conductive rocks, which have large electromagnetic responses. Cultural noise is the response from man-made items, such as fences and power lines, that interfere with the detection of subsurface conductive items.

The amount of published data concerning the magnitude of the response from a metallic casing is limited and is also a function of the sensor type and geometry, total conductance of the casing, and the depth to the top of the target, and therefore it is difficult to provide a range of possible responses. However, electromagnetic instruments have been utilized for a broad range of related problems ranging from detection of utilities to location of Unexploded Ordnance (UXO).

As an example, the mapping of an 18-inch diameter stainless steel pipe buried at 30 feet below surface has a response of more than 5000 ppm and is clearly defined by the data shown in (Figure 7-17). A magnetic survey of this area failed to detect this object, presumably because it is stainless steel (data and description from www.geophex.com). This data set also illustrates the data collection density required to detect objects of this size. The response from the steel pipe is limited to several meters width in spite of its large size.

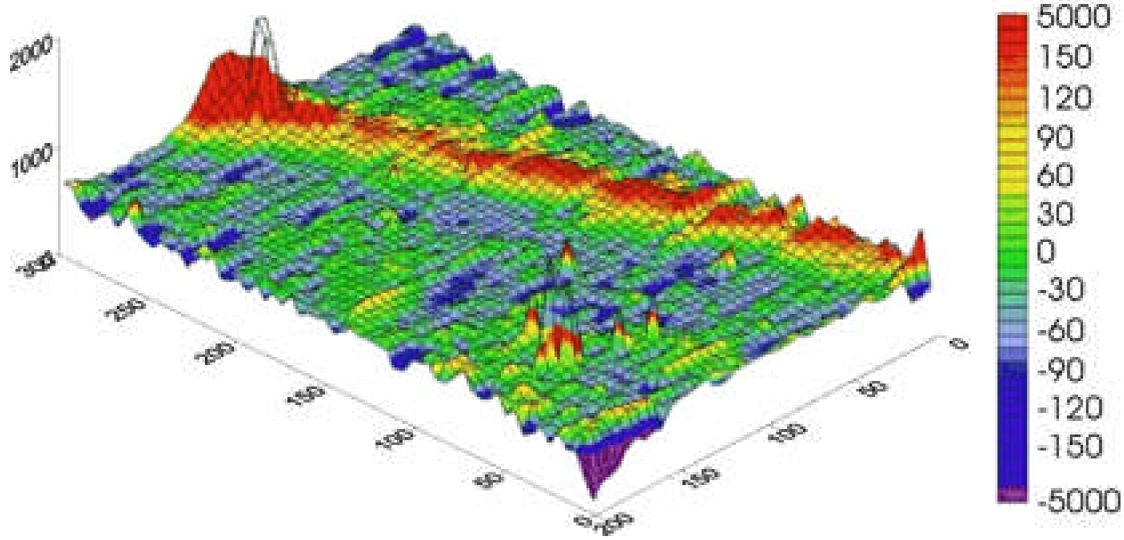

Figure 7-17. EM response of a buried stainless steel pipe

Examples of the application of EM methods to abandoned well search and similar investigations can be found in Allison, 2001; Carlson et al., 1996; Holladay et al. 1981; Paine et al., 1997; Huang et al., 2000; Huang et al., 2001; Sandberg et al., 2002; Xia, 2001; and Xia, 2002.

Resolution

Time and frequency domain electromagnetic instruments may be used in several different configurations depending on the required depth of investigation, the spatial extent and conductivity of the target. These variations in geometry affect the depth of investigation of the methods, the size of detectable targets, and the systems' ability to handle cultural effects. Survey design is therefore a critical, control on the success of any electromagnetic investigation.

Smaller, shallow targets will be most successfully detected using central loop sounding systems, either in the frequency or time domain because of the smaller area that the transmitter excites. These systems have the finest lateral resolution in that measurements can be made along traverses at intervals of several inches, allowing items with small spatial extent to be detected. In most survey situations complete coverage of the target area must be completed to ensure detection, as these sensors have an extremely low response to items not directly below the detector loop. Given that most central loop systems are smaller than 1 meter (3.28 feet) in width, collecting complete coverage can require large amounts of data to be collected.

For larger targets, particularly in mapping of brine plumes at shallow depth (generally less than 50 meters) and product and water lines, Electromagnetic Dipole-Dipole array systems can be used. These systems, as a function of their geometry, average a larger area and therefore are less sensitive to spatially small objects such as well casings but are able to detect changes in the overall conductivity structure that may be the result of brine leakage from improperly abandoned drill holes.

Using large transmitter loops, from 20 to more than 100 meters, TDEM methods can be used to image the overall resistivity structure at depths from 50 meters to several hundred meters. Smaller items, such as casing, and pipelines, will generally not be observable.

For large targets the helicopter EM system, which is generally a frequency domain system, can be used. Since these systems have a footprint of 50-100 meters, it is difficult for standard helicopter EM systems to resolve the spatially smaller anomalies associated with casing from abandoned wells.

Advantages and Disadvantages

The advantages and disadvantages of the electromagnetic method for abandoned well search are summarized below:

Advantages:

- The electromagnetic method can locate buried well casings that no longer have a surface expression.
- Airborne Electromagnetic surveys can provide rapid reconnaissance coverage of large areas using either fixed wing or helicopter systems.
- Data collection using ground based methods is rapid and modern digital instruments integrated with GPS systems allow timely and accurate interpretations to be completed.
- Signatures from both metallic sources and brine plumes can be detected.

- The magnetic permeability adds to the observed electromagnetic response.
- Some systems, particularly the airborne platforms, can collect magnetic and electromagnetic information concurrently.

Disadvantages:
- Small targets at depth cannot be detected.
- Cultural items, such as fences, power lines, water supply lines, water tanks, etc., create anomalies that can either mask or mimic the response from abandoned wells.
- The collection, processing, and successful interpretation of electromagnetic data can often require the technical assistance of specialists in this geophysical specialty.
- Helicopter surveys generally do not have the resolution required to routinely detect the response from casing.

7.2.3.5 Time and Cost Estimates

Field operations for ground electromagnetic surveys are straightforward and require little preparation other than permitting. Data collection proceeds by walking with the instrument at a slow pace; coverage of 5-6 miles per day can be expected in open areas with moderate topography. This rate is roughly equivalent to that of ground magnetic data collection. Airborne electromagnetic data collection allows a large area to be covered in a short time and can mitigate some permitting difficulties. However, airborne electromagnetic data will generally be lower resolution because of the distance covered during a single measurement and the greater distance between the target and the sensor. Airborne surveys may also be prohibitively expensive for small areas.

- **Mobilization:** Variable cost depending upon system and location of vendor.

- **Production (Data Collection):** Ground Survey: High Resolution Ground EM Survey: $150-$200 per line mile.

The area of detection for these systems is limited to the immediate vicinity of the transmitter loop, therefore complete coverage of the area is required. Assuming a line spacing of 3 ft., which allows complete coverage with the 3.28 ft. wide TDEM systems commonly used, 2 to 3 acres per day can be covered using a single man-portable system. Vehicle towed array systems that have been developed for UXO applications have stated production rates of up to 25 acres per day. Location information is provided by GPS systems. Given the resolution of these measurements it is necessary that all GPS measurements maintain sub-meter accuracy.

- **Airborne Survey:** $2500-$6000 per day for a low-elevation/high resolution survey.

This style of survey is generally performed from a helicopter platform as a towed system. The costs for this style survey, in addition to the mobilization costs, include daily rental of the helicopter (~$1500/day), setup ($500-$1000), and an hourly production rate depending upon the system selected.

- **Basic Data Processing:** Generally included in the production rate.

- **Advanced Processing, Interpretation:** Usually priced at typical technical consulting rates of $50 to $150 per hour.

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Telford, W. M., Geldart, L. P., Sheriff, R. E., and Keys, D. A., 1976, "Applied Geophysics," New York, Cambridge University Press, 860 p.

Ward, S. H., 1990, "Geotechnical and Environmental Geophysics," Society of Exploration Geophysicists, Tulsa, OK, 389 pp.

7.2.3.7 Selected Web Resources

Geonics Comp. Web Site Literature:
http://www.geonics.com/lit.html

Geophex Comp. Web Site Literature:
http://www.geophex.com/Publications/publications.htm

Georgia Tech Geophysics Site: Outline of use of EM31 and 34:
http://www.eas.gatech.edu/eas4420/eas4420.em.html

Fugro Airborne Services web site with an integrated case history of well detection in West Texas:
http://www.fugroairborne.com/CaseStudies/wtexasintro.shtml

7.2.4 The Controlled Source Audio-frequency Magnetotelluric Method

METHOD OVERVIEW
Primary Objectives: delineation of brine plumes or fluid leakage from boreholes.
Measured Parameter: electric and magnetic field amplitude and phase.
Property of Interest: resistivity structure of the subsurface.

7.2.4.1 Introduction

CSAMT refers to Controlled Source Audio-frequency Magneto-Tellurics. The primary targets for which the CSAMT method would be applicable for abandoned well search are brine plumes or other borehole leakage. The objective of the survey in this case would be to locate the source of the plume, which might emanate from an unknown improperly plugged or leaking borehole. Although somewhat expensive, the CSAMT method has advantages of relative insensitivity to cultural noise and greater depth of investigation than most other geophysical methods discussed in this manual. Because it is a depth profiling method, it is not appropriate for wide-area searches for specific well construction materials such as casings or pipelines.

The primary uses of the CSAMT method in the past have been for delineating ore bodies, geothermal targets, aquifers, and geologic structure from the surface to depths as great as 2 or 3 km. Shallow geophysical investigations have focused on characterizing aquifers, groundwater salinity studies, waste disposal site investigation, and containment structure leakage.

7.2.4.2 Physical Basis

Basics of the CSAMT Method

The CSAMT method is a frequency-based, electromagnetic sounding technique that uses a remote synchronous signal source. The electromagnetic signal is generated by a large, grounded dipole using frequencies in the range of < 1 Hz up to about 8,000 Hz. (A dipole is a pair of electrodes connected by insulated conducting wire, which is used to either generate or detect an electrical voltage.) Measurements of the components of the electric and magnetic field (E and H, respectively), made along linear arrays of stations, are used to calculate the resistivity structure of the earth.

The ratio of orthogonal, horizontal electric and magnetic field magnitudes (e.g. Ex and Hy) yields the apparent resistivity of the earth (sometimes called Cagniard resistivity). The difference between the phase of the electric and magnetic fields yields the impedance phase, which is often just called phase or phase difference.

The depth of investigation for CSAMT depends on frequency and on subsurface resistivity. In general, the lower the frequency the greater the depth of investigation; and the higher the ground resistivity, the greater the depth of investigation. The CSAMT method has proven useful for mapping the earth's crust in the 20 to 2,000 m depth range. Lateral resolution is controlled primarily by the receiving stations' electric field dipole lengths, usually 10 to 200 m. Vertical resolution is generally 5 to 20% of the depth.

Calculated resistivity values from CSAMT data relate to geology. Primary factors affecting resistivities include rock or sediment porosity, pore fluids, and the presence of certain mineral assemblages. For hydrological investigations, CSAMT data may provide critical information about geologic structure, lithology, water table depth and trends, pore fluid salinity. For abandoned well search, the method could serve as a means for detecting and delineating subsurface brine plumes.

7.2.4.3 Survey Methods

Survey Equipment and Procedures

Figure 7-18 shows a typical CSAMT survey setup. The source signal is provided by transmitting an alternating current over a range of frequencies from about 0.1 Hz to 8 kHz, into the ground via a long grounded dipole. Components of the electromagnetic field (amplitude and phase) are measured several kilometers away in the area of interest using a magnetic field antenna and electric dipoles from about 10 to 100 meters in length.

