ERDC/GSL TR-04-8

Geotechnical and Structures Laboratory

US Army Corps of Engineers®
Engineer Research and Development Center

Guidelines for Planning Unexploded Ordnance (UXO) Detection Surveys

Janet E. Simms, Robert J. Larson, William L. Murphy, and Dwain K. Butler

August 2004

Approved for public release; distribution is unlimited.

ERDC/GSL TR-04-8
August 2004

Guidelines for Planning Unexploded Ordnance (UXO) Detection Surveys

Janet E. Simms, Robert J. Larson, William L. Murphy

Geotechnical and Structures Laboratory
U.S. Army Engineer Research and Development Center
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

Dwain K. Butler

Alion Science and Technology Corportation
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

Final report

Approved for public release; distribution is unlimited

Prepared for U.S. Army Corps of Engineers
Washington, DC 20314-1000

ABSTRACT: This report represents guidelines for planning UXO detection surveys based on a phenomenological approach. The phenomenological evaluation considers the physical characteristics (topography, vegetation, soil type, and moisture) of a site and subdivides the site into areas that have a unique classification for the set of four physical characteristics. Values for three geophysical parameters (electrical conductivity, dielectric permittivity, and magnetic susceptibility) are assigned to each area based on the physical characteristics of that area. Given the physical characteristics, geophysical parameters, and ordnance usage history, a selection of geophysical sensors and platforms are identified that would be appropriate for conducting a UXO detection survey within each area of the site.

Contents

List of Figures

List of Tables

Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
feet	0.3048	meters
inches	0.0254	meters
ounces	0.0284	kilograms
pounds (mass)	0.4536	kilograms

Preface

This report describes the efforts undertaken as part of the Science and Technology (BA2/3) Major Thrust Area I, Site Characterization Issues and Approach Strategy, Work Unit "Identification and Evaluation of Key Site Parameters Impacting Technology." The work was funded by the U.S. Army Engineer Research and Development Center (ERDC) under the Environmental Quality Technology (EQT) Program. Dr. M. John Cullinane, Technical Director for Environmental Engineering and Cleanup, Environmental Laboratory (EL), was the EQT Program Manager; Mr. John H. Ballard, EL, was the Unexploded Ordnance (UXO) Focus Area Manager for EQT; and Dr. Janet E. Simms, Geotechnical and Structures Laboratory (GSL), was Principal Investigator for the work unit. The work was performed under the direct supervision of Dr. Lillian D. Wakeley, Chief, Engineering Geology and Geophysics Branch, GSL, and under the general supervision of Drs. Robert L. Hall, Chief, Geosciences and Structures Division, GSL, and David W. Pittman, Acting Director, GSL.

The work unit focused on describing the physical characteristics (geology, hydrology, topography, and vegetation) of a site and understanding how those characteristics influence the physical properties/parameters that the UXO detection sensors measure. Given this knowledge, a suite of geophysical sensors and platforms optimized for a site's physical variability can be identified.

At the time of publication of this report, Dr. James R. Houston was Director, ERDC. COL James R. Rowan, EN, was Commander and Executive Director.

1 Introduction

Background

The Army's mandate to centralize operations and reduce operational costs has led to the closing of military installations and the transfer of lands to the public and private sectors. Prior to releasing military land, the property must be declared free of unexploded ordnance (UXO) to the degree suitable for the future use of the land. For example, acreage intended for a wetlands habitat may require no or minimal UXO clearance, whereas land planned for a housing development will require UXO clearance to a depth of a few meters. In the past, UXO clearance operations have been done by brute force, that is, several explosive ordnance disposal (EOD) personnel equipped with hand-held magnetometers sweep an entire area on foot, placing a pin flag at each anomalous location. This approach often results in a sea of flags, where each flagged location must be reoccupied and excavated to determine the cause of the anomaly, the majority of which are explosive waste and cultural debris. The "mag & flag" method for UXO clearing is both time consuming and costly.

More recent efforts have concentrated on more efficient means of detecting anomalies (e.g., mobile/multiple sensor platforms, integration of sensors) and the discrimination of anomalies caused by UXO from those caused by other sources. These methods of UXO clearance primarily consider what types of UXO are likely to be present and which sensor(s) would be suitable for their detection/discrimination. Little attention has been given to the importance of how the surrounding environment influences the detection and discrimination of UXO. In some settings, the geologic and cultural background masks the signatures of UXO (Khadr et al. 1997; Butler et al. 1999). The environmental influences on geophysical sensor performance are sometimes referred to as phenomenological considerations. These considerations include topography, vegetation, hydrogeology, soil/rock type and mineral composition, soil moisture, stratigraphy, and other physical parameters that influence sensor performance and the quality of data generated by the sensor.

Approach

A report prepared by Jet Propulsion Laboratory (JPL) (1995) for the U.S. Army Engineering and Support Center, Huntsville, addressed the need to evaluate a site's environment and, based on that assessment, choose sensors that would maximize UXO detection. The JPL report provided a comprehensive review of sensor types and their applicability to UXO detection. In the JPL approach, a site's natural environment was determined based on available maps constructed on a national scale. An initial selection of sensors was made by superimposing sensor capabilities onto soil geology, topography, vegetation, and expected signature attenuation.

The guidelines presented here develop the concept put forth in the JPL (1995) report where the environmental characteristics of a site guide the selection of geophysical sensors. The phenomenological characteristics of a site are first identified. Based on these attributes, a site is divided into areas having similar characteristics that would have similar sensor requirements. A spatial sampling density is recommended based on the complexity of an area and, for some areas, suggestions are given to acquire additional information to further refine the decision process. The intent of these guidelines is to provide the UXO site manager with knowledge of the geo-environmental influences that impact geophysical sensor selection. With this knowledge, the site manager has the capability to develop an initial UXO detection effort based on a phenomenological approach, thereby reducing time and costs that would be spent on geophysical surveys.

The following chapters describe: (a) UXO characteristics; (b) the common sensors used for UXO detection; (c) the importance of considering local geology when choosing a geophysical sensor; (d) the parameters pertinent to UXO detection; and (e) a description of how phenomenology considerations can provide valuable understanding of the variability of a site when planning UXO detection efforts.

2 UXO Characteristics

To detect unexploded ordnance, it is important to be familiar with their characteristics (i.e., type, shape, length, diameter, material type, typical burial depth, etc). Most types of ordnance have a ferrous metallic housing or a composite body comprised in part of a ferrous metal, and they are generally spheroidal in shape. They can range in size from a munition less than 2 cm long to a 2,000-lb (907-kg) bomb a few meters in length. A compilation of ordnance is provided on the ORDATA II Version 1 cd-rom distributed by the Naval EOD Technology Division.[1]

Classifications

There are seven main categories of UXO (U.S. Environmental Protection Agency (EPA) 2002), based on size and method of delivery.

a. Small arms munitions (0.6 in. (15.24 mm) or less in caliber) present minimal explosive risks but may contaminate the environment with lead (Pb) compounds. They are fired from various weapons, including pistols, carbines, rifles, automatic weapons, and shotguns.

b. Grenades are small explosive- or chemical-type munitions that are hazardous to personnel and civilians because they are designed to land on the ground surface. Grenades may be hand-launched or fired from shoulder weapons. Several classes of grenades that may be encountered as UXO are fragmentation, smoke, blast, riot control, and illumination grenades. All grenades have three main parts: a body, a fuze with a pull ring, and a filler. Grenades have metal, plastic, cardboard, or rubber bodies and may contain explosives, white phosphorus, chemical agents, or illumination flares, depending on their intended use. Fragmentation grenades, the most common type of grenade, break into small, lethal, high-velocity fragments and pose the most serious explosive risks.

c. Mortar shells are munitions launched from gun tubes at a very high arc. Mortar shells range from approximately 50 to 280 mm in diameter and are filled with explosives, white phosphorus, red phosphorus, illumination flares, chemical agents, or other fillers. Typical U.S. sizes include 60-mm, 81-mm, and 4.2-in. (106.7-mm) mortars. Mortar shells, like projectiles,

[1] Naval EOD Technology Division, ATTN: Code 602, 2008 Stump Neck Road, Indian Head, MD 20640-5070. E-mail Ordata@eodpoe2.navsea.navy.mil

can be either fin stabilized or spin stabilized and are common ordnance deployed by ground troops. Mortar shell UXO is sensitive to disturbance.

d. Artillery projectile rounds range from approximately 15 to 400 mm in diameter and from 50 to 1,200 mm in length. Common U.S. sizes include the 90 mm, 105 mm, and 155 mm. Projectiles are typically deployed from ground-based gun platforms. A typical projectile configuration consists of a bullet-shaped metal body, a fuze, and a stabilizing assembly. Fillers include antipersonnel submunitions, high explosives, illumination, smoke, white phosphorus, riot control agent, or a chemical. Fuzing may be located in the nose or base. Fuze types include proximity, impact, and time delay, depending on the intended target.

e. Submunitions typically land on the ground surface, making them potentially accessible and hazardous to humans and animals. Submunitions include bomblets, grenades, and mines that are filled with either explosives or chemical agents. Submunitions are used for a variety of purposes, including antipersonnel, antimateriel, antitank, dual-purpose, and incendiary. They are scattered over large areas by dispensers, missiles, rockets, or projectiles. Submunitions are activated in a number of ways, including pressure, impact, movement, and disturbance while in flight or near metallic objects.

f. Rockets and missiles pose serious UXO hazards because residual propellant may burn violently if subjected to sharp impact, heat, flame, or sparks. Rockets and missiles consist of a motor section, a warhead, and a fuze. A rocket is an unmanned, self-propelled ordnance, with or without a warhead, designed to travel above the surface of the earth and whose trajectory or course cannot be controlled during the flight. Missiles have a guidance system that controls their flight trajectory. The warhead can be filled with explosives, toxic chemicals, white phosphorus, submunitions, riot-control agents, or illumination flares. Rockets and missiles may be fuzed with any number of fuzes. The fuze is the most sensitive part of an unexploded rocket or missile.

g. Bombs may penetrate the ground to variable depths. Dud-fired bombs that malfunction and remain on or near the ground surface are extremely hazardous. Bombs commonly range from 100 to 3,000 lb (45.4 to 1,361 kg) in weight and from 1,000 to 3,600 mm in length. Bombs consist of a metal container (the bomb body), a fuze, and a stabilizing device. The bomb body holds the explosive chemical or submunitions filler, and the fuze may be antidisturbance, time delay, mechanical time, proximity, impact, or a combination. Figure 1 presents a variety of the UXO described above.

Depth of Penetration

The depth to which an ordnance item can penetrate the earth and its recovery depth are dependent on ordnance characteristics, firing parameters, and environmental conditions. Ordnance characteristics include shape, size, and

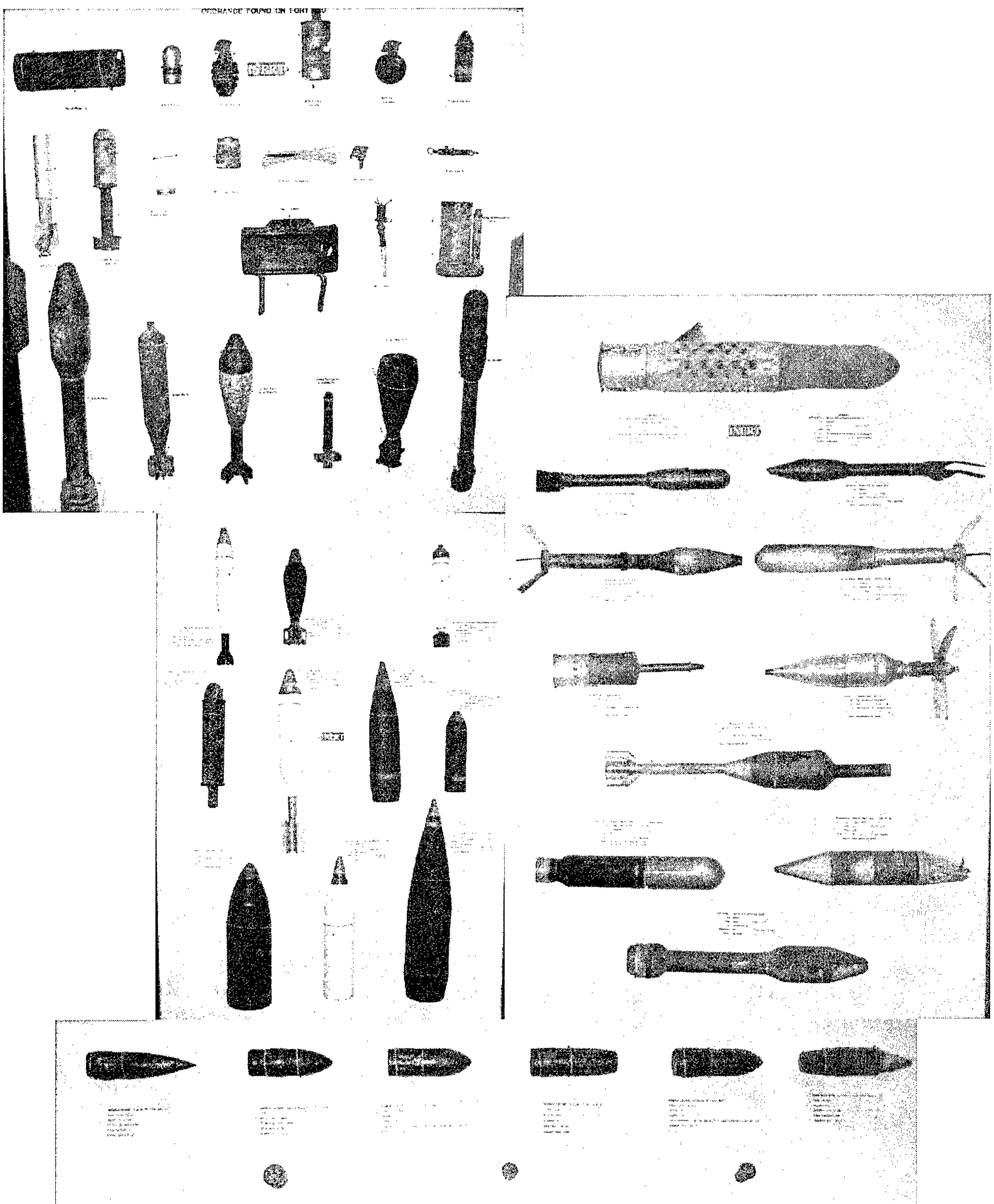


Figure 1. Variety of UXO types

weight, whereas firing parameters address type of propellant used, trajectory, and striking velocity and angle. The type of soil/rock, vegetation, and soil moisture are some environmental factors that influence how deep an ordnance item will penetrate into the ground. Some general observations for soils from the U.S. Department of the Army (1986) are:

a. Penetration depth decreases with increase in soil density.
b. For materials having the same density, the finer the grain size the greater the penetration.
c. Penetration depth increases with increasing water content of the soil.