Usually, a spread of measurement dipoles is laid out by placing a series of electrodes (commonly copper-sulfate filled porous pot electrodes) in the ground connected to each other through a central geophysical data processing unit. The transmitter and receiver units are then synchronized and the signal is transmitted at a suite of different frequencies. A suite of frequencies is used in order to investigate, or sound, to different depths: lower frequencies sensing deeper than higher frequencies. Using an eight-channel receiver, up to 7 electric field dipoles can be measured simultaneously with just one magnetic field measurement (the magnetic field tends to vary slowly over the length of the receiver spread).

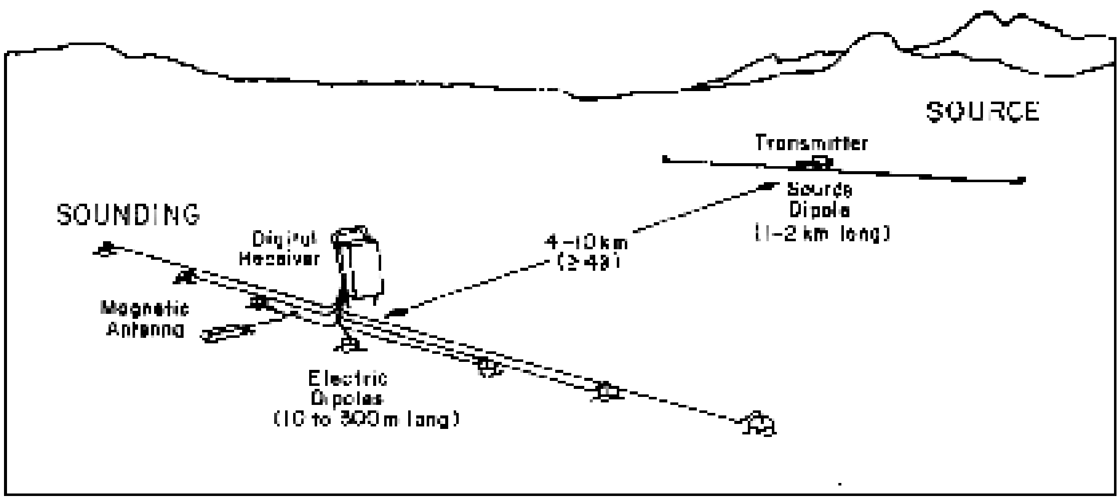

Figure 7-18. **A typical CSAMT survey setup.**

Data Processing and Interpretation

The final field data consists of apparent resistivity and phase angle between the electric and magnetic fields. Processing routines are then used to demultiplex the data and display it in the form of pseudosections, which are profile plots of station location versus frequency (Figure 7-19). Pseudosection data are difficult to interpret, so usually inversion modeling programs are then run on the raw data in order to provide an estimate of resistivity structure with depth (Figure 7-20). The models are generally shown as color-contour maps which illustrate the resistivity trends in the subsurface.

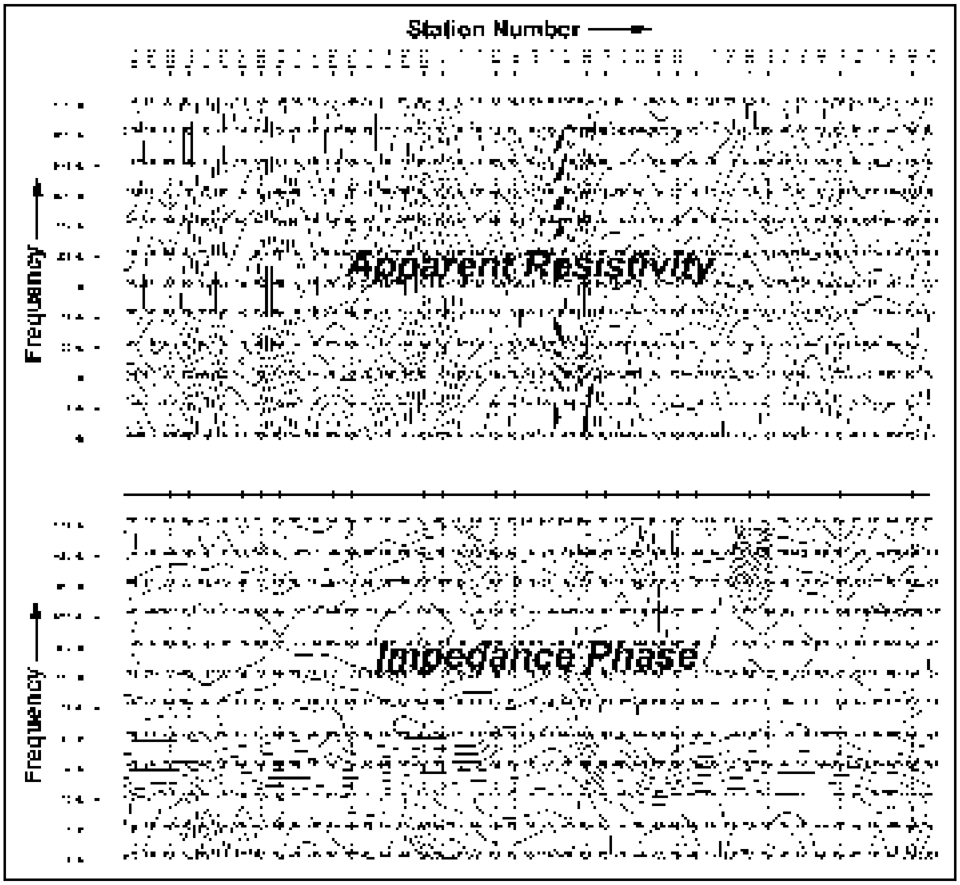

Figure 7-19. **CSAMT pseudosections of apparent resistivity and impedance phase.**

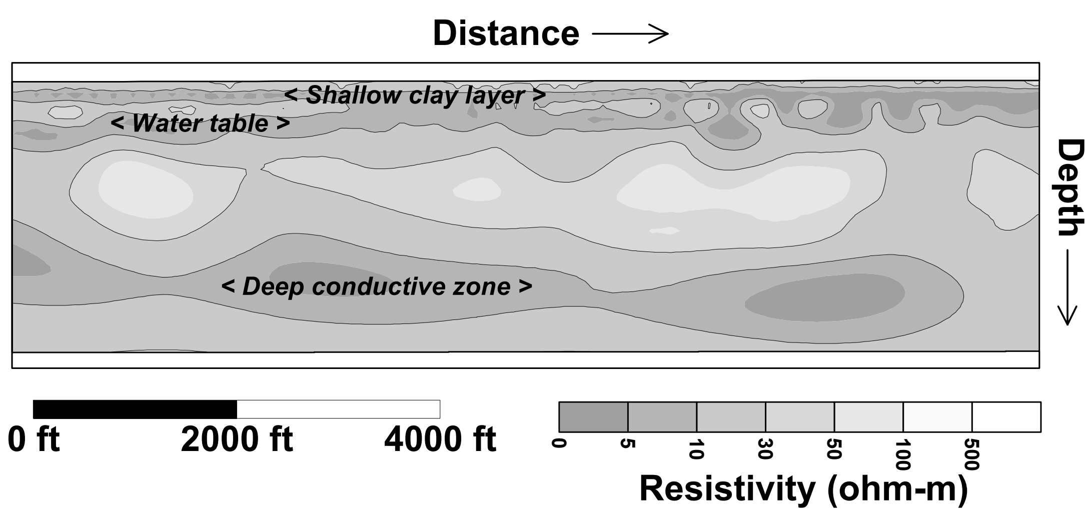

Figure 7-20. A resistivity depth model from inversion of CSAMT data.

7.2.4.4 Applicability

Well-Related Targets

The primary targets for which the CSAMT method would be applicable for abandoned well search are brine plumes or other borehole leakage. The objective of the survey in this case would be to locate the source of the plume, which might emanate from an unknown improperly plugged or leaking borehole. In this situation, the CSAMT method would best be utilized only after 1), there is either surface or monitor well evidence in the area that suggests the presence of a brine plume or other leakage in the area, and 2), other methods that can detect actual well construction materials, such as the magnetic, ground-based EM, or GPR method, have been used and failed to locate any abandoned wells. Because it is a depth profiling method, CSAMT, would not be appropriate for wide-area searches for specific well construction materials such as casings or pipelines. Buried pipelines are often indicated by anomalous CSAMT data; however, because of their orientation, CSAMT data are usually insensitive to well casings, unless electrodes are placed directly on top of, or very near, the buried casing. Delineation and time-lapse monitoring of a well-related brine plume is also possible with the CSAMT method.

The CSAMT method, like the Resistivity method, yields an estimate of the subsurface resistivity structure. There are several cases in which a resistivity anomaly might occur which is related to an abandoned well. First, an un-cased or improperly plugged borehole might provide a conduit for deeper, more saline groundwater to migrate upwards and laterally in a porous zone containing less saline groundwater. Another situation might arise if a borehole is providing a conduit for water from below the water table to leak upwards into the unsaturated, or vadose zone. Lastly, fluids leaking from the borehole may contain a significant amount of either hydrocarbon contamination or drilling fluid residue. Drilling fluids, although widely variable in composition, are generally conductive. They would most likely be more conductive than most fresh groundwater sources.

Whether or not a borehole-related plume can be seen as a resistivity anomaly in CSAMT data will depend on the contrast in its resistivity versus that of the surrounding rock pore fluids. Movement of these fluids through the borehole and into other formations or toward the surface is governed by hydraulic pressure constraints in the earth. In most of the cases discussed above, a low resistivity (high conductivity) anomaly would be expected in the geophysical data, in the vicinity of a borehole-related plume.

The CSAMT method has been used quite successfully in recent years for detecting and monitoring conductive fluids in the ground. Most of these types of investigations have focused on characterizing aquifers, groundwater salinity studies, waste disposal site investigation, and containment structure leakage (e. g., McNeill, 1988; Bartel, 1990, Hanson et al., 1993, Carlson et al., 2000, and others). Particular case studies where the CSAMT method was used successfully to locate well-related brine plumes may be found in Fryberger and Tinlin (1984), and Zonge et al., (1984).

Sensitivity and Limitations

Depth of penetration for CSAMT can range from about 10 m to several kilometers depending on ground resistivity and the frequencies used. Lateral resolution is controlled by the length of the electric field dipoles used, which are normally between l0 and 200 meters long. For abandoned well search where borehole-related plumes are the search target, CSAMT dipole spacing would likely be on the order of 3 to 20 meters, and the depth range of interest would be limited to the upper 500 meters or so of section. A useful relationship for estimating the maximum depth of investigation for CSAMT data is given by:

$$D = 356 * \mathrm{sqrt}(\rho/f)$$

where D is the approximate depth of investigation in meters, ρ is the apparent resistivity of the ground in Ohm-meters, and f is the frequency in Hz. Note that while many CSAMT systems generate signal down to 1 Hz or less in frequency, in practice, there is a physical limitation on the lowest frequency that can be used in an area without making measurements which are considered to be in the near-field, where geometric factors make modeling the data extremely difficult.

Vertical resolution decreases with increasing depth, therefore small, well-related plumes at great depths will not be resolved by the CSAMT method (or other electrical or EM methods). The vertical resolution of CSAMT data is approximately 5 to 20 percent of the depth, depending upon resistivity contrasts, geologic complexity and electrical noise. Using 10 percent as an average, a 5 m thick saline plume in fresh groundwater could be resolved to a depth of about 50 m (10 percent is a fairly conservative estimate).