Geological factors such as frost heave, flooding, erosion, and human activities (agricultural, construction, recreation) can cause movement of ordnance after its initial penetration.

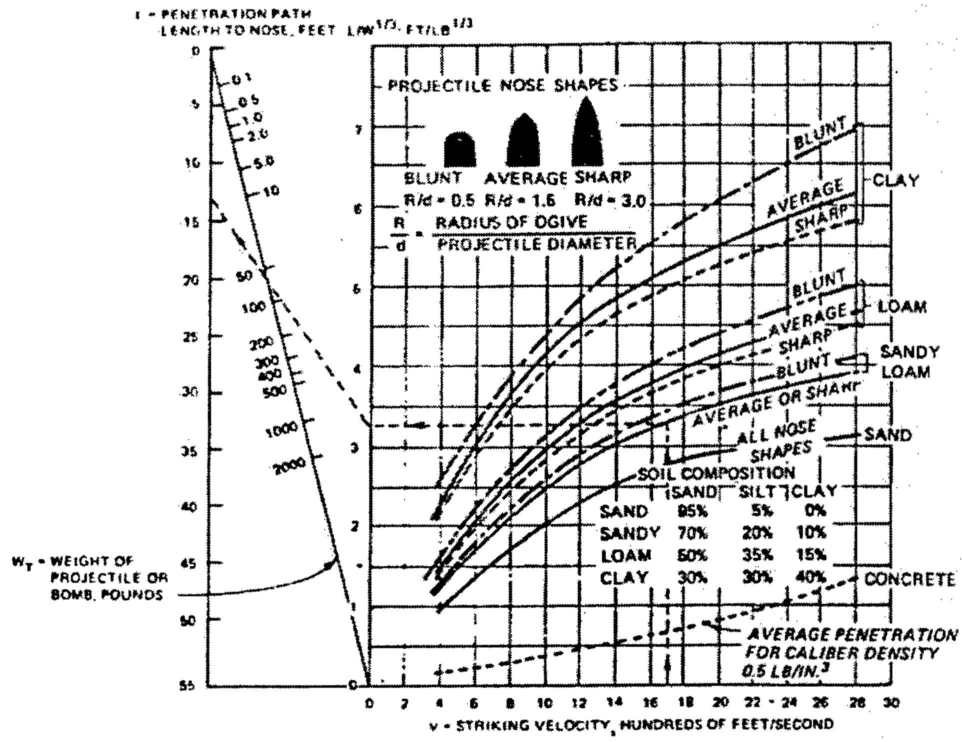
After a projectile impacts the ground surface, it typically follows a J-shaped path. Because of the curved path trajectory within the subsurface, the depth of burial is usually less than the actual path length. For projectiles that follow a J-shaped path, the straight portion is about two-thirds of the total path length (U.S. Department of the Army 1986). Both test data and equations have been used to estimate the depth of penetration of a projectile. Figure 2 is a nomogram reproduced from "Fundamentals of Protective Design for Conventional Weapons" (U.S. Department of the Army 1986). It is constructed from test data for bombs and large- and small- caliber projectiles (refer to note in Figure 2). Given the striking velocity of the projectile, the penetration path length can be estimated. This is not the depth of burial, but rather the length of the subsurface path the projectile follows. Distance beneath ground surface is usually 10 to 30 percent less than the projectile path length.

Crull et al. (1999) compared three mathematical approaches for estimating the penetration of ordnance into selected soil and rock types. The first approach is an equation developed by the U.S. Army Corps of Engineers Waterways Experiment Station (WES) (U.S. Department of the Army 1986). It requires the least input and was actually developed to describe the penetration of fragments into soil. In this case, the fragment is assumed to be a projectile. The equation is given as:

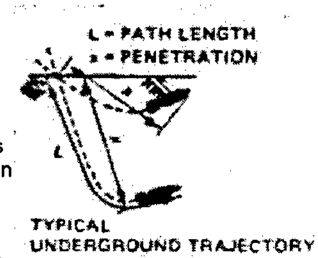
$$t_p = 1.975 W_f^{(1/3)} k_p \log\left(1 + 4.65\left(V_s/10^3\right)^2\right)$$

where

t_p = penetration depth, in.
W_f = fragment weight, oz
k_p = constant depending on soil type (refer to table below)
V_s = striking velocity, ft/sec



The graph and nomogram give the relation between velocity and penetration path length, measured to the nose, for projectiles or bombs of various weights penetrating into several soils. Curves marked blunt, average, and sharp are for projectiles of different nose shapes, as sketched. Where no appreciable effect of nose shape on penetration has been observed, only a single curve is drawn. The dependence of penetration path length on projectile weight, as given by the nomogram, agrees with observations for projectiles or bombs having caliber densities from 0.15 to 0.65-lb/in.^{3}. Most bombs and artillery projectiles have caliber density values (weight of projectile in pounds divided by the cube of the diameter in inches) within the above range.



Trajectories in soils are usually straight for two-thirds or more of the path length, but curve near the end of the path (see sketch). For this reason, final distance from the surface is usually 10% to 30% less than the penetration path given here.

Curves given are for average soil types. Penetrations into rich plastic clay are approximately 30% greater than those observed in clay. The dotted curve at the bottom of the graph gives average penetration into good quality reinforced concrete, and is added here for rough comparison.

EXAMPLE The dotted line shows that a projectile of average nose shape and weight of 60-lb striking sandy loam soil with a velocity of 1700-ft/sec will have a path length of approximately 12.5-ft, measured to the nose. Because of the curvature of the underground trajectory, the actual penetration from the surface will be somewhat less.

SOURCE British and American tests with bombs and large caliber projectiles at velocities below 1100-ft/sec. Small caliber tests for the Corps of Engineers, USA extending over entire velocity range. The curves agree with measurements to ±20%.
NDRC Weapon Data.

Figure 2. Nomogram for calculating projectile penetration depth (after U.S. Department of the Army 1986)

Soil Penetration Constants	
Soil Type	k_p (in / oz$^{1/3}$)
Limestone	0.775
Sandy soil	5.29
Soil with vegetation	6.95
Clay soil	10.6

A listing of penetration depths obtained using the WES equation for different geologic media is given in Table 1. The calculated depths tend to follow the general rules regarding material density and particle size.

Table 1
Ordnance Depth of Penetration, WES Equation

	Depth of Penetration, ft			
Ordnance Item	Limestone	Sand	Soil Containing Vegetation	Clay
155-mm M107	2.0	14.0	18.4	28.0
105-mm M1	1.1	7.7	10.1	15.4
75-mm M48	0.7	4.9	6.5	9.9
40-mm M822	0.5	3.2	4.2	6.4
37-mm M63	0.6	3.9	5.2	7.9
2.36-in. Rocket	0.1	0.4	0.5	0.8

The second approach is known as the HULL hydrocode (Durrett and Matuska 1972) and was originally designed for simulation of nuclear weapons effects. The Hull programs are physics-based, using the principles of conservation of mass, momentum, and energy to solve two- and three-dimensional, multimaterial, multiphase dynamic-continuum mechanic equations. Input to the Hull hydrocode requires the geometry, weight, and striking velocity of the ordnance. In addition, equations of state of the ordnance and soil must be defined.

The third method evaluated by Crull et al. (1999) is a computer program developed for predicting projectile penetration into curvilinear geologic/structural targets. The program, PENCRV3D (Adley et al. 1997), predicts the trajectory and response characteristics of a projectile in three dimensions (3D) as a function of time. A differential-area force-law formulation is used to solve the six equations required for describing the 3D motion. The input to PENCRV3D includes ordnance geometry, striking angle, striking velocity, and soil parameters. To describe the soil, the program contains a database of soil definitions varying from well-cemented sand to wet clay and assigns a numeric value to each soil type.

Calculation of penetration depths requires some assumptions because information is generally not obtainable for certain parameters. The striking velocity of the ordnance is required for all methods but is generally a parameter that is unknown. To err on the conservative side, the muzzle velocity given a maximum charge (Table 2) is used and it is assumed that the ordnance strikes normal to the ground surface. The example in Adley et al. (1997) illustrating the use of PENCRV3D utilized a 155-mm M107 impacting a medium-dense, medium or coarse sand at a striking angle of 30 deg from horizontal and a striking velocity of 215 m/sec (705 ft/sec). A comparison of penetration depths extracted from Crull et al. (1999) with those estimated using the nomogram (Figure 2) is given in Table 3. As expected, the penetration depths obtained assuming a maximum muzzle velocity are consistently greater than those based on a slower striking velocity. The HULL code gives the greatest depth estimate. Penetration depths calculated using the WES equation, assuming a maximum muzzle velocity, are similar to the upper range limit estimate obtained using the nomogram, especially for ordnance items smaller than a 155 mm. At the lower striking velocity, the WES equation and nomogram provide comparable depth of penetration values. The depth of penetration from PENCRV3D, which also compensates for ordnance geometry, is shallower than the estimates from the other methods.

Table 2
Ordnance Weight and Velocity

Ordnance Item	Weight, lb	Muzzle Velocity, ft/sec
155-mm M107	96.75	2244
105-mm M1	33.95	1550 (charge 7)
75-mm M48	14.6	1250
40-mm M822	5.5	1100
37-mm M63	1.61	2650
2.36-in. Rocket	3.4	265

Note: from Crull et al. (1999)

Table 3
Comparison of Ordnance Penetration Depths into Sand

	Depth of Penetration, ft					
	Maximum Muzzle Velocity and Normal Striking Angle			Striking Velocity 705 ft/sec Striking Angle 30 deg		
Ordnance Item	WES Equation	Hull Hydrocode	Nomogram[1]	WES Equation	PENCRV3D	Nomogram[1]
155-mm M107	14.0	16.8	9.5-12.2	5.1	3.0	5.3-6.8
105-mm M1	7.7	9.4	5.8-7.4	3.7	----	3.4-4.4
75-mm M48	4.9	5.7	3.9-5.0	2.8	----	2.5-3.2
40-mm M822	3.2	2.9	2.3-2.9	2.0	----	2.0-2.5
37-mm M63	3.9	4.1	2.1-2.7	1.3	----	1.2-1.5
2.36-in. Rocket	0.4	0.46	< 1	----[2]	----	----[2]

[1]Depth of penetration range is 10% to 30% less than the projectile path length
[2]Striking velocity greater than maximum muzzle velocity

Figure 3 presents a relative comparison of depth of penetration for different striking angles. As the strike angle increases, the depth of penetration also increases, reaching a maximum penetration depth when the ordnance impacts normal to the ground surface. This pattern was observed in the depth estimates presented in Table 3. Figure 3 depicts an interesting behavior of a projectile when it strikes the ground at low angles (< 20 deg). At these "grazing" angles, it is possible for the projectile to return to the surface because of the J-curve path the projectile follows. In practice, the depth of penetration is less than that determined using a maximum velocity at vertical impact. Recovery data compiled from multiple UXO cleanup operations indicate that the majority of ordnance and explosive (OE) items are found at depths less than 61 cm (2 ft) (Figure 4). It is important to emphasize again that the depth of burial of a recovered OE item does not necessarily correspond to its penetration depth because of influences (geological processes and human activities) that can cause movement of the item after initial placement.

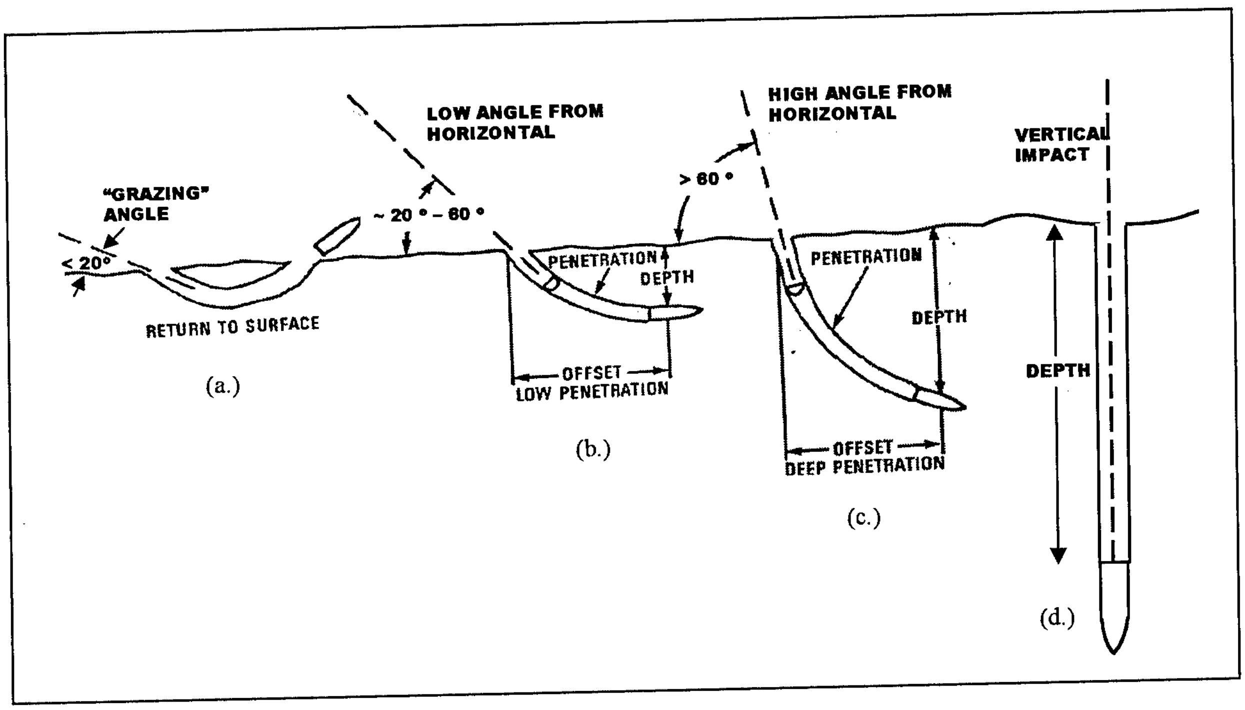


Figure 3. Projectile paths at different impact angles

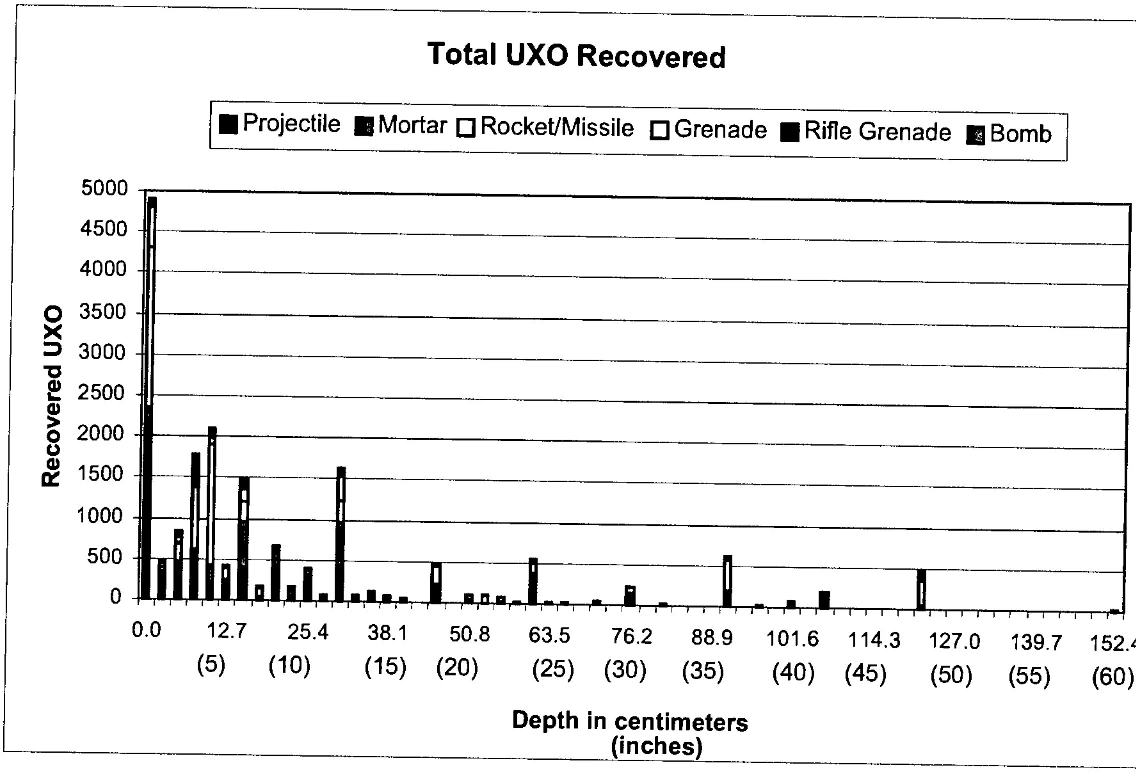


Figure 4. Recovery depth of over 18,000 UXO items, including projectiles, mortars, rockets/missles, grenades, rifle grenades, and bombs (NDCEE 2003)

3 Geophysical Sensors for Detecting UXO

The characteristics of UXO described in the previous section dictate which geophysical methods are applicable for detecting UXO. Because UXO is primarily comprised of metal, magnetometry and electromagnetic induction methodologies work well for UXO detection. Both technologies are reliable, provide rapid data acquisition, permit mountable sensor arrays for faster acquisition of high-resolution data, and can be used on hand-held, cart, or vehicle platforms. It is common practice to integrate a global positioning system (GPS) into the data collection process to obtain accurate location information so an anomaly position can be reoccupied for further investigation. Standard UXO detection surveys are ground-based, however, prototype airborne magnetic and electromagnetic induction (EMI) configurations are showing promising results (Doll et al. 2003a). The sensors are mounted on a helicopter and flown close to the ground surface (< 2 m); therefore, their application is in open or low-brush-covered areas. The increased standoff distance decreases the detection depths, particularly for smaller targets. At sites where larger targets are expected, an airborne system has applications toward reducing the UXO site footprint and thus decreasing the time and cost of UXO detection surveys.

Another geophysical method that has been demonstrated during several technology demonstrations is ground penetrating radar (GPR). It is an electromagnetic method that has not proven practical for large area UXO detection surveys but may be applicable for discrimination and identification purposes.

Magnetometry

Magnetometers detect ferrous material such as iron-based metals and soil/rock containing iron-bearing minerals. The magnetic sensor responds to the material property termed magnetic permeability. A physical property related to the permeability is magnetic susceptibility, which is a measure of the degree to which a material can be magnetized. The magnetic susceptibility of a material can be measured in the laboratory or field.

The majority of magnetic sensors employed in geophysical surveys measure the earth's total magnetic field (TMF). Dual magnetic sensors are sometimes used, in which case a gradient measurement can be computed. Typically, the cesium vapor sensors in common use have an operating range extending one order of magnitude (for example, 17,000 to 100,000 nT) and can sample at typical rates of 10 to 50 samples per second for UXO survey applications. UXO detection surveys performed by EOD personnel often utilize fluxgate magnetometers that measure only the vertical component of the earth's magnetic field and commonly have only an audible output. This type of magnetic sensor is generally employed in "mag & flag" survey operations (magnetometer sweep mode).

Electromagnetic Induction

EMI devices respond to material that is capable of conducting an electrical current. Typical materials include both ferrous and non-ferrous metal, moisture-bearing soil and rock, and soils and rocks containing metallic minerals.

There are two classifications of EMI instruments, time domain electromagnetic (TDEM) and frequency domain electromagnetic (FDEM). While both types of instruments rely on the same basic physical principles, it is the TDEM systems that are commonly used for UXO detection. The primary reason for this is that TDEM devices can be specifically designed to minimize the influence of geologic materials. The commonly employed TDEM systems for production UXO surveys sample one or two time gates along the time-decay curve and are sometimes described as "simple" TDEM instruments. A typical sampling gate is 400 to 800 μsec (nominal frequency 1.2 to 2.5 kHz). Prototype and research TDEM systems sample multiple time gates, typically in excess of 20, and/or measure the individual components of the electromagnetic (EM) field. These systems extend the operating range below 10 μsec to over 20,000 μsec (nominal frequency 40 Hz to 1 MHz).

FDEM systems that may have applications for UXO detection are multifrequency, with a range of 10s to 10,000s of hertz. The FDEM instruments are influenced more by geology but may minimize its influence through an appropriate selection of operating frequencies. These systems are under evaluation and are presently employed for research purposes at standardized test sites or small live UXO sites.

Maximum Detection Depth

In general, a larger target can be resolved at a greater depth than a smaller target of the same type and orientation using the same detection sensor. For both magnetic and TDEM sensors, the U.S. Army Corps of Engineers (2000) has developed empirical formulas relating the diameter of a target to the maximum depth at which the target can be resolved.

$$\log(d) = 1.354\log(dia) - 2.655 \qquad \text{(mag)}$$

$$\log(d) = 1.002\log(dia) - 1.961 \qquad \text{(TDEM)}$$

where *d* (in meters) is the depth to the top of the buried UXO and *dia* (in millimeters) is the diameter of the UXO minor axis. These relations are based on data collected at several UXO-contaminated areas and are intended to provide general guidance, not to be used as an absolute reference.

4 Target Influence on Sensor Response

The response of a geophysical sensor to a target is dependent on the material contrast between the target and surrounding medium, depth of burial and orientation, and target dimensions. Some general rules apply to the target-environment relationship and are depicted graphically below in terms of the target detectability (resolution):

Target Depth	↑	Detectability	↓
Target Size	↓	Detectability	↓
Target Separation	↓	Resolution	↓
Target/Medium Contrast	↓	Detectability	↓
Target Orientation	varies	Detectability	varies

The figures that follow illustrate these phenomenological concepts. They were generated using a forward modeling routine for computing the total magnetic field response of a prolate spheroid (Butler et. al 1998; McFee and Das 1990).

Burial Depth

For a given target and given environment, as depth of burial increases, the ability to detect a target decreases. This is governed by the physical laws that describe the field strength as a function of distance from the target. For example, for a magnetic dipole, the rate of falloff is $1/r^3$, where r is the distance to the target. Figure 5 illustrates the effect of target depth on the total magnetic field signature for a typical UXO target.

Target Size

If multiple targets are buried at the same depth and within the same geologic material (targets composed of the same material and buried having the same orientation with adequate spacing between targets), then the signal strength acquired directly over the largest target will have a greater magnitude than that directly over the smaller targets (Figure 6). This is intuitive, the larger the target the greater the measured response. Also of concern are the presence of multiple targets buried at the same (x, y) location but at different depths (Figure 7) and targets having overlapping signatures because of insufficient lateral separation

(Figure 8). Observe in Figure 8b that as the lateral separation between the two targets increases, the anomaly signature begins to reveal multiple targets.

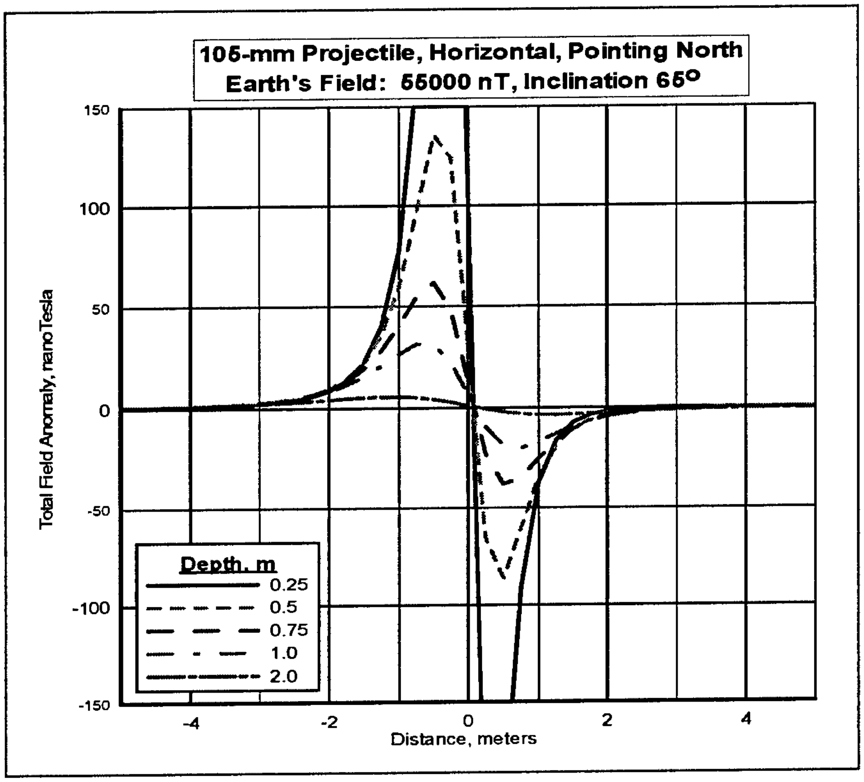


Figure 5. Reduction in total magnetic field response as sensor-target separation increases. Sensor height is 0.25 m.

Surrounding Environment

A more vexing issue is the influence of the surrounding geology on sensor response and how it interacts with the response from a target. As the contrast between the target material properties and the host medium decreases, the ability to separate the UXO response from that of the geologic background becomes more difficult. This issue is addressed more thoroughly in the next section.