The CSAMT method is sensitive to various noise factors such as power-lines, sub-stations, cathodic pipe protection systems, and other sources of cultural EM noise. Buried pipelines and fences can also cause anomalous noise in the data as well. However, because the CSAMT method utilizes a stable, active source signal at a suite of prescribed frequencies, the data are usually less sensitive to these noise sources than most other EM and electrical methods. In addition, CSAMT can, in general, provide greater depth of penetration and lateral resolution than an electrical resistivity survey, which might be used for similar objectives in an abandoned well search (brine plume or vadose zone leakage from a borehole).

The primary limitations of the CSAMT method are the survey logistics, which can be complex because they involve setup and synchronization of a remote transmitter with a linear array of grounded dipoles at the receiver site. In some highly populated areas, this might be problematic. The method is also limited to deeper investigations of the subsurface: the very near-surface (upper 1 to 3 meters) cannot be resolved using this method, although its ability for deep imaging is also one of the major advantages of the CSAMT method.

7.2.4.5 Time and Cost Estimates

The time and cost of a CSAMT survey are somewhat greater than those for other geophysical methods such as fast EM techniques or the magnetic method; however, the scope and objectives for abandoned well search using CSAMT are completely different. CSAMT, like the resistivity method, would best be used for delineating well-related brine plumes or other leakage from boreholes into surrounding formations.

Because CSAMT uses an electrical dipole as a transmitter, which is up to 1500 m long and located several kilometers from the receiver dipoles, there is some time required in setting up the transmitter. The transmitter may also be moved several times over the course of a survey to accommodate changing survey geometry. A survey crew of 3 to 4 people is usually required to conduct the survey, one of whom operates the transmitter, and several at the site of receiver dipoles (one person to run the geophysical receiver, and 1 or 2 others to layout wire and plant electrodes). The survey may be conducted on foot in areas with no vehicular access due to terrain or other reasons.

The requesting client and CSAMT survey contractor must consult regarding particular objectives, site characteristics, and required survey parameters in order to obtain a cost estimate. A CSAMT survey usually consists of the following basic cost factors (the costs shown are general estimates only, based on typical survey prices applicable at present):

- Mobilization and demobilization: Variable cost (includes the cost of shipping all survey equipment to the site).

- Production (data acquisition): ~ $ 1600 to $ 1800 per day for a 4-man field crew. Approximately 25 to 100 stations per day depending on dipole length (station spacing) and terrain.

- Downtime (for example, due to inclement weather): typically 0.5 to 1.0 times the production rate.

- Expenses (per diem, lodging, fuel, incidentals): Variable cost.

- Basic data processing (includes data compilation, processing, logistic reports, etc.): this is usually included in the production rate.

- Extra processing, interpretation, interpretive report: often priced at typical technical consulting rates of ~ $ 50 to $ 150 per hour.

A comprehensive list of vendors that provide CSAMT and other geophysical survey services is shown in Appendix D of this manual.

7.2.4.6 References

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Environmental Geophysics, Vol.II, S. Ward, ed., Society of Exploration Geophysicists, Tulsa, OK, p. 219-233.

Carlson, N., Zonge, K., Ring, G., and Rex, M., 2000, "Fluid Flow Mapping at a Copper Leaching Operation in Arizona," The Leading Edge, 19, no. 7, p. 752-755.

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Zonge, K. L., Figgins, S. J., and Hughes, L. J., 1985, "Use of Electrical Geophysics to Detect Sources of Groundwater Contamination," Proceedings of the 55th Annual International Meeting of the Society of Exploration Geophysicists, Session: ENG1.7.

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Zonge, K. L, and Hughes, L. J., 1991, "Controlled Source Audio-Frequency Magnetotellurics," in Electromagnetic Methods in Applied Geophysics, Vol. II, Application, M. Nabighian, ed., Society of Exploration Geophysicists, Tulsa, OK, p. 713-809.

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7.3 The Ground Penetrating Radar Method

METHOD OVERVIEW
Primary Objectives: location of metallic or non-metallic well casing or abandonment plugs.
Measured Parameter: reflected radar wave energy.
Property of Interest: changes in dielectric permitivity.

7.3.1 Introduction

Ground Penetrating Radar (GPR) is a high-frequency electromagnetic method commonly used for engineering and geotechnical applications. Its primary applications include detection of utilities, voids, underground storage tanks, and structural investigations such as rebar analysis within concrete structures. With the advent of lower frequency antennas, deeper environmental applications have increased. GPR has been proven effective in locating both metallic and non-metallic buried objects buried below the surface.

GPR could be used to find abandoned wells that have non-metallic well casings or concrete abandonment plugs without casing, circumstances in which magnetic or electromagnetic methods would not be effective. The GPR method, however, is probably less cost-effective than either of these methods because required line spacing would be quite high in order to resolve these targets. GPR could also detect metallic casing materials, however, the depth of investigation for GPR would be significantly less than that for the magnetic method, and it may be less effective in conductive soils than electromagnetic methods for this purpose. In practice, the primary application of the GPR method to abandoned well search would be for detailed, small area searches, where wells are known to exist but must be located, and for areas where non-metallic casings or concrete plugs without casing are suspected.

7.3.2 Physical Basis

Ground penetrating radar is a geophysical imaging technique in which an electromagnetic pulse is transmitted into the earth from an antenna placed on the earth's surface. This pulse is reflected and diffracted by both the geologic structures and by any anomalous features that may be present in the subsurface. The reflected and diffracted waves are received by an antenna on the earth's surface. A series of such measurements made along a line, when plotted side-by-side, provides a high-resolution picture of the details of the features present on a vertical slice through the earth beneath the survey line.

GPR utilizes an antenna to transmit electromagnetic pulses into the ground in the radar frequency range (16 MHz to 50 GHz). The depth of penetration for GPR depends on the actual frequencies used and the electrical properties of the subsurface. Reflections of the radar pulse may originate from inhomogeneities at layer interfaces, fluid saturated zones, cavities, and buried objects such as cables, pipes, foundations, and rubble. Depending on the frequencies used, the GPR method is capable of extremely high-resolution imaging of the shallow subsurface. The primary factors that control GPR reflections are the electrical and magnetic properties of the subsurface, and geometric factors related to how the electromagnetic energy is propagated.

The method depends primarily on two electrical properties of subsurface materials: conductivity and dielectric permitivity. Electrical conductivity is the ability of a material to conduct an electric current, given in units of Mhos per meter. Rocks and soils are often described by a property called resistivity, given in units of Ohm-meters, which is the reciprocal of conductivity. Resistivity is analogous to resistance in a simple electric circuit, except that it is a bulk property of the material.

Dielectric permitivity is a property of materials which is related to both the conductivity and magnetic permeability of the material. The relative dielectric permitivity (RDP) of a material is a dimensionless quantity which represents the capacity of a material to store and then allow the passage of electromagnetic energy when a field is imposed upon it. Soils, rocks or sediments that are “dielectric” will permit the passage of most of the electromagnetic energy easily. The more electrically conductive a material is, the less dielectric it is, and it will tend to impede the passage of electromagnetic energy. Differences in dielectric properties can be due to sediment or soils differences, water or other pore-fluid variations, lithologic changes, bulk density or porosity changes. Strong or subtle reflections, or changes in the reflective character of radar energy are observed as a result of these differences. Significant reflections will also occur over voids, metallic objects, or other buried man-made objects in which the electrical properties contrast greatly with the surrounding soils or material (Figure 7-21).

In practice, the relative dielectric permitivity (RDP) is an important parameter that is used for converting radar reflection travel times into depth estimates. These values can be obtained from literature or the manufacturers of GPR equipment and software for the most common mediums encountered during field surveys. The relative dielectric permitivity, RDP is:

$$\mathbf{RDP = c/v}$$

where c is speed of light (about 0.3 meters per nanosecond), and v is the velocity of the radar energy as it passes through the medium. Radar data are recorded as two-way travel-times and amplitudes of the reflected radar pulses. In order to calculate the depth to a reflection, the data needed are the time of the reflection and the velocity of the radar energy within that medium. It must be noted that return times are usually given in two-way travel time, that is, from the transmitting antenna to the reflector and back, so this must be accounted for in the depth calculations.

The depth of investigation for GPR is a function of the transmitting antenna frequency and the electrical conductivity of the soils in the survey area. Lower frequency antennas achieve greater depth of penetration than higher frequency antennas, but have poorer spatial resolution. This is a fundamental concept in most geophysical methods: there is an unavoidable tradeoff between resolving power and depth of investigation, and this is based on the frequency of the energy employed. For the GPR method, electrical conductivity of the ground and subsurface materials also control the effective depth of investigation. Conductive soils, especially clay-rich, attenuate radar waves much more rapidly than resistive dry sand and rock.

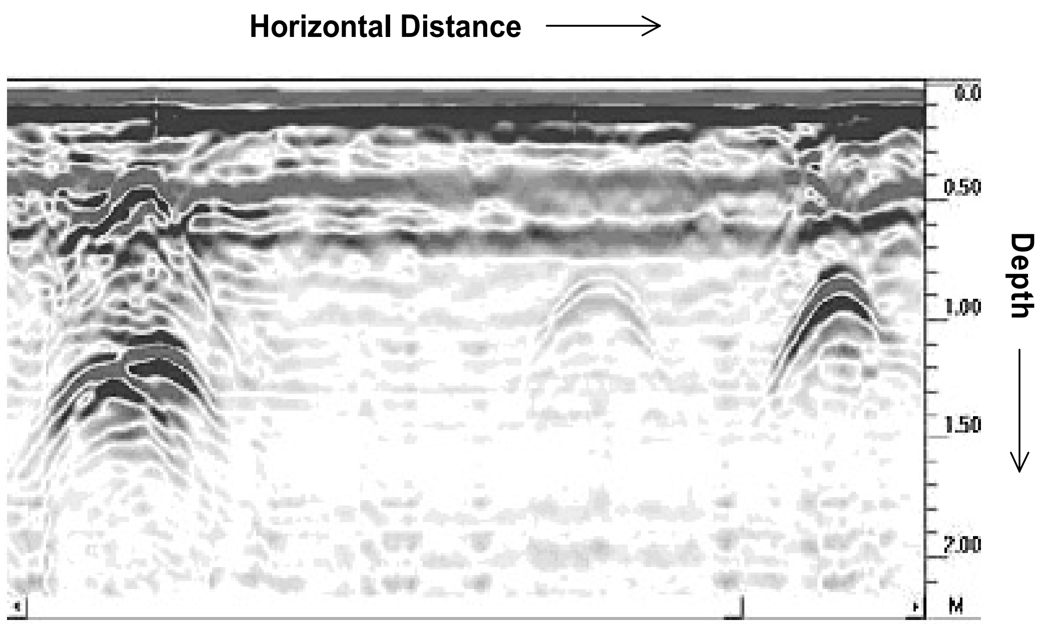


Figure 7-21. **A radar reflection section. The vertical dimension has been converted from two-way travel time to an estimate of depth in meters below the surface. The left-most anomaly, seen at about 1.5m depth, represents reflections from two parallel, buried gas pipes. The right-most anomaly, seen at about 1.0 m depth, is a reflection off of a steel pipe; the faint (lower amplitude) reflection seen to the left of this is a PVC pipe buried at the same depth. (Figure courtesy of Zonge Engineering & Research Organization.)**

7.3.3 Survey Methods

Equipment

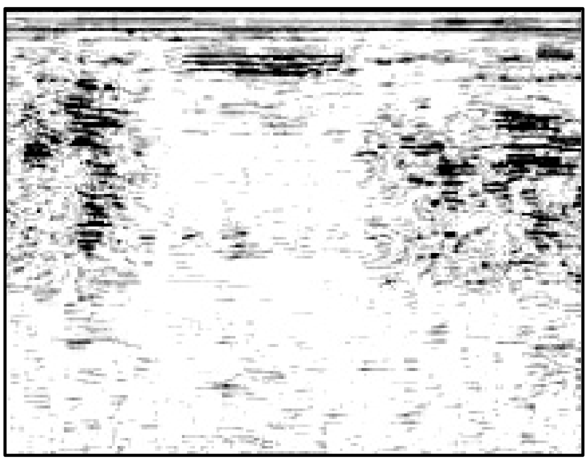
There are many manufacturers and commercially available GPR systems available today. Most are produced for general-purpose surveys using one center-frequency antenna. These systems generally consist of 3 elements: control unit, receiving unit, and transmitting unit. The control unit generates the electrical pulse that is sent to the transmitting antenna and records and stores the survey data. Most control units can display cross sectional plots of the data and allow for some basic processing. The receiver and transmitting antennas are often located together in the housing but can also be found as separate units. The transmitting antenna delivers the radar pulse and the reflected pulses travel back to the receiver antenna.