Target Condition

The condition of the UXO also is a factor that influences the ability of a sensor to detect it. Since most ordnance items are comprised of ferrous metal, they deteriorate and rust over time. The measured signal response of a corroded UXO is smaller than that of one in pristine condition. Nonferrous UXO components, such as aluminum tail fins on some ordnance items, also will exhibit reduced signatures as their condition is degraded. Figure 9 shows the response

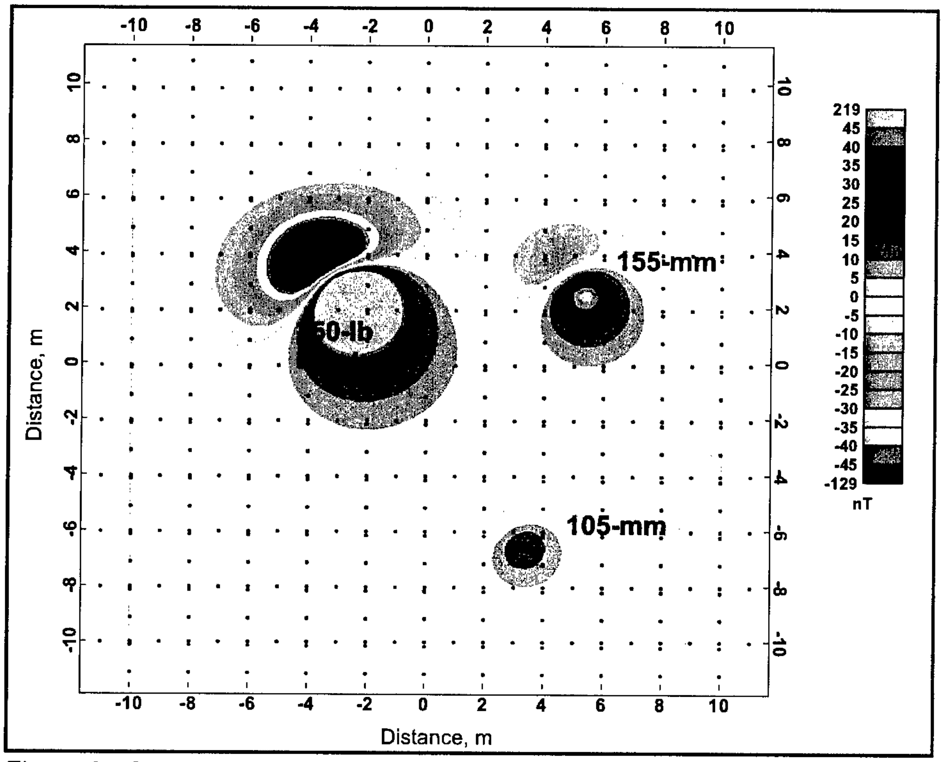


Figure 6. Comparison of total magnetic field response of various size targets at the same depth and orientation

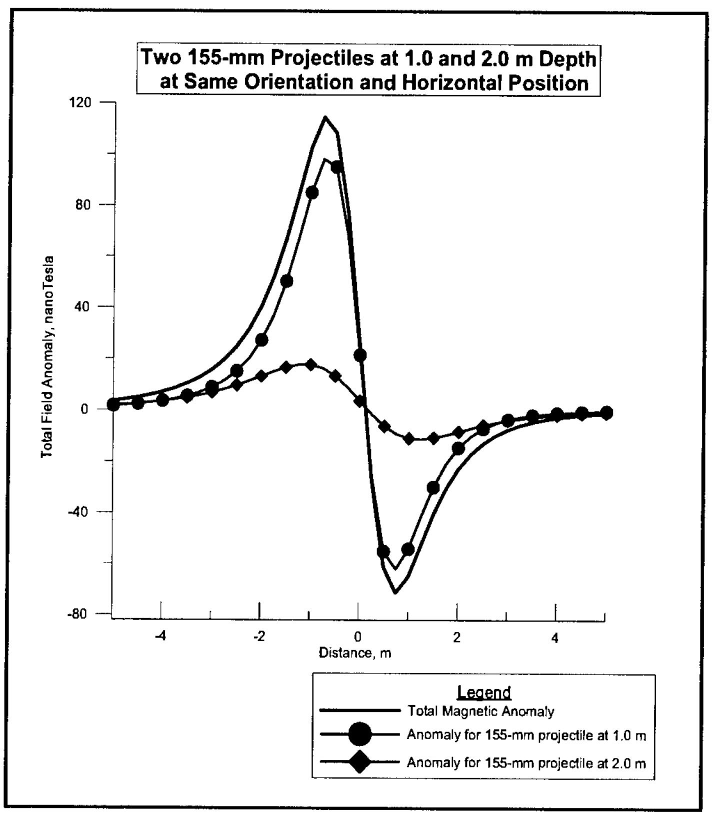


Figure 7. Magnetic anomaly plot showing difficulty in resolving multiple targets when they occupy the same horizontal position (x, y) but different burial depths

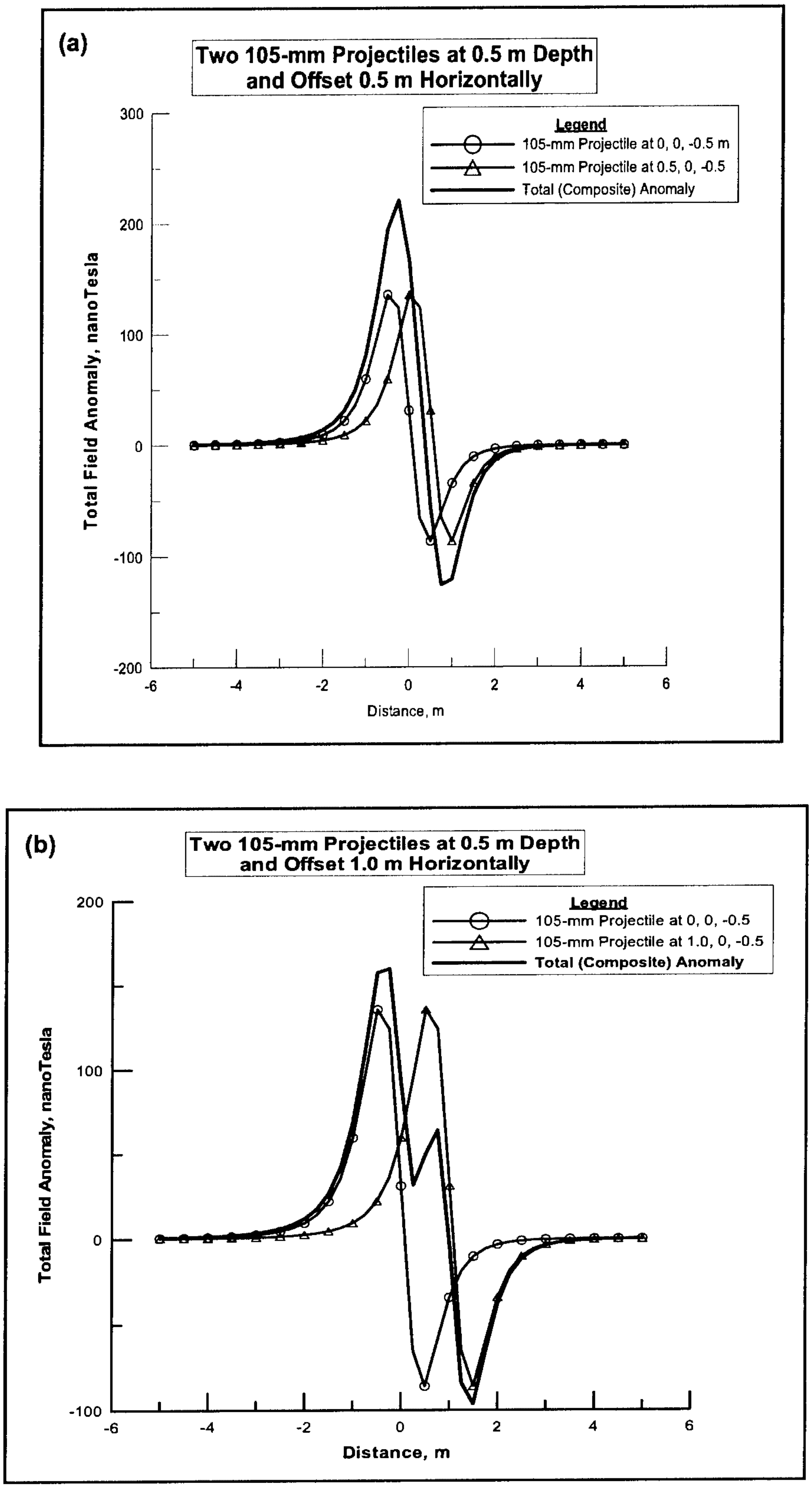


Figure 8. Total magnetic field response of proximal targets; (a) 0.5-m lateral separation, (b) 1.0-m lateral separation

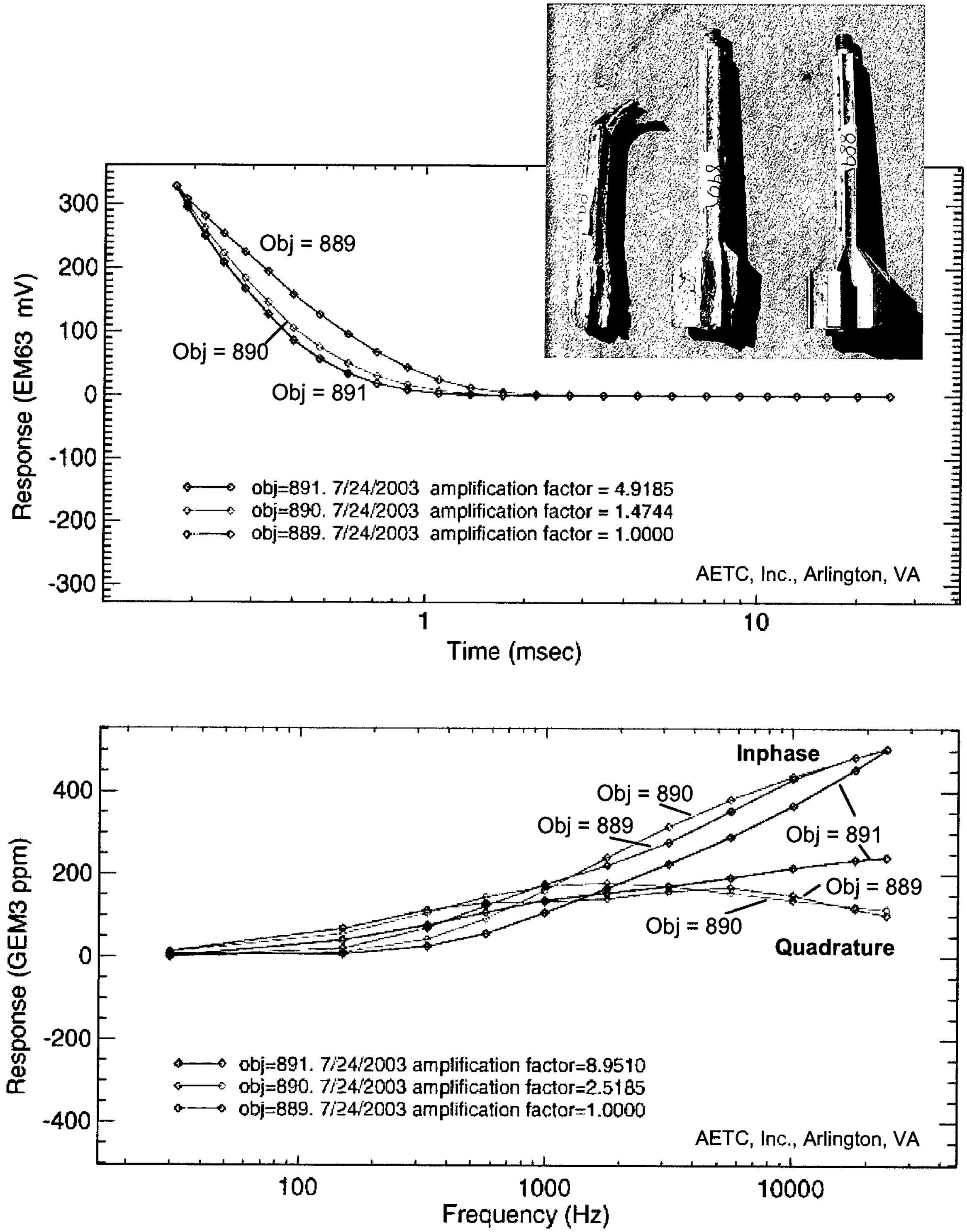


Figure 9. Comparison of response from three like targets in different stages of decay (plots courtesy of AETC, Inc., Arlington, VA). The curve with an amplification factor of 1.0 corresponds to the nearly pristine target, whereas the curve having the largest amplification factor belongs to the most weathered target.

from three aluminum tail fins of a 90-mm M371A1 HEAT recoilless rifle round for two EM sensors (EM-63, GEM-3). One tail fin is in nearly pristine condition, whereas the other two are in varying stages of decay (see inset of figure). The curves for the weathered targets have been amplified so they plot at the same scale as the pristine target. All fins were oriented nose down.

Target Orientation

The orientation of a target within the subsurface can also influence the shape and magnitude of the received signature. The angle at which the earth's magnetic field or the field from an EMI transmitter impinges upon the target determines the degree of interaction between the field and target. The curves in Figure 10 show how the magnetic signature over a 175-mm projectile varies as the nose of the target is rotated about its midpoint from a horizontal position. The maximum magnitude increases as the dip angle approaches 90 deg (vertical), when the tail end of the projectile is closest to the sensor, and then decreases as the target again approaches the horizontal. In some instances, the target may not be detectable at some combinations of orientation and burial depth (assuming burial depth is not excessive). It is also possible that the response received from a smaller target is greater than that of a larger target at the same depth, again dependent on target orientation (Figure 11).

Target Composition

An often overlooked and generally ignored UXO characteristic is composition. In many cases, UXO is comprised entirely of steel; however, in some cases the main body, fins, and other sections are made of different metal types; aluminum is a common secondary metal. Only recently have studies addressed the impact of composite UXO on sensor response (O'Neill et al. 2002). Figure 12 shows the TDEM (EM-63) response over a 120-mm HEAT projectile. The data were collected with the nose pointing both up and down. The separation in curves at later times is likely caused by greater signal penetration into the target, responding to different metal types being closer to the sensor.