Procedures
Most GPR surveys are conducted in continuous scan mode. In this method, the antenna is placed directly onto the ground and pulled along a survey line while data is collected and recorded continuously. GPR systems are often towed or rolled along the ground by automobiles, sleds, carts, or by field operators on foot (Figure 7-22).

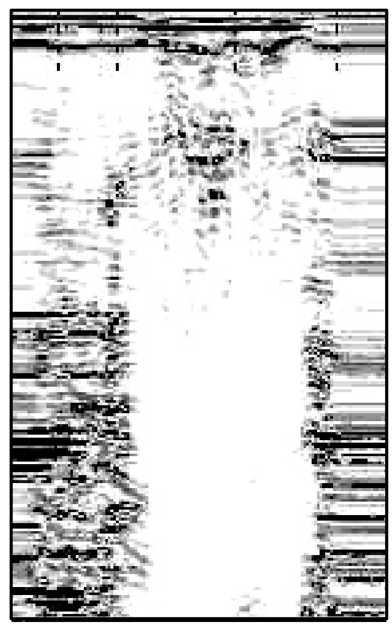
The data acquired during the survey can be used to generate a cross-sectional profile along the survey line. Most GPR systems allow for position markers to be added directly into the data during acquisition. This is important so that reflection anomalies can be precisely located along the survey line. GPR systems may also be positioned by integration with real-time GPS (Appendix B).

Figure 7-22. A GPR system in use. The system shown here is the Noggin 500 system, which operates in the 250 – 750 MHz range, and is designed for high-resolution imaging of the shallow subsurface (up to 8 meters depth, depending on materials). The system is manufactured by Sensors & Software, Inc. of Mississauga, Canada. (Figure courtesy of Sensors & Software, Inc.)

Most GPR data is processed and interpreted on 2-D profiles representing cross-sections of the earth. Reflections and diffractions from geologic variations or buried objects are indicated by high-amplitude reflections, a change in reflection character, or the absence of reflections in the case of a subsurface void (such as an air-filled borehole or wash-out cavity), (Figure 7-23). Very high-resolution data, acquired with either very close line-spacing, or from a 2-D ground array of antennas, may be processed and analyzed as plan-view depth slices of the amplitude of reflected radar energy. Both profile and depth slice GPR data may have various signal processing and filtering techniques applied in order to better illuminate the targets of interest.



(a)



(b)

Figure 7-23. (a), A GPR image of an inaccessible subsurface drywell with a concrete access cover. The drywell was scanned with a 200 MHz antenna. (b), A GPR image of an accessible subsurface drywell with a steel manhole cover. (Radar images courtesy of Impact Environmental, a division of Impact Environmental Consulting, Inc.)

7.3.4 Applicability

Well-Related Targets

Targets that can be detected using GPR include both metallic and non-metallic well casing, caps, or concrete abandonment plugs, pipelines, or related objects. Metallic objects generally produce strong reflectors that can easily be seen in GPR data.

Subsurface voids, such as borehole wash-outs, might also produce GPR anomalies due to the contrast of electrical properties between air and the soil or rock medium. Materials such as plastic or wood can also be seen in GPR records but can be difficult to detect at depth, or if their electrical properties are similar to the surrounding soil medium.

Sensitivity and Limitations

The depth to which radar energy can penetrate is partly dependent on the frequency of the antenna employed and partly on the conductivity of the ground. As discussed above, higher frequency antennas provide higher resolution but at the cost of decreased depth of investigation. Conversely, low frequency antennas provide greater depths of investigation but at the cost of resolution. In practice, the GPR method is probably only applicable for imaging very shallow casings or abandonment plugs (burial depths from just below the surface up to one or several meters in burial depth maximum).

Commercially available antennas range in center frequencies from 16 MHz to 50GHz. Typical cart-mounted antennas used for shallow geophysical work, which provide for continuous data collection over a survey area, range from about 100 to 500 MHz in frequency and provide depths of investigation from about 1 to 10 meters, respectively, in ideal conditions. Cart-mounted or sled-pulled systems operating in this frequency range (100 to 500 MHz) would best provide the functionality required for a typical abandoned well search. Lower frequencies (<100 MHz) are generally used for static sounding or probing and can provide depths of investigation greater than 10 meters.

For abandoned well search, one of the greatest limitations that the GPR method presents is its limited depth of penetration in highly conductive soils (primarily due to moisture or clay content). Another limitation relates to the size of the target of interest. For abandoned well search, this would be a well casing, cap, or concrete plug. Borehole diameters are typically in the range of 3 to 24 inches (8 to 60 cm) in diameter. The relatively high operating frequency range of the GPR system necessary to resolve this size target would limit the depth of penetration. In general, an object may be resolved if its dimensions are greater than the wavelength of the radar wave impinging upon it. An estimate of radar wavelength can be calculated if the frequency and velocity (or RDP) of the material is known:

$$\lambda = \mathbf{v} / \mathbf{f}$$

where λ is the wavelength (in meters), v is the velocity of the radar energy (waves) in the material (in meters per second), and f is the frequency (in Hertz). For well caps, casings, and related structures which are buried at depths of up to 2 meters, an antenna frequency in the range of 200 to 500 MHz might be used.

Another factor that affects the ability to detect abandoned well related targets is the GPR line spacing. Off-line features would only be detected for distances on the order of the wavelength of radar energy being used. A very small line spacing would be required to image buried well casings, plugs, or caps; in many cases this would be 1 to 3 ft (1 m or less). This requirement would limit the cost-effectiveness of a GPR survey for abandoned wells to fairly small areas.

In practice, the primary application of the GPR method to abandoned well search would be for detailed, small area searches, where wells are known to exist but must be located, and in particular, for areas where non-metallic casings or concrete plugs without casing are suspected.

7.3.5 Case Histories and References

Data and documentation on the specific application of GPR to abandoned well search can be found in some internal reports, advertising, and marketing literature of vendors of geophysical services or GPR instruments. Most published case histories regarding the use of GPR for shallow environmental or engineering work are for other applications, although these studies may serve as useful analogies to abandoned well search. In particular, shallow applications of GPR for delineation of subsurface objects such as pipelines, tanks, foundations, archaeological remnants, utilities, and unexploded ordnance (UXO) would be similar in scope to a GPR survey for well casing or related materials (e. g., Barner et al., 2001; Brady et al., 2000; Conyers, 2001; El-Behiry, 2002; Lesmes, 1998; Takata et al., 2001).

7.3.6 Time and Cost Estimates

A GPR survey for abandoned well search would be moderately more time-consuming per unit of search area compared to most ground EM or magnetic surveys. This is mainly due to the dense line spacing required for resolving small, well casing or related targets, as well as the requirement that the radar antenna be in very near contact with the ground surface. Since this is usually accomplished by some sort of towed or pushed system, the search area may need to be "brushed" which means time for removal of vegetative and other ground surface obstacles. For these reasons, a GPR survey would be considered fairly labor intensive and expensive for abandoned well search.

GPR surveys generally require little in the way of setup, aside from clearing the area and laying- out the survey lines. Data along lines are usually acquired at a slow walking pace, depending on terrain and vegetation. Vehicle towed GPR systems are available, and data acquisition can be somewhat faster using these; however, for this application, the requirement for dense line coverage (1 to 3 ft spacing) is the same, and navigating a vehicle or ATV accurately along tightly spaced lines can be cumbersome.

The requesting client and GPR survey contractor must consult regarding particular objectives, site characteristics, and required survey parameters in order to obtain a cost estimate. A GPR survey usually consists of the following basic cost factors (the costs shown are general estimates only, based on typical survey prices applicable at present):

- Mobilization and demobilization: variable cost.
- Production (data acquisition): ~ $ 200 to $ 800 per man-day of field service.
- Downtime (for example, due to inclement weather): typically 0.5 to 1.0 times the production rate.
- Expenses (per diem, lodging, fuel, incidentals): Variable cost.
- Basic data processing (includes data compilation, processing, logistic reports, etc.): this is usually included in the production rate.
- Extra processing, interpretation, interpretive report: often priced at typical technical consulting rates of ~ $ 50 to $ 150 per hour.

Rental rates for GPR systems generally include a preparation fee of $100 to $300, in addition to daily rental rate of about $100 per day, plus incidentals such as on-site printer fees if records are desired on-site, and software rental fees for visualization and post-processing of the data (post-processing may include conversion from time to depth sections, filtering, etc.).

A comprehensive list of service and equipment vendors for GPR and other geophysical survey methods is given in Appendix D of this manual.

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8.0 MONITOR WELLS

METHOD OVERVIEW
Targets: all wells.
Objective(s): Detection brine, hydrocarbon in aquifers. Detection of changes in pressure or static water level. These would indicate migration through an open wellbore.
Methodology: Monitor pressures and / or sample existing monitor wells or water wells. Install new monitor wells where geology is appropriate.
Primary cost items: Sampling and chemical analysis of aquifer fluids. Installation of monitor wells.

Monitor wells may be used to detect changes in pressure, water level or chemical composition of fluid in an aquifer. Changes in these parameters may indicate leakage from an abandoned wellbore. Monitor wells are commonly used to detect horizontal or downward migration of contaminants from many surface facilities that have the potential to impact local groundwater resources. The use of monitor wells for detection of migration through open wells as been considered by U.S. EPA (Aller, 1984), and U.S. EPA, Region 5 has recognized the potential of monitor wells for detection of migration from zones where industrial wastes are injected (US EPA, 1991). Potential conduits for migration include improperly plugged wells and faults.

For cavern storage facilities, monitor wells are most applicable as a continuous check for emerging signs that a leak is developing. This would occur after a site has begun solution mining of a cavern, or during use for hydrocarbon storage. Pressures developed in the cavern will increase or change the rate of existing migration up an open wellbore, and monitor wells would permit the detection of correlated changes in pressures and brine contents of overlying aquifers that communicate with the open wellbore.

Monitor wells may serve in detecting the following conditions for which open wellbores are one possible cause:

Unexplained changes in aquifer pressures

Fluid flow into an aquifer may occur at a sufficient rate to measurably change fluid pressures around the wellbore and in a neighboring monitor well. Hydrocarbon that is liquid, or highly compressed, at pressures existing at the depth of the cavern will vaporize or expand at lower pressures as it migrates upward. Thus, migration of light hydrocarbon may lead to disproportionate volumes of fluid being displaced in the receiving aquifer. Flow associated with this displacement, and shifts in pressure associated with the low specific gravity of gasses may cause rapid changes in pressures within the monitored aquifer.

Brine plumes detected in less saline or freshwater aquifers.

A likely precursor to migration of product from a storage cavern via an open wellbore is the migration of brine. During solution mining, fluids must be pumped through the growing cavern at a sufficient rate to complete the mining project efficiently. To achieve adequate rates, the cavern will be pressurized to drive the saturated brine up the production string. If the expanding cavern wall intersects an existing, open wellbore or other path for leakage, it is likely that brine will be driven upward, either to the surface or to a shallower aquifer. Formations that underlie a site at different depths will usually have different concentrations of dissolved salts. As a result, vertical migration will affect dissolved ion concentrations in less-saline or freshwater aquifers. The presence of a localized brine plume, in the absence of other probable causes, would be an indicator of the presence of an open wellbore.

Dissolved gases in the subsurface that are suspected to be hydrocarbon product.

Dissolved or gaseous hydrocarbon may be an indication of a leak from a cavern. It is critical to identify relative proportions of compounds to differentiate product from other possible sources such as naturally occurring gas deposits.

Use of monitor wells in detecting the conditions just described is complicated by the likelihood that any abandoned, open wellbore intersects numerous porous and permeable zones between the top of the cavern and the surface. Brine (and later product) may migrate laterally from the wellbore into any of these. For these reasons, the installation of monitor wells for the purpose of detecting abandoned wellbores is only practical under rather specific conditions. Feasibility and applicability of monitor wells should be assessed by qualified geologists and reservoir engineers.

Sampling of existing monitor wells and water wells may provide early warning of a potential problem. Existing monitor wells may have been required at a cavern storage site where ponds are used to manage displaced brine. These monitor wells are usually constructed for sampling of the first shallow and areally extensive aquifer below a pond. Water wells are common in rural areas where many cavern storage facilities are located. These wells necessarily tap transmissive and freshwater zones. However, extensive pumping is likely to impact both pressures and solute content in these wells so that any changes may be difficult to interpret.

Unfortunately, detection of brine or hydrocarbon in a drinking water aquifer signals that some damage has already been done. Therefore, it is preferable to monitor deeper aquifers that contain brine.

A new network of monitor wells is relatively expensive, especially if they are completed in a deep zone, well below drinking water aquifers. Hence, thorough review of existing information is critical for assessing the need for, and design of, any monitoring program.

8.1 Methods/Procedures

Monitoring wells should only be installed after a thorough assessment of the geology and hydrology at a site. In general, monitor wells may be effective at sites underlain by porous and permeable horizons that extend over all or most of the site. This will maximize the probability of communication between an open wellbore and the monitor well. As indicated in the introduction, an abandoned wellbore may form a closed conduit through any given porous and permeable zone without leaking into it. Hence, multiple wells may be required to monitor as many zones as practicable.

Zones that are candidates for monitoring should be assessed for thickness and transmissivity. The experience of local oil companies and drilling consultants, analyses of cores, and state records of drilling are invaluable in estimating transmissivity of candidate zones. A reservoir engineer should assess likely rates of fluid or hydrocarbon migration, and project the horizontal extent of contamination and pressurization associated with a range of leak scenarios. This will guide the placement and spacing of monitor wells.

The U.S. EPA has issued guidance for designing monitor wells that are intended to detect migration from the injection intervals of Class I industrial waste disposal wells. Many of the considerations presented in that document are relevant to cavern storage wells. In particular, there is a trade-off in the optimal thickness of zones selected for monitoring.

Thinner zones are more “sensitive” in the sense that a smaller brine leak will spread more rapidly to a monitor well. However, thinner porous and permeable intervals may be less continuous across an area and be less transmissive.

8.1.1 Construction

A typical monitor well design is depicted in Figure 8-1. The screen permits the withdrawal of samples, and allows the fluid column in the well to equilibrate with the fluid in the aquifer. To assure that the screen is in communication only with the intended interval, and to prevent migration between intervals, the annulus between the wall of the drilled hole and the casing is filled with a cement/bentonite grout. The surface completion is protected with steel posts and the well cap is sheltered with a locking cover. A reference point for surveying is installed in the concrete slab in which the protective cover is mounted.

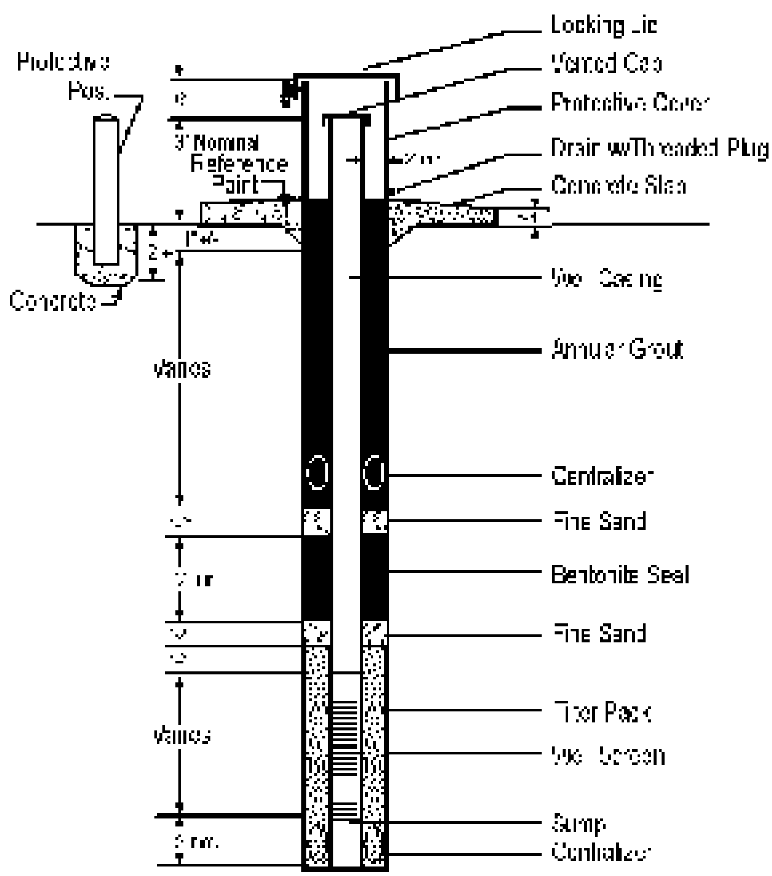

Figure 8-1: **Monitor Well Construction**

Most states require that a qualified geologist describe formation materials as they are extracted from the borehole. Additionally, each well must be surveyed for location and elevation. States commonly specify that locations be surveyed with respect to the state plane coordinate system or the Universal Transverse Coordinate (UTM) system. Elevations are referenced to mean sea level. Precise reference to elevation is a critical step for describing the potentiometric surface.

8.1.2 Monitoring the Potentiometric Surface

Pressure may be measured in a monitor well, using a transducer, or may be measured by determining the depth to the fluid surface in the monitor well. The height of fluid in a well, and hence the pressure exerted at the base of the fluid column balances the pressure in the aquifer. For freshwater at standard conditions, one foot of water column is equivalent to 0.433 psi.

Differences in water level are easily measured to an accuracy of 0.01 feet. However, tidal and barometric variation occurs in the short term. Also, shallow aquifers are recharged by rainfall and changes in water levels of communicating surface waters. These influences must be taken into consideration in determining frequency of sampling and background variation in water levels.

8.1.3 Sampling Aquifer Fluid for Analysis

Sampling of aquifer fluid is accomplished by bailing or pumping fluid from the well. Fluid is first bailed from the well so that fresh fluid, that is less affected by wellbore conditions, will enter from the aquifer. Commonly, three well volumes of fluid are withdrawn, or the well is bailed to dryness, then allowed to recharge.

Sampling procedures and sample preservation differ, depending on the target analytes. In the context of monitoring a storage cavern, these procedures may not be specified to the degree of detail necessary for monitoring under an environmental permit. However, procedures promulgated by states and the US EPA are useful guidance. The operator may consult the US EPA manual "Test Methods for Evaluating Solid Waste" (SW-846) and guidance documents published by individual states. Design of sampling should also be in consultation with a qualified laboratory that will be performing the analysis.

8.2 Applications of Monitor Wells

Monitor wells are effective in detecting migration of contaminants within an aquifer when the location of the source, such as a surface spill, is known. Facilities that have released contaminants into groundwater typically install wells within - and just outside - the margins of known contamination. The placement of these wells is guided by the spatial pattern of pressures (fluid heights) in the aquifer. This pattern, plotted as a potentiometric surface, identifies the direction of groundwater flow. This guides the location of wells up- and down-gradient of the region of known or suspected contamination.

Unfortunately, the location of an unknown abandoned wellbore is not known prior to its detection. Hence, this cannot be used as a guide to the location of monitor wells. However, the U.S. EPA and a few states have mandated use of monitor wells at specific sites to monitor for outbreaks of brine or waste from the injection zones of industrial waste (Class I) wells. EPA has published guidance as to the types of zones considered adequate for effective monitoring (US EPA, 1991).

8.2.1 Potentiometric Surface Measurements

Pressure in an aquifer is ultimately the result of compression of the entire system by the weight of rock and fluid in layers above. However, these pressures are modified by flow from adjacent regions, sources and sinks for recharge and discharge, fluid density, and shifts in the earth's crust that increase or release forces in various directions. These influences act to create pressure differences among horizons at different depths. Barometric and tidal variation also influence pressures over short time scales. Because of these influences, the initial measurements of aquifer pressure rarely provide evidence of fluid flows associated with migration. Migration is more likely to become apparent through correlation in time to known changes in cavern pressures or contents.

Expected changes in aquifer pressures, in response to flow from a wellbore should be estimated as part of designing the monitoring program. Pressures may be calculated using an appropriate solution of a two-dimensional saturated flow equation, or a one-dimensional solution for radial flow. Silliman and Higgins (1990) presented a method to estimate inter-aquifer flow in an open wellbore, based on a simultaneous solution for inward radial flow to an open wellbore in a deep confined aquifer, and outward radial flow from the wellbore in an aquifer above. The scenarios presented indicated that the steady-state pressure response of the system is largely determined by the transmissivities of the aquifers, and not by the characteristics of the open wellbore, over a wide range of possible wellbore resistances. The modeled transmissivities were typical of freshwater aquifers utilized for drinking water, and the pressure differential used in a numerical example was relatively low, compared to those generated in deep wells. Over a wide range of wellbore resistances, leakage rate was on the order of magnitude of 1gallon per minute (GPM). Hydrological parameters for aquifers and wells vary, of course, over a wide range. However, this example is cited because it provides insight as to the order of magnitude for inter-aquifer flow.

The authors of this manual utilized a similar flow rate to that projected in the illustration of Silliman and Higgins (1990), 1 GPM, to project transient pressure rise in a shallow aquifer after initiation of flow. This scenario is analogous to a situation where the expanding wall of a cavern that is being solution-mined encounters an open wellbore. Transient pressure rise was modeled using an exponential-integral solution for two-dimensional flow.