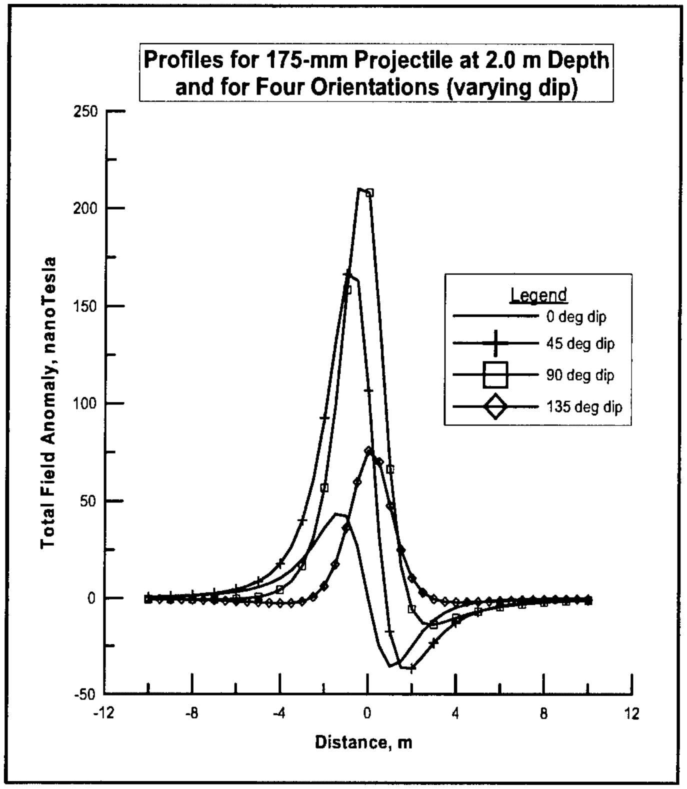


Figure 10. Comparison of profiles over a target at different dip angles

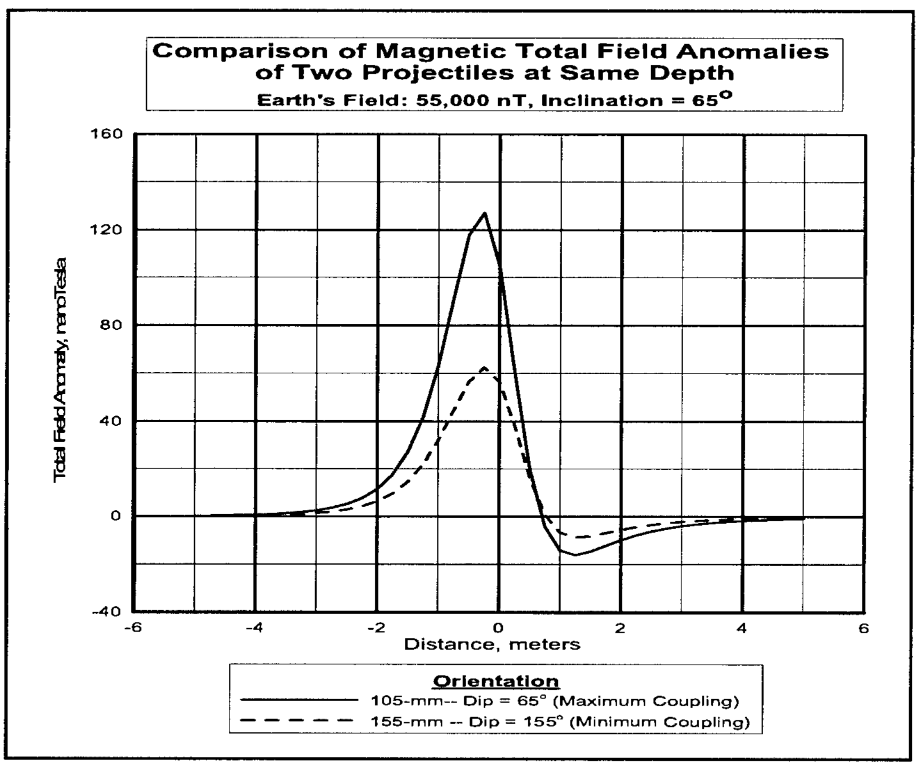


Figure 11. Magnetic anomaly response of two projectiles showing that a larger target can exhibit a smaller anomaly than a smaller target at the same depth, depending on orientation in the subsurface

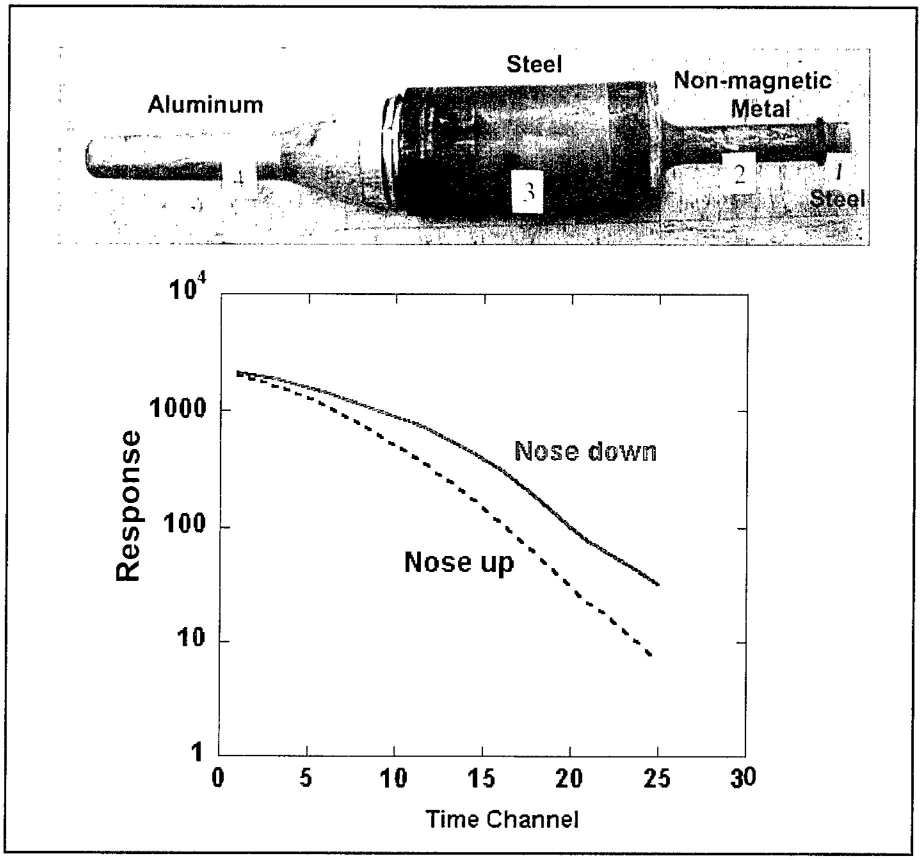


Figure 12. Effect of target composition on TDEM response (after O'Neill et al. 2002)

5 Site Variability and Its Influence on UXO Detection

For all geophysical technologies, the sensor measurement is a composite signature of the host medium, target, clutter, and any cultural influences. The host medium (geologic background) is generally soil but could be rock or soil with rock inclusions. The target, in the context of this report, is considered to be UXO. The term "clutter" encompasses everything, excluding the geologic background, that is not of interest and interferes with the target signature or has a similar response as the target. Clutter can include natural sources such as ground surface undulations, vegetation, tree roots, and animal burrows, as well as man-made items related to ordnance (waste and fragments) and cultural debris (cans, wire, reinforced concrete, farm implements, etc.). Cultural interference sources include buildings, fences, utilities, roads, vehicles, overhead power lines, and transmitting towers.

Many UXO sites have low noise backgrounds, and differentiating anomalies from the background are not a major problem. However, as mentioned earlier, some UXO cleanup activities have encountered sites where clutter, local geology, or localized geologic features have impeded the detection of UXO. Figure 13 shows total magnetic field anomaly maps that illustrate the extremes that can be encountered (Butler 2003). Regarding the low noise site, the anomalies are distinct and can be distinguished from the background. The extremely noisy data emphasize the difficulty in discriminating anomalies caused by UXO from those caused by shallow ferrous objects and the remnants of buried communication lines (clutter). The center plot shows two areas (1 and 2) that exhibit significant geologic anomalies whose magnitude is great enough to mask the presence of some UXO.

Geologic Anomaly

The geologic anomaly example in Figure 13 (center plot) represents a data set acquired over the 40-acre site at Jefferson Proving Ground (JPG), IN (McDonald and Nelson 1999). JPG was initially considered to be an "average" site, having a silty soil with no prominent or suspected features that would interfere with UXO detection. Figure 14 shows an enlarged view of the geologic anomaly in Area 1. The anomaly spans over 30 m in the east-west direction and about 10 m north-south. Volume magnetic susceptibility readings were acquired

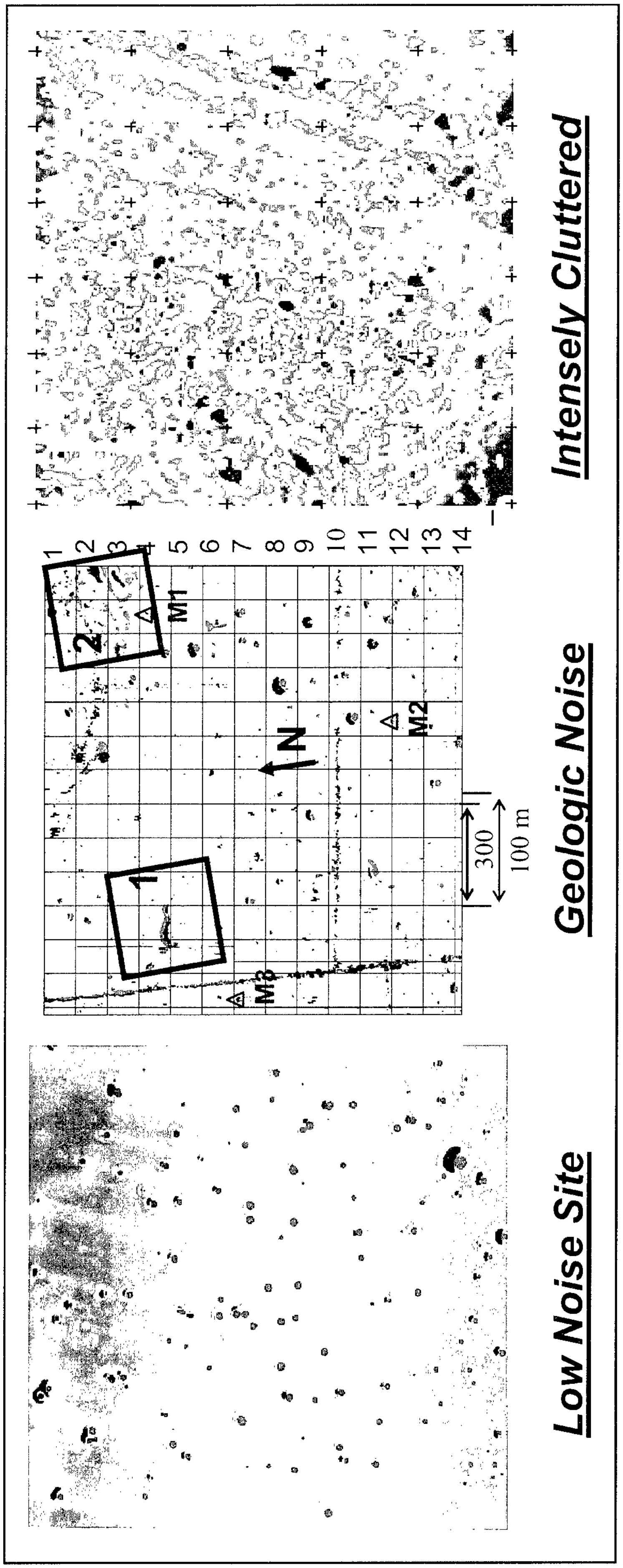


Figure 13. Range of noise conditions that may be encountered at UXO-contaminated sites (after Butler 2003)

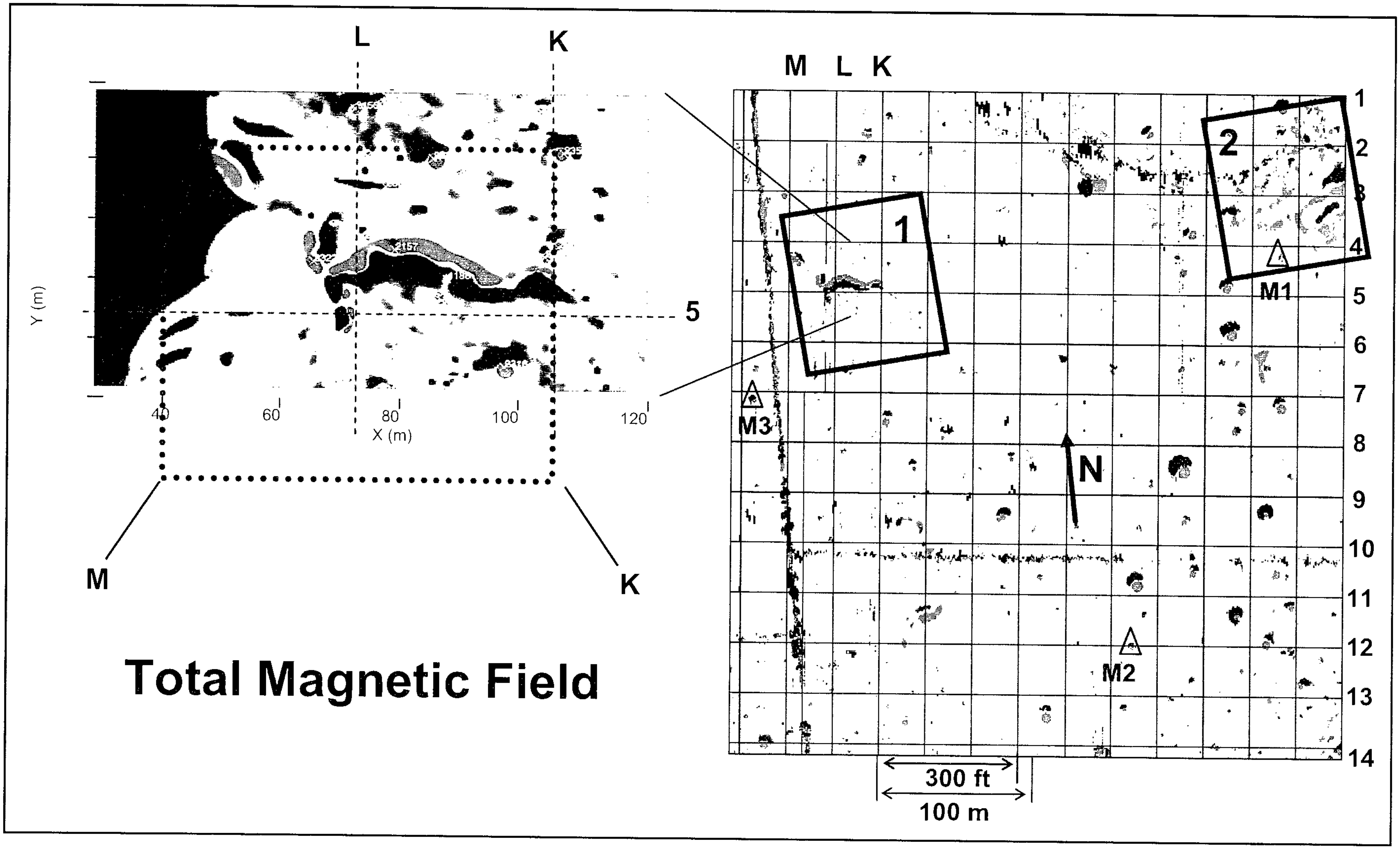


Figure 14. Example of geologic noise over a significant spatial extent (Area 1) observed in magnetic total field data (McDonald and Nelson 1999)

using a 6.1-m (20-ft) spatial sampling interval over the area bounded by grid lines K through M and 4 through 6 (Figure 15). As expected, the magnetic susceptibility anomaly has the same basic shape as exhibited by the total magnetic field data.

Total magnetic field data collected over a 2-m^2 area within the influence of the geologic anomaly in Area 1 at JPG is shown in Figure 16. Within the 2- by 2-m square the values vary over 80 nT, a magnitude great enough to mask the presence of smaller UXO. This emphasizes the variability a geophysical parameter can exhibit within a small area and the need to predict and compensate for these occurrences.

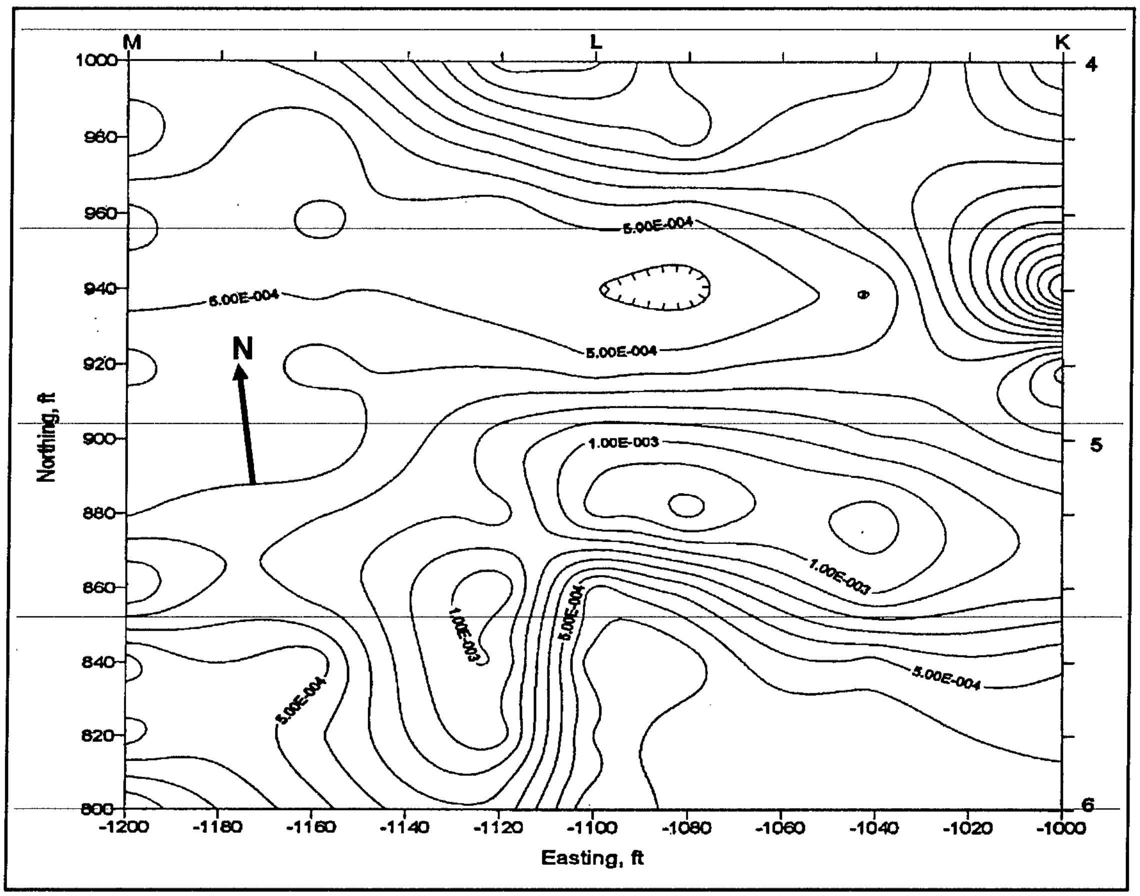


Figure 15. Magnetic susceptibility anomaly corresponding to total magnetic field data in Figure 14

Natural Geologic Background

Some soils of Hawaii contain a large percentage of magnetite and pose a challenge for UXO detection efforts. A test site on Maui was constructed to evaluate geophysical instruments for use in the Kaho'olawe cleanup project. An analysis of the soil at the Maui Test Site indicated that it is representative of the soil on Kaho'olawe (Khadr 1997). The soils on Kaho'olawe are of volcanic origin, consisting of tholeiitic[2] basalt parent rock with up to 20 percent magnetite. Volume magnetic susceptibility values measured on samples from two sites on Kaho'olawe ranged from 800 to 3000×10^{-5} SI. A comparison of magnetometer (G-858) and TDEM (EM-61) data collected over grid B1 at the Maui Test Site is given in Figure 17 (Khdar 1997). The magnetometer data are affected much more by the high magnetic background. The unfiltered TDEM data reveal the majority of targets, and the filtered data expose all but one, a 2.75-in. rocket buried horizontally at a depth of 30 in. (76 cm). The data in Figure 17 represent moderate size targets. Both types of sensors had difficulty resolving smaller targets (e.g., fragments, 20 mm's, and mortars).

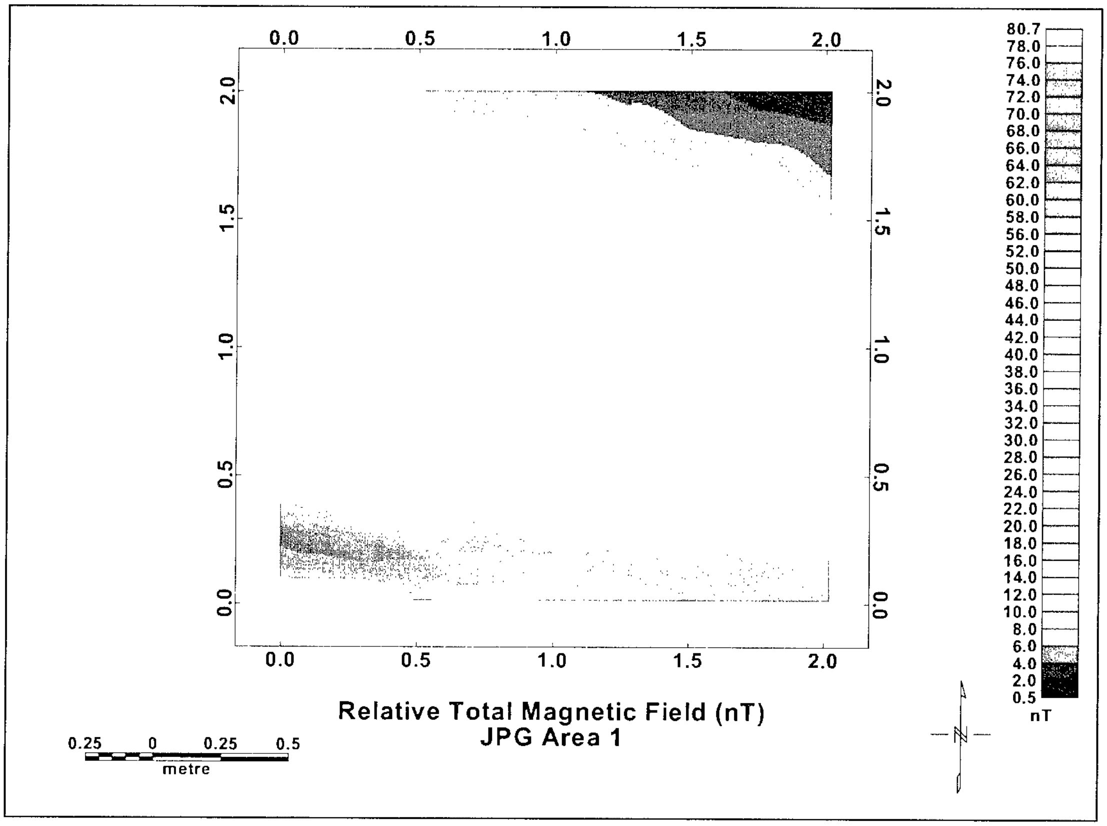
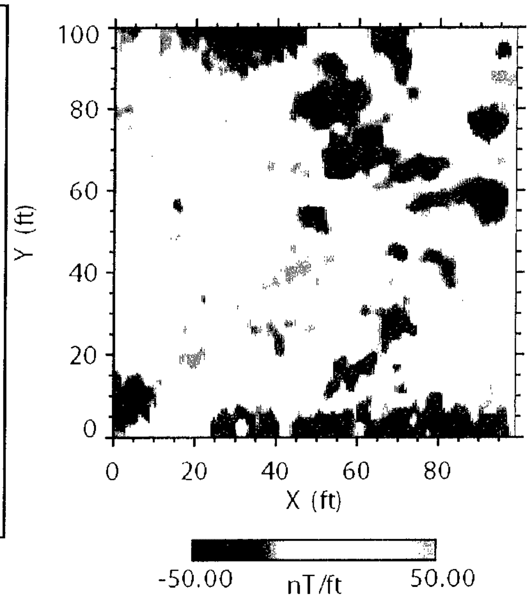


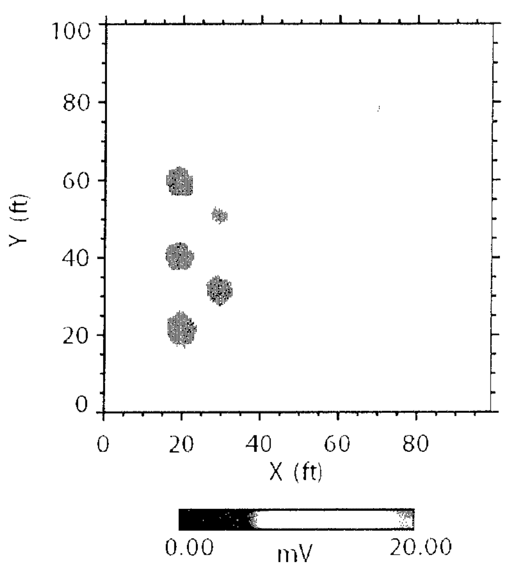
Figure 16. Total magnetic field data over 2- by 2-m area within the Area 1 geologic anomaly at the JPG 40-acre site. Within this small area the TMF variations caused by geologic sources exhibit a gradual change spanning 80 nT.

[2] Tholeiitic basalt contains quartz and little or no olivine; alkali basalts are usually olivine-bearing and richer in potassium and sodium.

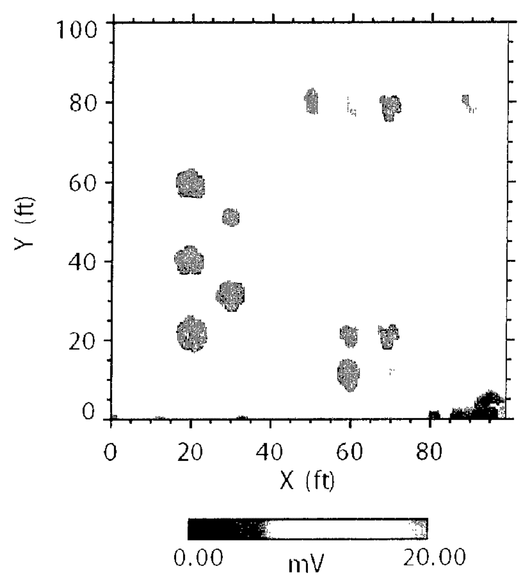
Target Type	X (ft)	Y (ft)	Depth (in.)	Orientation
3" projectile	60	10	16	horizontal, N/S
3" projectile	60	20	16	vertical
3" projectile	70	10	23	horizontal, N/S
3" projectile	70	20	23	vertical
5" projectile	20	20	24	horizontal, N/S
5" projectile	30	30	30	horizontal, N/S
5" projectile	20	40	30	vertical
5" projectile	30	50	36	horizontal, N/S
5" projectile	20	60	36	vertical
2.75" rocket	50	80	18	horizontal, N/S
2.75" rocket	60	80	24	horizontal, N/S
2.75" rocket	70	80	24	vertical
2.75" rocket	80	80	30	horizontal, N/S
2.75" rocket	90	80	30	vertical



G-858 Magnetic Vertical Gradient



EM-61 Differential, unfiltered



EM-61 Differential, high-pass filtered

Figure 17. Examples of magnetic and TDEM data collected at a geologically noisy site, Maui Test Site (data courtesy of AETC, Inc., VA). The TDEM system tends to be affected less than the magnetometer by the natural magnetic background.

6 UXO Detection Planning

An early stage in the UXO detection planning process is development of a conceptual site model (CSM) (EPA 2002). The CSM is a dynamic document used to guide the investigation at the site. It contains information on the nature and extent of OE contamination and is routinely updated to accommodate new information. The U.S. Army Corps of Engineers has its own form of CSM called Footprint Analysis (FA). FA refers to the process of defining the geographical extent of UXO-contaminated area by evaluating its past and present site conditions and activities. A draft document detailing standard procedures for performing an FA has been prepared for the U.S. Army Engineering and Support Center, Huntsville (2002). The flowchart in Figure 18 is modified from that document. In the FA workflow, five steps are involved in establishing the OE footprint. The first four stages incorporate historical and current site conditions to define an OE boundary and areas of potential concern (AOPCs). The fifth stage involves conducting preliminary geophysical field investigations, the results of which are used to reevaluate the footprint.