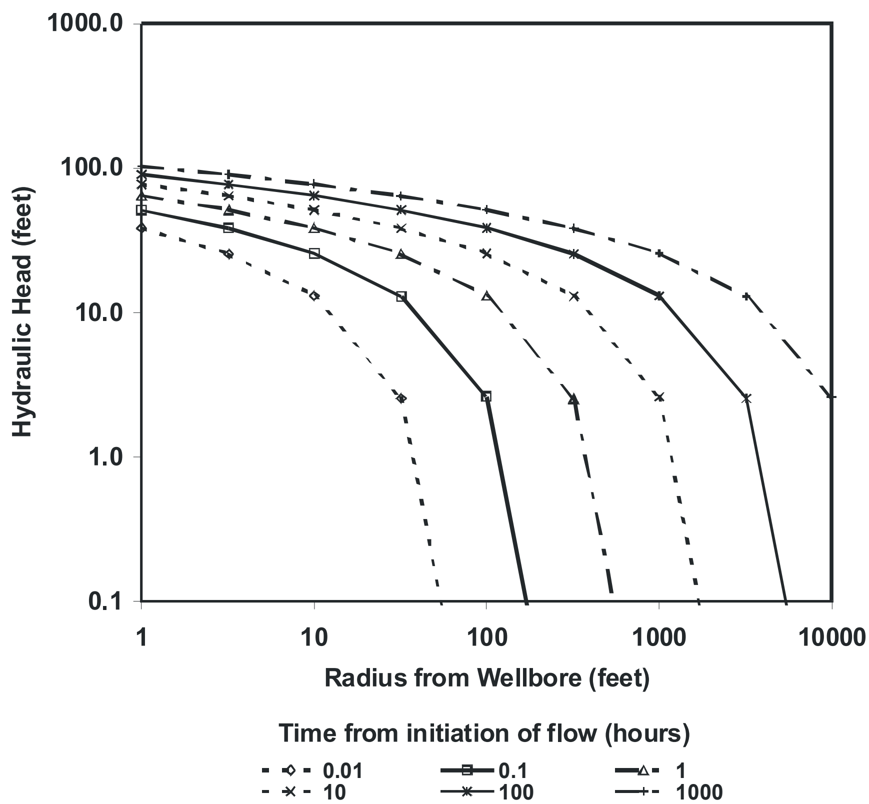

Figure 8-2. Pressure rise at times extending to 1000 hours after initiation of flow, and at radii extending to 10,000 feet.

Pressures are expressed as feet of hydraulic head, because this is often the measurement that would be obtained from a monitor well. For reference, we assume that a ten-foot change in water level is readily measurable and much greater than background variation due to tidal and barometric effects. This ten-foot change in water level would be measured within one hour at a distance of 100 feet, and would be measurable at 1000 feet distance after 100 hours. These results suggest that water levels in monitor wells spaced approximately 1000 feet apart would show readily measurable changes within four days. If changes are measured in three monitor wells, then a suspected direction and rough location for the source of the pressure transient (suspected wellbore) may be inferred.

In many instances, pressure differences between the cavern and overlying aquifers would be much greater than that represented above, leading to much greater flow rates and pressure transients. For example, gaseous hydrocarbon product that is bubbling up a wellbore might occupy 10% of the volume, reducing the density of fluid column correspondingly by 10%. For a 2000-foot wellbore, this would increase the effective pressure differential in the upward direction by 87 psi.

8.2.2 Brine or Hydrocarbon Concentrations

Brine or hydrocarbon product that migrates up an open wellbore may exit into shallower aquifers and, if detected, provide early warning of a problem. As indicated previously, an improperly cased wellbore might or might not be open to a particular aquifer that is being monitored. Historical records of casing depths for known wells in the vicinity, combined with geological information may indicate aquifers that have a high probability of receiving migrating fluids. For instance, early drilling practice in a region may have been to case to a certain depth, drill to the target depth, then leave mud or debris in the hole if it is found to be non-productive. This would suggest monitoring of a porous and permeable zone below the commonly used depth of casing.

Detection of brine or hydrocarbon product in a monitored zone requires that the monitor well be located within a certain distance, and down-gradient from the source of contamination. Because the location of the source is not known, the average distance from monitor wells to any wellbore can only be controlled through the selected monitor well spacing. If a consistent direction of groundwater flow is measured, then most of the monitor wells may be placed down-gradient.

This suggests that installation of monitor wells should proceed in phases, where three wells are installed early in the process to determine the direction of groundwater flow. Another reason to install a limited number of wells at an early phase is to characterize background variation in concentrations that may result from seasonal recharge, sampling conditions and other sources of variation. Changes in analyte concentrations that are observed during operation of the facility may then be compared to this background variation, and those that are significant may be investigated further.

Design of a monitor well program involves consideration of trade-offs among such factors as monitor well spacing, targeted time lag between the occurrence of migration and detection, natural groundwater flow rates, and the thickness and porosity of an aquifer. A full analysis should be performed by a qualified hydrologist. However, a simple calculation will illustrate some of these considerations.

Fluid that enters a homogeneous aquifer from a wellbore will occupy a radially expanding volume. The relationship between the flow rate, time, and the radius of a volume that is assumed to be cylindrical is as follows:

$$r = \sqrt{\frac{192 \text{ x } Q \text{ x } t}{\phi\pi}}$$

where:

r	=	Plug-flow radius of region occupied by fluid around the wellbore (feet).
Q	=	Flow rate (GPM).
t	=	Duration of migration (days).
Φ	=	Porosity (unitless).
192.5	=	Constant for unit conversion.

Possible values for this example are selected as follows:

Q	=	1.0 GPM. This was suggested as an order-of-magnitude estimate of flow in the previous section.
t	=	90 days. Convenient sampling frequency.
Φ	=	10 %.

Substituting:

$$r = \sqrt{\frac{192.5 \text{ x } 1.0 \text{ x } 90}{0.1 \text{ x } \pi}}$$

$$= 235 \text{ feet}$$

The above calculation suggests that detection of an abandoned wellbore by means of detecting brine migration would occur after a significant time lag. As indicated in the previous section regarding potentiometric surface measurement, pressure responses would be measured much more rapidly over a wider area. Later sampling of brine would serve to confirm the pressure response.

8.3 Time and Cost Estimates

Costs for Construction and Sampling of Monitor Wells

Shallow monitor wells, installed to depths as much as 200 feet, may be drilled with a mud rotary rig and cased with PVC pipe. Typical costs for this installation in an alluvial region are about $32 per foot, plus mobilization and supplies. More than one well may be installed per day if the depths are less than approximately 40 feet.

Wells of greater depth require heavier casing and, if extending below the Underground Source of Drinking Water (USDW), require at least one additional concentric string of casing to protect the USDW. Monitor wells in excess of 1000 feet may cost over $100,000 to install each well.

8.4 Equipment and Service Vendors

Most licensed water well drillers are able to install shallow monitor wells. States require that a qualified geologist log the cuttings, and that each well be surveyed for location and elevation. States commonly specify that locations be surveyed with respect to the state plane coordinate system or the Universal Transverse Coordinate (UTM) system. Elevations are referenced to mean sea level. Precise reference to elevation is a critical step for describing the potentiometric surface.

Wells deeper than approximately 500 feet usually require heavier-duty rigs and additional strings of casing. Specifications for such monitor wells should be provided to water well and drilling contractors for alternative evaluation and recommendations. All such recommendations should be substantiated with cost comparisons and an assessment of relative risk.

8.5 References

General Reference

Aller, L. 1984. Methods for Determining the Location of Abandoned Wells. US EPA, EPA-600/2-83-123.

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APPENDIX A

Other Geophysical Methods Considered for Abandoned Well Search

The following were also considered as potential geophysical methods for locating abandoned wells: microgravity, seismic, induced polarization (IP), complex resistivity (CR), natural source magnetotellurics (MT), and magnetometric resistivity (MMR). Some of these methods may have limited application in particular circumstances. At this time, however, they are considered less cost-effective and less applicable to abandoned well searches than the other methods presented in this manual, due to the various reasons discussed below.

1. Microgravity

The microgravity method may be useful in a search for abandoned wells under very specific and limited conditions. The primary targets associated with wells (casings and brine plumes) are not feasible targets for this method. However, the microgravity method does have potential application to mapping voids associated with abandoned wells, under limited conditions. Small voids may be due to washout zones near the wellbore, or larger voids or solution caverns may develop in soluble rock units due to migrating fluids. Very deep caverns will not be resolvable using the microgravity method; however, caverns or large voids in the depth range of about 0 to 100 meters, may be resolvable depending on the size of the cavern, density contrast, near-surface density variations, and other noise (Figure A-1).

Gravity surveys are conducted in order to determine lateral changes in subsurface density. The modeled density variations are then interpreted in terms of geologic structure or lithology. The mass distribution within the earth determines the shape of the gravitational potential field. Modern gravimeters are extremely sensitive instruments that can measure the vertical acceleration of gravity with a precision of roughly one part per billion. Common gravimeters are actually relative instruments; that is, they measure differences in gravity, and are usually referenced to an arbitrary base station. Gravity anomalies are given in units of milliGals or microGals, 1 microGal being about the best measurement precision available at this time. Various data reduction procedures are applied to observed gravity signals in order to isolate the subsurface anomalies of interest. One of these reductions requires correction for the station elevation, and for high-precision gravity (microgravity) work, elevations must be determined very precisely. For this and other reasons, the microgravity method is somewhat expensive and time-consuming on a per station, or coverage area, basis.

The gravity method, like all potential fields methods, suffers from ambiguity; that is, many different subsurface density distributions will create the same observed gravity anomaly. This inherent ambiguity, plus that resulting from observation, reduction, and processing of these data, limit the accuracy of interpretation that is critical to small-scale engineering or environmental studies. For this reason, gravity data are best interpreted in conjunction with either control data from drilling, or with other collateral geophysical data. Nevertheless, the microgravity method has been successfully applied to many environmental and engineering problems such as mapping subsurface voids (including natural or man-made), reservoir monitoring, mapping paleo-channels, near-surface faults, dewatering fissures, karst, and hydrological conditions (e.g., Butler, 1991; Hare, 1999; Hinze, 1990).