In the first stage, Evaluate Historical Usage, uses of the site when it was a Department of Defense (DoD) facility, as well as subsequent and current uses, are identified. The objective of this stage is to determine potential areas of OE use. Information can be obtained from maps, aerial photos, ordnance usage records, known areas of ordnance use (firing ranges, bombing targets, disposal pits, etc.), newspaper articles, and interviews with personnel (former and present). An initial boundary of the potentially contaminated area can be drawn based on this information. It is within this first stage that the Archives Search Reports (ASR) is conducted. The current site conditions are identified during the second stage, Document Current Conditions. The locations of both natural and cultural features are noted and generally confirmed through a field reconnaissance, which may also identify other features or AOPCs. This information is used when planning field investigations and response actions. The third stage, Evaluate Changed Conditions, looks at how a site has changed over the years and how these changes may impact the site footprint. For example, if an area has been excavated to a depth greater than that of the deepest expected UXO, then that area can be removed from the AOPCs list. The fourth stage, Adjust Boundaries, involves adjusting the footprint boundary to accommodate changes made in the previous stages. A field reconnaissance is usually conducted to confirm boundary locations. Once the site footprint has been established, the fifth stage, Conduct Field Investigations, can be initiated. It is

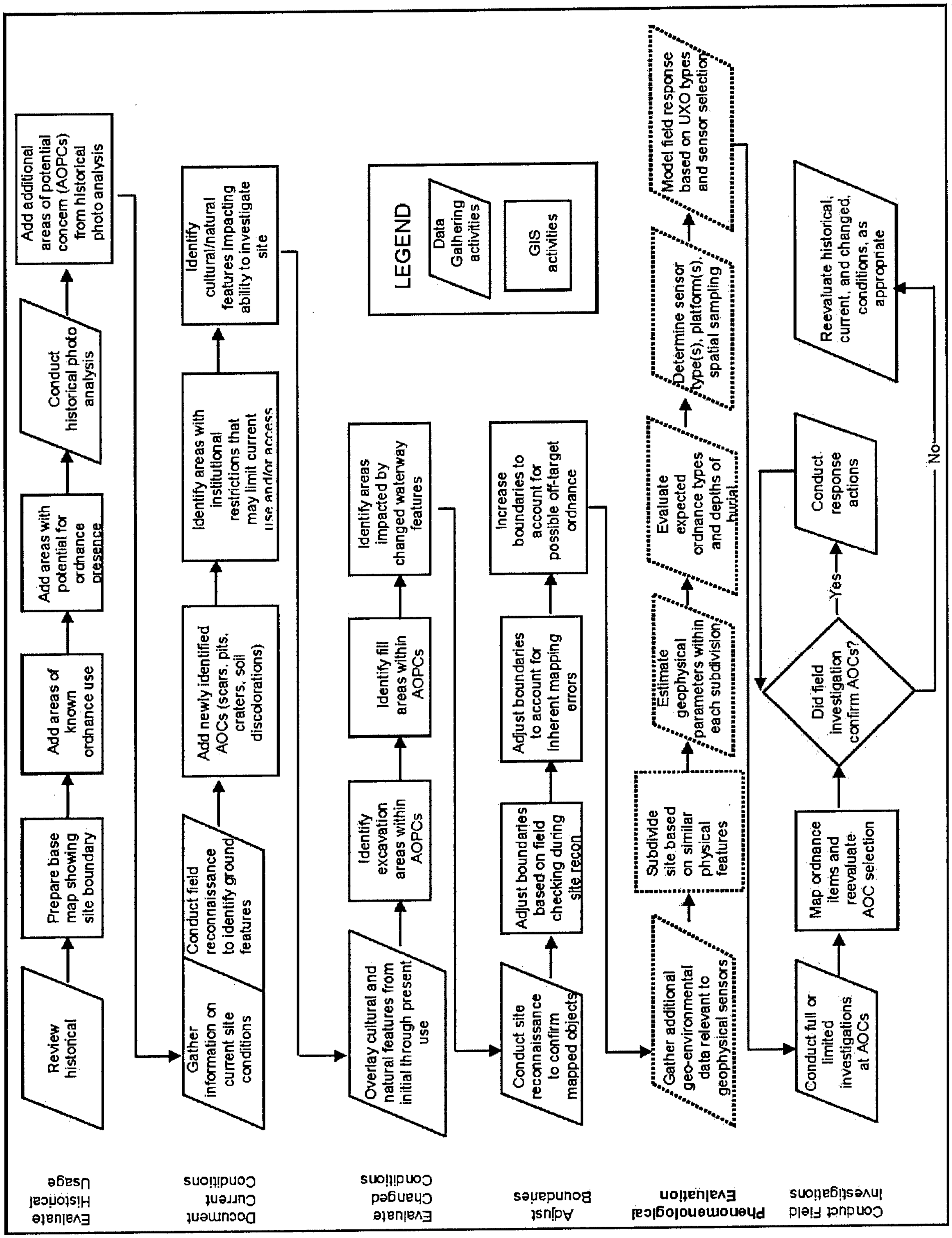


Figure 18. FA scheme modified to incorporate Phenomenological Evaluation

within this stage that geophysical investigations are conducted and the results used to refine the footprint and perform statistical estimations of the density of UXO present. The geophysical investigation consists of five elements. The first element, Survey Planning, involves development of a sampling strategy and selection of geophysical instrumentation. During these steps it is determined how the geophysical survey will be conducted and what sensors will be employed. A geophysical instrument prove-out is a field test used to guide the instrument selection. The prove-out has several objectives, including determining the influence of site geology and terrain conditions on sensor performance. However, prior to conducting a geophysical prove-out, it is beneficial (for both time and cost) to perform a phenomenological evaluation of the site to optimize the use of geophysics for conducting UXO surveys. This stage is represented by the row of dashed boxes in Figure 18. The six tasks comprising Phenomenological Evaluation are discussed thoroughly later in this chapter. Described below are indirect methods to assist in evaluating the effects of the geo-environment on the geophysical sensors and determining what sensors/platforms are best suited for the range of conditions encountered within UXO-contaminated areas. The guidelines presented here will facilitate planning of both the preliminary geophysical surveys for the prove-out and the surveys conducted at a live UXO site.

Importance of Phenomenology

Evaluating an area based on its phenomenological characteristics involves identifying both regional and local geo-environmental trends and understanding how these trends interact and influence the physical properties that dictate the geophysical sensor response.

How geologic environments influence site characteristics

Overview. The geologic environment has a direct influence on airborne and surface geophysical surveys. The objective of this section is to provide an overview of the physical processes that lead to the ultimate distribution of surface and near-surface materials. Although the depositional environment of sediments is extremely complex, the general settings are recognizable with some guidance (Figure 19). The geologic environment of any given area consists of the subsurface geology and the surface geomorphology. Both realms are in continuous change that includes alteration of mineral and rock materials. The subsurface materials change primarily through the process of diagenesis, which is mineral alteration and growth (e.g., compaction, lithification). Weathering changes the surficial geologic materials. Compared to the subsurface, the surficial changes occur at a more rapid rate, perhaps with the large-scale exception being rock fracture. Tectonic alterations (faulting, folding, etc.) affect both the subsurface and surface materials. The subsurface is affected directly by changing stress fields and mineral alteration.

The geologic structure of a region sets the surface drainage trends and patterns. The ground surface is affected primarily by surface drainage and the interaction of weathering agents (chemical and physical) on the exposed bedrock and regolith (surficial fragmented and unconsolidated materials). The fragmented surface and near-surface materials will be termed *sediments* in this

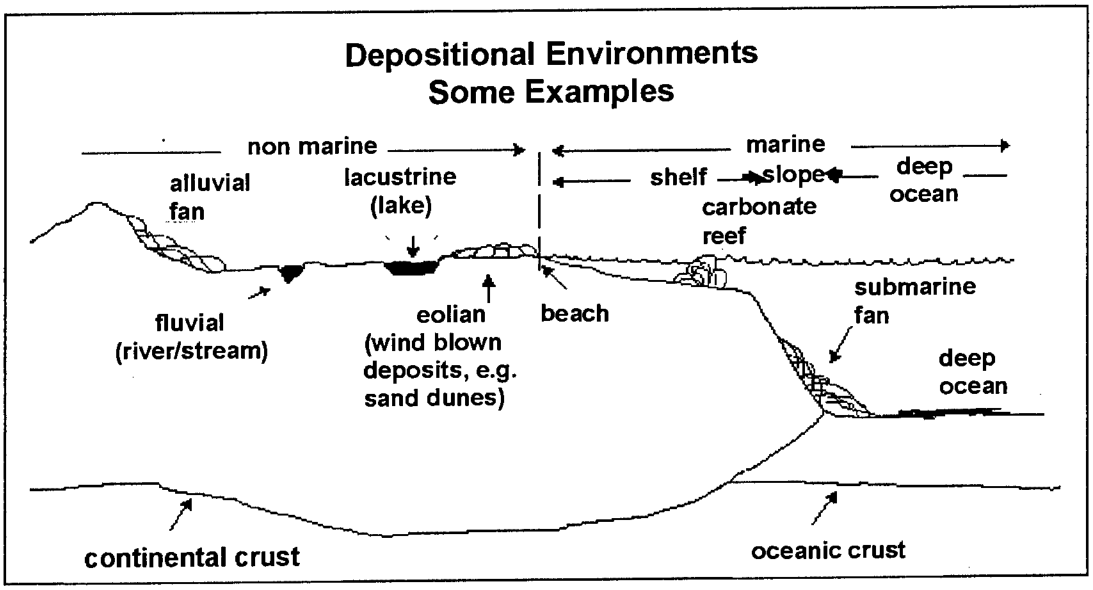


Figure 19. Types of depositional environments

section because of the pervasive influence of fluid, primarily water, transport and deposition. Sediments will pertain to rock materials redistributed and deposited in or by a medium (water, wind, and ice) and gravity. The term *soil* will be reserved for the near-surface naturally weathered (in situ) materials exhibiting soil zonation of the uppermost level (exception buried paleosoil). Soil will also refer to materials redistributed by man and defined using engineering context (soil borings, soil classification, etc.).

Surface soils and sediments consist of fragments of rocks, secondary minerals, decomposing organic matter, water, and air. Upon entering the ground, meteoric water dissolves carbon dioxide, carbonic acid, sulfates, nitrates, and humic compounds from the organic layer. At an intermediate depth in the ground the dissolved material consists of carbonate, sulfate, calcium, magnesium, sodium, potassium, and small amounts of other materials such as iron. Deeper in the ground, dependent upon component solubility, many materials are deposited/precipitated, such as iron and calcium compounds. At a given site, the mineral and rock fragments in soil may be fluvial sediments; the iron a stain, precipitate, or mineral replacement; and the silicon (along with dissolved calcium, magnesium, etc.) may form grain-to-grain cement, encrustations and/or caliche. Such mineral accumulations of cement, replacement, or deposition are common and varied. These features all influence the response of sensors used for UXO detection.

Knowing the geologic source and nature of the shallow subsurface materials permits the forming of a pre-survey expectation of natural anomalies, their probable distribution density, array configuration, size, and depth. Given a perspective of surface and near-surface geologic processes and settings, the understanding of the field geophysical data will be enhanced and more complete in meeting the objectives of the site survey. This section introduces field investigators to developing a geologic perspective of any field site, including the probable geologic feature scale, distribution, composition, and history.

Spatial and temporal scale of geologic features. Evidence of the earth's dynamic systems can be observed on site or on maps (geomorphology). Landform development in any given area is a result of earth material deposition, large- and small-scale geologic structural formation, and climatic processes. The large-scale perspective of any site can be interpreted from a physiographic map. The United States can be naturally divided into physiographic provinces by the distribution of geology and climate. The mountain systems, interior plains, and coastal plains are the major features of the North American continent (Figure 20). Each geomorphic province is unique in geologic structure, composition (rock type), and climate (Figure 21). Even if geologic settings were identical, the landforms and soils in Arizona, Mississippi, Wisconsin, and Maine would be markedly different because of their different climates and the weathering processes acting on them.

Major geologic features affect the distribution of rock materials on a regional scale, but they are also partially responsible for the small-scale processes and features that influence rock material distributions at geophysical survey sites. Soil material source areas and compositions can be determined from maps. By viewing maps of different scales, geologic features can be identified in a spatial and temporal context. Larger scale maps provide a broad interpretation of landform features and processes affecting site surficial geology. The multitude of materials, processes, climates, and forces acting on and near the earth's surface produce a variety of unique geologic features. Fluvial and shore zone environments are responsible for almost all surficial geologic depositional environments. Incorporating geologic data (written or observed), specifically surficial processes, will be enhanced by recognizing the geomorphic, hydraulic, and sedimentary processes and will aid in identifying specific minerals and mineral/rock accumulations that can influence a geophysical survey.

Rock formation. Rocks are identified on the basis of their composition and texture. The composition is the result of the available source rock material, and the texture of a rock indicates its process of formation. There are three basic rock types, igneous, metamorphic, and sedimentary. Although they can be similar in composition, igneous and metamorphic rocks differ in texture. Igneous rocks have interlocking mineral grains, metamorphic rocks have a laminar or banded (coarse lamina) texture, and sedimentary rocks are derived from preexisting rocks (fragments or precipitate).