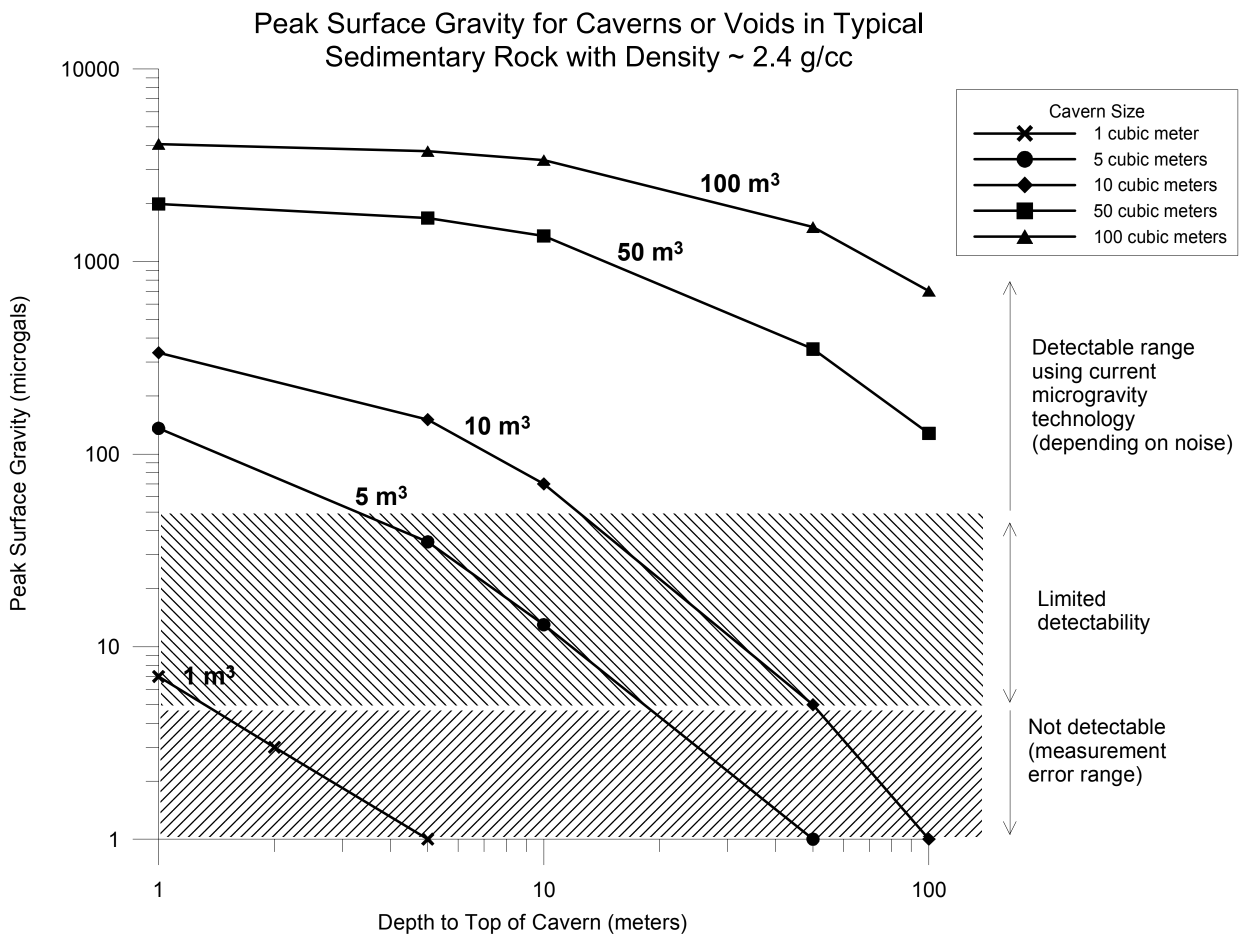

Figure A-1. Peak surface gravity amplitude for caverns or voids in typical sedimentary rocks assuming a density contrast 2.4 g/cc. The estimates are based on air-filled voids with an equidimensional (cubic) shape. Resolution of caverns and voids will depend on the size of the cavern, the depth, the density contrast, near-surface density variations, and other noise factors.

2. Reflection and Refraction Seismic

Seismic methods are relatively expensive and time consuming. The limited well-related targets which could be imaged with seismic methods (cavities, plumes, possibly pipelines) could also be imaged with other less expensive methods.

The shallow seismic reflection method measures the arrival times of acoustic waves at the surface which have been reflected from subsurface interfaces where changes in acoustic impedance occur. Although the seismic reflection method lacks the horizontal resolution to detect a wellbore directly, shallow, high-resolution seismic surveys might be used for detecting solution cavities, brine or other plumes associated with abandoned wells. Aside from the traditional seismic methods which utilize compressional wave energy to model the earth, recent research has focused on the using shear waves and surface waves for delineating conditions in the near-surface. Field procedures, data processing and interpretation of seismic reflection data are probably cost-prohibitive for abandoned well search however.

The seismic refraction technique differs from the seismic reflection technique in that the acoustic energy recorded, processed, and modeled is from acoustic waves which are refracted along impedance-change boundaries for some distance before returning to the surface to be recorded by the geophones. The refraction method requires that the earth be made up of layers of material that increase in seismic velocity with each successively deeper layer (so that critically refracted waves may propagate). This is a rather severe constraint for many shallow applications where the uppermost section often has low-velocity layers or lenses of earth material. Nevertheless, the method is relatively quick and cheap compared to reflection methods, and has been successfully used for many shallow environmental and engineering applications. The refraction method may be useful for delineating shallow cavities or possibly brine plumes associated with abandoned wells; however, as for seismic reflection, other methods would be more applicable and cost-effective for these types of well-related targets.

3. Induced Polarization (IP)

The IP method is an extension of the resistivity method (Section 7.2.1) that provides additional information about the chargeability, or energy storage capacity, of the earth. As opposed to resistivity, the IP effect is related to the phase, or imaginary component, of the calculated impedance from the survey measurements. The added information yielded in an IP survey aids in interpretation of anomalies. Compared to changes in resistivity, there are relatively few conditions that create an IP response; therefore, taken with the resistivity, the data provided by an IP survey can be quite diagnostic of the source of an anomaly. Like resistivity, buried metallic objects, metallic mineralization, and certain clays have a strong IP effect. Unlike resistivity, however, clean water or brines have no IP effect. IP effects are often observed for contamination plumes, waste, and even green waste, where resistivity anomalies may be entirely absent. The IP method has been particularly successful at delineating landfills and buried debris for site evaluation and remediation (Carlson et al., 2001).

For abandoned well search, the primary application of both the IP and resistivity methods would be to locate brine or hydrocarbon plumes related to abandoned wells. Brine plumes would most likely consist of salt-water incursion into fresher water zones. Resistivity data can delineate salt-water from fresh-water, however, IP data in general cannot. The delineation of hydrocarbon plumes may be possible using IP, and this is currently an active area of research (specifically, spectral IP, or CR, see below). The IP method may also have future potential for locating well-related structures made of wood or plastic, as some recent research indicates that these materials may have a small IP response (e.g., Weller, A., 2001).

4. Complex resistivity (CR)

The complex resistivity (CR) method, sometimes referred to as spectral IP, provides the most complete set of resistivity and IP data of all the available IP techniques. CR is a frequency domain method that measures the amplitude and phase relationship between the current put into the ground and the voltage received. The primary advantage of the CR method is that it utilizes information on the variation of resistivity with frequency; the particular form or pattern of the frequency dependency is often indicative of the source material.

The method might be used to delineate cavities or brine plumes associated with abandoned wells; however, because of the complexity of data processing, analysis, and interpretation of CR data, it is probably not feasible for this application. Literature and case-studies using the CR method are very limited for engineering and environmental applications- it has been primarily used in mineral exploration. Some very recent research indicates that the CR method may prove useful for delineating hydrocarbon or non-aqueous phase liquid (NAPL) plumes (e.g., Chambers et al., 2001; Lewis et al., 2000).

5. Natural Source Magnetotellurics (MT, AMT)

In MT (Magnetotelluric) and AMT (Audio-frequency magnetotelluric) methods, natural electromagnetic field pulsations at the surface of the earth are utilized in order to measure induced currents in the ground. Components of the electromagnetic field are measured using a magnetic field antenna and electric dipoles on the surface. MT and AMT methods are identical to the CSAMT method discussed in detail in Section 7.2.4 of this manual, except that the source is natural variations in the electromagnetic field at the surface of the earth.

MT and AMT work well in particular environmental conditions; however, noise levels are often unpredictable due to the nature of the source (naturally exited telluric currents in the earth), and cultural electromagnetic (EM) noise can be a problem. Due to these difficulties, and the relatively small-scale targets which are of interest related to abandoned wells, other EM methods or controlled source MT (CSAMT) would probably have more success.

6. Magnetometric Resistivity (MMR)

Magnetometric Resistivity (MMR) is an electrical surveying method in which current is sent into the ground through a pair of electrodes, and the anomalous conductivity structure of the subsurface is defined by measuring the secondary magnetic field arising from this galvanic current flow. It differs from traditional resistivity methods in that the potential, or receiving, electrodes are replaced with a high sensitivity coil or magnetometer in order to measure the magnetic field. The MMR method is particularly effective at mapping current channeling and imaging beneath a conductive surface layer, where traditional resistivity methods are often ineffectual.

MMR has not been used as extensively as other electrical methods. It may have potential for application to locating well-related targets such as cavities and fluid leakage; however, like the CR method, it is difficult to judge its technical merit due to its lack of a track record for applications other than mineral exploration.

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APPENDIX B

GPS Positioning for Geophysical Surveys: Terminology, Accuracies, and Costs

Regardless of the type of survey involved, the precise location of the geophysical sensors (e.g., magnetometer, electrodes, etc.), as well as the location of cultural features relative to the geophysical data, must be known. While not strictly necessary for locating an abandoned well, elevation is also important for several of the geophysical methods described in this manual which need to account for any significant topographic variations. The overall costs of a survey will be dependent on many factors, including the type of instruments required for positioning the survey stations.

Conventional methods for positioning include using tape or chain and a hard copy map which is annotated in the field with station locations and cultural features, or using conventional survey instruments such as total stations, electronic distance meters, or theodolites. Most modern geophysical surveys now use GPS (Global Positioning System) techniques for positioning. The cost of integrating GPS positioning can vary greatly depending on the particular GPS instrument and technique used. The following table summarizes some of the most common methods, their measurement precisions, and general costs.

Table B.1. Common GPS Terminology, Accuracies, and Costs

GPS Terminology (Type of GPS Position)	Type of Instrument	Typical Applications	Approximate Precision	Instrument Costs
Navigated, Single-point, Code-only, Psuedorange	Hand-held GPS receivers	Recreation, Gross navigation	Horizontal: ~ 5-30 meters Vertical: ~ 10-60 meters	Purchase: ~ $100 - $300
DGPS, Real-time DGPS	Single unit using broadcast code corrections from a service provider's satellite	GIS surveys, Geophysical surveys	Horizontal: ~ 1 m Vertical: ~ 2 m	Purchase: ~ $ 5,000 – 10,000 + service for satellite broadcast corrections (Real-time DGPS): ~$1000/yr Rental: ~ $ 100/day
Phase-differential, Carrier-phase, Kinematic, RTK, Static, Fast-static, Rapid-static	Geodetic quality GPS receivers* (possibly including radios for RTK) *2 receivers required, one as reference station, one as roving unit	Geodetic surveys, Aircraft navigation, Geophysical surveys	Horizontal: ~ 1 cm Vertical: ~ 2 cm (depending on distance from reference to rover, occupation time, and mode of solution)	Purchase: ~ $ 40,000 - $60,000 Rental: ~ $300/day

*DGPS- Differential GPS
*RTK- Real-Time Kinematic
*GIS- Geographic Information Systems

APPENDIX C
Guidelines for Contracting Geophysical Services*

1. Consider hiring an independent geophysicist as a consultant for defining objectives and writing the request for proposal (RFP).
2. Define the scope of work in a written contract with input from both the customer and the chosen contractor. A well-written contract gives clear objectives and requirements for all phases of work.
3. Good communication between the customer and contractor is important.
4. Daily progress reports and plots of preliminary data are useful to monitor progress and data quality.
5. Quality-of-measurement issues must be defined. Often the accuracy of positioning each measurement in 3-D space (see Appendix B) has a strong influence on survey cost.
6. Flexibility is important in the contract. Variations to the agreed scope of work are common in geoscientific projects as the project progresses and knowledge increases.
7. Costs for standby time due to bad weather, instrument operation costs, instrument down-time, and insurance coverage are important. Costs for analysis and reporting should be clear. Define the time schedule for each phase.
8. Cost estimates are more accurate if done by an experienced estimator during a site visit with the customer. The characteristics of the survey site is often the biggest variable in a geophysical survey cost estimate, because survey parameters and methodology are dependent on site conditions.
9. A phased approach is highly recommended in the application of geophysics. Often a preliminary survey is necessary to determine the efficacy of a method, and dictate whether the method or another method will be most effective for the objective. Ground truth the results at each stage.
10. Survey production rates depend upon:
    - ease of access and commute time to the property,
    - local topography and vegetation,
    - season and weather,
    - atmospheric effects (magnetic storms, lighting, telluric currents, etc),
    - experience and resourcefulness of the field survey crew,
    - instrumentation age and upkeep,
    - the type of survey required and quality of measurement,
    - local cultural noise/interference sources to the signals of interest,
    - hours of daylight,
    - local work restrictions,
    - safety considerations.
11. For high-quality results the geophysicist must have access to all relevant maps, photos, borehole information, and other geoscientific reports for the property and local area.
12. A bailout clause should be included in all contracts to permit either the customer or the contractor to terminate the contract. If field tests do not meet the objectives then both sides can withdraw gracefully.

*This list is modified from a list courtesy of Hayles GeoScience Surveys, Ltd., www.haylesgeoscience.ca

APPENDIX D
LIST OF VENDORS

Service and Equipment Vendors for Environmental & Engineering Geophysics in North America

Vendor / Website	Geophysical Instrument Sales & Rentals *	Geophysical Surveys, Service & Consulting	Phone	Address	City, State & Zip	Country
Advanced Geosciences, Inc. www.agiusa.com	Resistivity, IP Instrument Sales & Rentals	----	512-335-3338	12700 Volente Rd., Bldg. A	Austin, TX 78726	US
Airmag Surveys www.airmagsurveys.com	----	Surveys, Service & Consulting: Airborne Magnetic	215-673-2012	P.O. Box 21059	Philadelphia, PA	US
Blackhawk Geosciences www.blackhawkgeo.com	----	Surveys, Service & Consulting: Gravity, Magnetic, EM, Resistivity, IP, GPR, Seismic	303-278-8700	301 Commercial Road	Golden, CO	US
Condor Consulting, Inc. www.condorconsult.com	----	Surveys, Service & Consulting: Airborne Magnetic and EM	303-423-8475	4860 Robb St., Suite 206	Wheat Ridge, CO	US
Dualem Inc. www.dualem.com	Em, Airborne Em Instrument Sales & Rentals	Surveys, Service & Consulting: Airborne Magnetic and EM	905-876-0201	540 Churchhill Ave	Milton, Ontario L9T3A2	Canada
EDCON Worldwide Gravity and Magnetics www.edcon.com	Gravity, Magnetic Instrument Sales & Rentals	Surveys, Service & Consulting: Gravity, Magnetic, Airborne Gravity, Magnetic and EM	303-980-6556	171 S. Van Gordon St., Suite A	Denver, CO 80228-1703	US
ElectroMagnetic Instruments, Inc (EMI) www.emiinc.com	Magnetic, EM Instrument Sales & Rentals	----	510-232-7997	1301 S. 46th St. UCRFS Bldg. 300	Richmond, CA 94804	US
Exploration Instruments, LLC www.expins.com	Gravity, Magnetic, Resistivity, Gpr, Seismic Instrument Sales & Rentals	----	512-346-4042	2600 Longhorn Blvd, Suite 108	Austin, TX 78758	US
Frontier Geosciences Inc. www.frontiergeo.com	----	Surveys, Service & Consulting: Resistivity, IP, GPR, Seismic, EM, Borehole logging	604-987-3037	237 St. Georges Ave	N. Vancouver, BC V7L4T4	Canada

APPENDIX D (Continued)

Vendor / Website	Geophysical Instrument Sales & Rentals *	Geophysical Surveys, Service & Consulting	Phone	Address	City, State & Zip	Country
Fugro Geosciences, Inc. www.fugro-usa.com	----	Surveys, Service & Consulting: Resistivity, GPR, EM, Magnetic, Seismic	504-292-5082	4252 Rhoda Drive	Baton Rouge, LA 70816	US
Fugro Airborne www.fugroairborne.com	----	Surveys, Service & Consulting: Airborne Magnetic, EM, Gravity, Radiometric	713-369-6123	6100 Hillcroft	Houston, TX 77081	US
Geometrics www.geometrics.com	Magnetic, Em, Resistivity, Magnetotelluric, Seismic Instrument Sales & Rentals	----	408-954-0522	2190 Fortune Drive	San Jose, CA 95131	US
Geonics Limited www.geonics.com	Em, Vlf Instrument Sales & Rentals	----	905-670-9580	1745 Meyerside Drive, Unit 8	Mississauga, Ontario L5T 1C6	Canada
Geophex, Ltd. www.geophex.com	Em Instrument Sales & Rentals	Surveys, Service & Consulting: Resistivity, EM, Gravity, Magnetic, Seismic, GPR, Borehole logging	919-839-8515	605 Mercury St.	Raleigh, NC 27603	US
Geophysical Survey Systems, Inc. (GSSI) www.geophysical.com	Em, Gpr Instrument Sales & Rentals	----	603-893-1109	13 Klein Drive	N. Salem, NH 03073	US
Georadar, Inc. www.georadar.com	Gpr Instrument Sales & Rentals	----	408-867-3792	19623 Via Escuela Drive	Saratoga, CA 95070	US
Golder Associates, Inc. www.goldergeophysics.com	----	Surveys, Service & Consulting: Gravity, Magnetic, EM, Resistivity, GPR, Borehole logging	425-883-0777	18300 NE Union Hill Road, Suite 200	Redmond, WA 98052	US
Hager-Richter Geoscience, Inc. www.hager-richter.com	----	Surveys, Service & Consulting: Gravity, Magnetic, EM, Seismic, VLF, GPR	603-893-9944	8 Industrial Way D-10	Salem, NH 03079	US
HydroGeophysics, Inc.	----	Surveys,	520-647-3315	2302 N. Forbes Blvd.	Tuscon, AZ	US

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Vendor / Website	Geophysical Instrument Sales & Rentals *	Geophysical Surveys, Service & Consulting	Phone	Address	City, State & Zip	Country
www.hydrogeophysics.com		Service & Consulting: Gravity, Magnetic, EM, Resistivity, Borehole logging			85745	
K.D. Jones Instruments Corporation www.kdjonesinstruments.com	Seismic, Magnetic, Gps, Em, Resistivity, Ip Instrument Sales & Rentals	----	888-396-9291	P.O. Box 750	Normangee, TX 77871	US
Mala GeoScience USA, Inc. www.malags.se	Gpr Instrument Sales & Rentals	----	603-627-5841	2040 Savage Road	Charleston, SC 29416	US
Microgeophysics Corporation (MGC) www.members.aol.com/microgeo	----	Surveys, Service & Consulting: Seismic, GPR, EM, Resistivity, IP, Self-Potential, Magnetic, Gravity	303-424-0499	10900 W. 45th Ave.	Wheat Ridge, CO 80033	US
Northwest Geophysical Associates, Inc. www.nga.com	----	Surveys, Service & Consulting: Magnetic, EM, Resistivity, GPR, Seismic, VLF, Borehole logging	541-757-7231	1600 SW Western Boulevard, Suite 200	Corvallis, OR 97333	US
Paterson, Grant & Watson Limited www.pgw.on.ca	----	Surveys, Service & Consulting: Gravity, Magnetic, Airborne Gravity and Magnetic	416-368-2888	8th Fl, 85 Richmond St. West	Toronto, Ontario M5H 2C9	Canada
Quantum Geophysics, Inc. www.quantumgeophysics.com	----	Surveys, Service & Consulting: Gravity, Magnetic, EM, Resistivity, Seismic, GPR, Self-Potential, VLF, Borehole logging	610-917-9100	29 Richard Lee Lane	Phoenixville, PA 19460	US
RMS Instruments www.rmsinst.com	Magnetic, Em, Airborne Magnetic And Em Instrument Sales & Rentals	----	905-677-5533	6877-1 Goreway Drive	Mississauga, Ontario L4V 1L9	Canada
Sander Geophysics www.sgl.com	----	Surveys, Service & Consulting: Airborne Gravity, Magnetic,	613-521-9626	260 Hunt Club Road	Ottawa, Ontario K1V1C1	Canada

APPENDIX D (Continued)

Vendor / Website	Geophysical Instrument Sales & Rentals *	Geophysical Surveys, Service & Consulting	Phone	Address	City, State & Zip	Country
		Radiometric				
Scintrex www.scintrexltd.com	Gravity, Magnetic, Gpr, Resistivity, Ip, Em, Vlf, Seismic, Radiometric Instrument Sales & Rentals	----	918-438-9255	900 Woodrow Lane, Ste 100	Denton, TX 76205	US
Sensors & Software, Inc. www.sensoft.on.ca	Gpr Instrument Sales & Rentals	----	800-267-6013	1091 Brevik Place	Mississauga, Ontario L4W 3R7	Canada
Technos Inc. www.technos-inc.com	----	Surveys, Service & Consulting: Gravity, Magnetic, EM, GPR, Seismic, VLF, Radiometric	305-634-4507	3333 NW 21st St.	Miami, Florida 33142	US
www.terraplus.com	Gravity, Magnetic, Airborne Magnetic And Em, Resistivity, Ip,Vlf, Gps, Seismic,Gpr Instrument Sales & Rentals	----	303-799-4140	625 Valley Road	Littleton, CO 80124	US
Xenon Geosciences, Inc. (XGI) www.xenongeosci.com	----	Surveys, Service & Consulting: Gravity, Magnetic, EM, Seismic, GPR, Resistivity, Borehole logging	877-248-3689	Box 2027	Dayton, OH 45429-0027	US
Zonge Engineering & Research Organization, Inc. www.zonge.com	Em, Resistivity, Ip, Magnetotelluric Instrument Sales & Rentals	Surveys, Service & Consulting: Gravity, Magnetic, EM, Resistivity, IP, Magnetotelluric, Gravity, Seismic, GPR	520-327-5501	3322 East Fort Lowell Rd.	Tucson, AZ 85716	US

* Many providers of geophysical services also produce or distribute instrumentation.

APPENDIX D (Continued)

Additional Commercial Resources

Vendor / Website	Service / Product	Phone	Address	City, State & Zip	Country
SPOT Image Corporation	Source of Remote Sensing Images	(800) ASK-SPOT (703) 715-3100	1897 Preston White Drive	Reston, VA 20191-4368	USA
InfoTerra www.infoterra-global.com/	Source of Remote Sensing Images	+44 (0) 1252 362000	Delta House, Southwood Crescent	Farnborough, Hampshire GU14 0	NL
Cambe	Oil and Gas Records	(713)-659-8363	1500 Gray	Houston, TX 77002	USA
Riley's Electric Log Service	Oil and Gas Records	(832) 448-0490 (800) 592-1424	10616 Rockley Road 7608 N. Harvey	Houston, TX 77099 Oklahoma City, OK 73116	USA
Kansas Blue Print	Maps	(316) 264-9344 (888) 457-2583	700 S. Broadway	Wichita, KS 67211	USA
Kansas Geological Survey	Maps	(316) 943-2343	4150 Monroe	Wichita, KS 67204	USA
Eby Engineering	Maps	(870) 863-5285	109 N. Jackson	El Dorado, AR 71730	USA
IHS Energy	Maps	US: (888) 645-3282 (713) 840-8282	5333 Westheimer, Ste 100	Houston, TX 77056	USA and Canada
Tobin	Maps	Denver: 303-831-3555 Houston: 713-334-2242	1625 Broadway, Ste 500 9800 Richmond Ave	Denver, CO 80202 Houston, TX 77042	USA
United States Geological Survey (USGS) edc.usgs.gov/Webglis/glisbin/finder_main.pl?dataset_name=NAPP	USGS National Aerial Photography Program (NAPP) Photos				USA

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APPENDIX E

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