Igneous rocks solidify from magma masses within the earth's crust. Intrusive igneous rocks (e.g., granite) are those formed within the subsurface and have large coarse grains resulting from slow, long-term (cooling) crystalline mineral growth. Compositionally, the rocks produced may be potassium- and aluminum-rich silicate rock (granite - quartz and orthoclase feldspar minerals) or may be more iron, magnesium, and calcium rich (gabbro – plagioclase feldspar, augite, and olivine minerals). Other minerals also occur in these rocks. Igneous rock formed from the extrusion of magma onto the earth's surface is called lava. Lava cools much more quickly than the equivalent magma beneath the surface and thus the resulting rock has a fine-grained texture. The extrusive equivalent

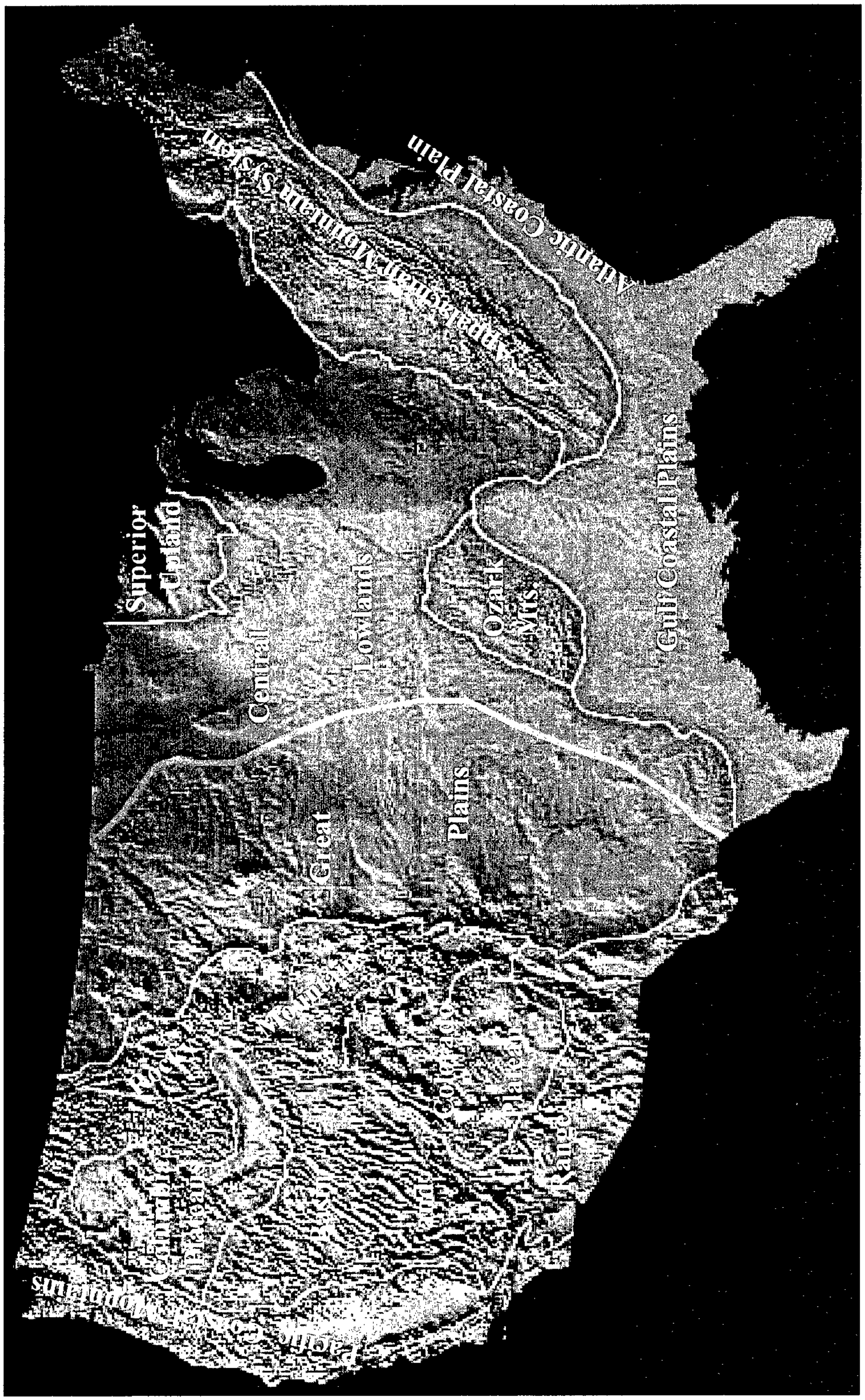


Figure 20. Physiographic regions of the United States

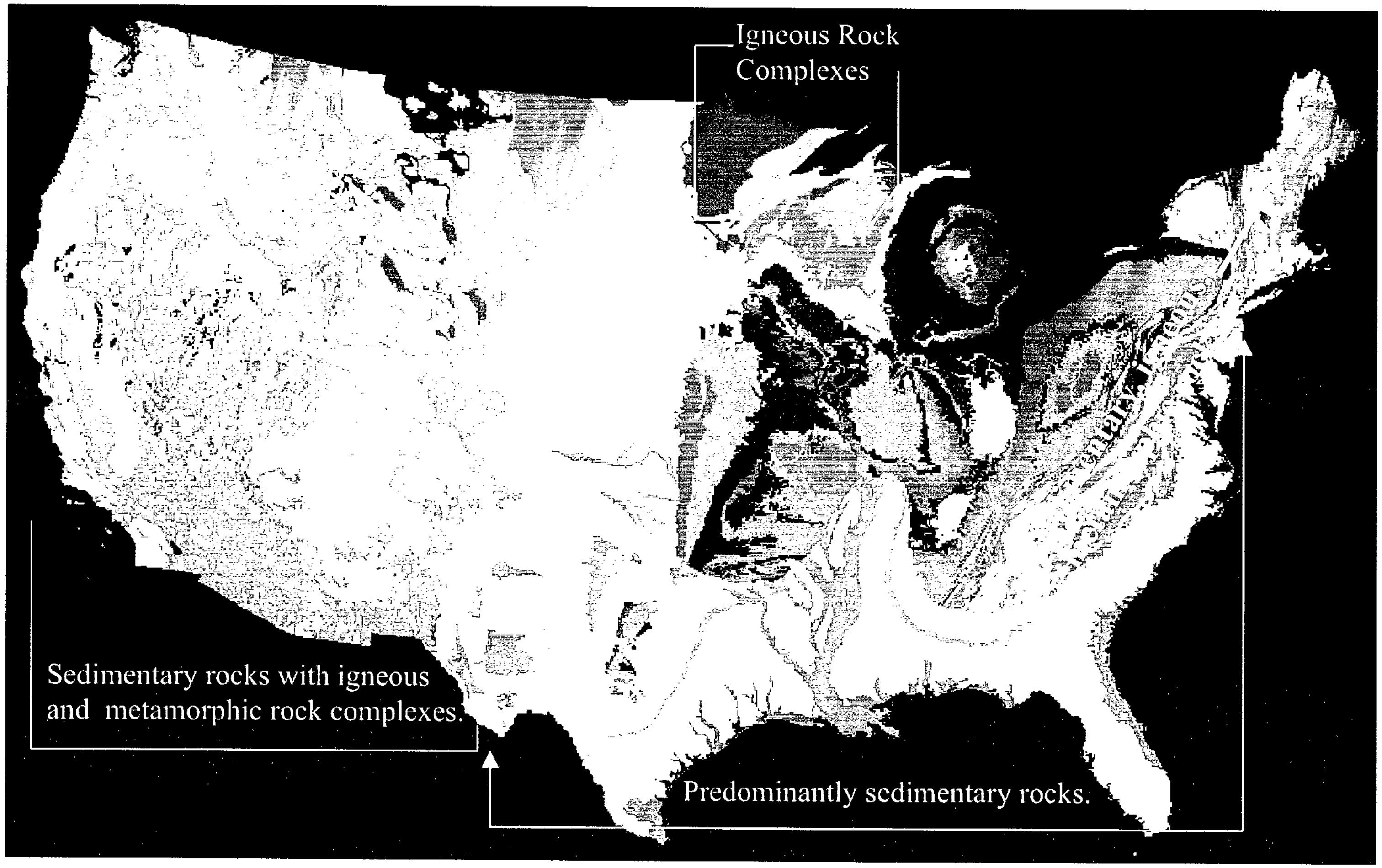


Figure 21. Geologic map of the United States with generalized rock type designations

of granite is rhyolite, and basalt (Hawaiian islands) is the extrusive equivalent of gabbro. Magnetite is a widespread mineral (iron oxide) occurring in igneous rocks and contact metamorphic rocks. Weathering and fractionation during erosion, transport, and depositional dynamics can cause iron-bearing minerals to become concentrated in soils. Magnetite weathered from basalt is likely to be smaller grained than that from gabbro (intrusive equivalent). In concentrations, magnetite is an ore for the production of iron.

Metamorphic rocks are formed by subjecting preexisting rock material (igneous, metamorphic, or sedimentary) to crystallization under high temperature and pressure conditions deep in the subsurface. It is also possible that localized metamorphism can occur adjacent to molten igneous intrusions (contact metamorphism). During metamorphism (recrystallization) it is possible for minerals to increase in size and it is also possible that the original rock mineral assemblage (suite) can totally change depending upon the degree of metamorphism (heat, pressure, and time dependent). At some point in the rock cycle, the degree of metamorphism increases and the threshold to a molten mass (igneous rock) is approached.

Sedimentary rocks form through the compaction and cementation of sediments (cobbles, pebbles, sand, silt, clay) or the precipitation of minerals (salt, gypsum, etc.) from a solution of dissolved mineral material. The sediments can contain rock and mineral clasts (grain or fragment) from igneous, metamorphic, or other sedimentary rocks. Fractionation of mineral or rock clasts occurs during the depositional process, and it is possible that a sedimentary rock can contain a localized concentration of denser metallic minerals (e.g., magnetite sands). A sedimentary rock of this nature could produce larger-scale geophysical anomalies or be subjected to weathering processes that concentrate the metallic minerals in smaller pockets that produce anomalies near the surface in a survey site.

Voids are features in the bedrock that can contain mineral accumulations. Voids are rarely found in unconsolidated sediments due to the inability of unconsolidated or weakly cemented earth materials to support a void for any extended period of time. In any given bedrock geologic environment the probability of voids occurring is greatest closest to the surface due to the dissolving of rock material by infiltrating surface water. The shallow voids often give way to larger voids (caves). In such terrain, shallow solution cavities or depressions in bedrock (often limestone and dolomite sedimentary rock) can occur. These shallow surface features may become vessels of concentrations of mineral material deposited by fluvial processes; these deposits may produce geophysical anomalies. Similarly, void spaces, being zones of massless space (empty space other than gases), will affect geophysical surveys if the voids are near the surface. Bedrock fractures (channelways for moving water) are often in observable patterns related to the applied tectonic stress directions, thus causing the fractures (usually linear) to have a pattern. If fluid pathway fractures become shallow voids or depressions, accumulated mineral masses may produce anomaly patterns observable in survey results.

Mineral weathering and transport. Every survey site is undergoing weathering processes. The extent of weathering depends on the climate, rock (sediment, soil, etc.), and duration of time over which the weathering processes have been acting. Physical actions (disintegration) and chemical reactions (decomposition) are continuously active at different rates in all meteorological conditions. At the surface of the earth, rocks are exposed to meteoric water, which is the most active natural chemical on earth and is found in the pore space of soils and rocks. Meteoric water contains dissolved atmospheric gases, including oxygen, nitrogen, and carbon dioxide. Surfaces of mineral grains release cations (Na^+, Ca^{2+}, Mg^{2+}, and K^+) when leached by infiltrating meteoric waters. In the weathering process, the first-formed minerals (sodium- and calcium-rich igneous minerals) decompose first. The weathering sequence (for primary igneous and metamorphic rock minerals) is generalized as follows:

a. Weathers first: Iron- and magnesium-rich minerals – olivine, pyroxenes, hornblende, calcium-rich feldspars (plagioclase series)
General compositions: $(Mg,Fe)_2SiO_4$; $Ca(Mg,Fe)Si_2O_6$

b. Weathers next: Biotite mica, sodium-rich feldspars (plagioclase series), potassium-rich feldspar (orthoclase)
General compositions: $NaAlSi_3O_8$; $CaAl_2Si_2O_8$; $KAlSi_3O_8$

c. Weathers last: Muscovite and quartz
General compositions: $KAl_2(AlSi_3O_{10})(OH)_2$; SiO_2

Weathering of any rock produces mineral particles that are rounded by both concentrated chemical attack on their edges and abrasion during transport. The rounding of mineral grains by chemical attack causes weakening and removal of the grains thereby decreasing the resistance of the host rock mass to continued weathering. The released grains are available for transport by available media. Released minerals include the primary minerals (quartz, feldspars, etc.) and accessory minerals (magnetite, olivine, biotite, etc.).

The extent of rounding during transport depends on mineral resistance to abrasion, distance of transport, and the velocity of the transport medium. Some common rock types exhibiting resistance to abrasion, with the most resistant listed first, are: chert, quartzite, granitic rocks, basaltic rocks, dolomite, limestone, sandstone, porous lavas, gneiss, schist, and volcanic glasses (Kuenen 1956). Similarly, some common minerals with relative resistance, with the most resistant listed first, are (Thiel 1941): quartz, tourmaline, orthoclase feldspar, titanite, magnetite, garnet, ilmenite, epidote, hornblende, apatite, augite, hematite, kyanite, and siderite. The more resistant minerals (those at the beginning of the list) are more likely to persist in soils.

Particle size distribution. Natural processes weather, erode, and transport rock fragments. Flowing water can transport/move material up to boulder size and wind (excluding hurricane, tornado, etc.) can transport material up to coarse sand size. The transported material is sorted by particle size during transport and deposition. The specific gravity and shape of a mineral clast are important factors in the settling velocity during transport. The specific gravities of some common minerals are provided in Table 4. Note that the minerals containing metallic elements (iron, gold, etc.) have the greatest specific gravities. Magnetite is one of the denser of the common rock-forming minerals, along with the other minerals containing iron (hematite, ilmenite, and pyrite), and will settle out of suspension before lighter minerals. The shape of a mineral can be a result of the space in which it forms between other mineral grains, effects of transport and abrasion, and crystalline structure. After some distance of transport, biotite mica and the clays will typically be flakes (platelets), whereas other minerals will be rounded to subrounded granular masses. Flakes, once in suspension in water transport, will settle out less quickly than the granular minerals because of their shape and lower specific gravity. Materials of high specific gravity resist erosion, have greater settling velocities, and tend to accumulate in stream bottoms/pools. This is often reflected in a soil deposit as an accumulation of iron-rich minerals (magnetite, hematite, etc.) that generate a magnetic anomaly with the potential to mask UXO detection.

Table 4
Specific Gravity of Some Common Minerals

Mineral Name	Specific Gravity, g/cc
Augite	3.19
Biotite Mica	2.7 – 3.1
Clays	2.0 – 2.7
Diamond	3.5
Gold	15.5 – 19.4
Hemitite	4.9 – 5.3
Hornblende	3.0
Ilmenite	4.5 – 5.0
Magnetite	5.16 – 5.18
Olivine	3.27 – 3.37
Orthoclase Feldspar	2.5 – 2.75
Pyrite (fool's gold)	4.95 – 5.10
Quartz	2.65 – 2.66
Tourmaline	2.9 – 3.2

Generally, sediments at a site will have been transported by and deposited from a single source of wind, ice, or water. However, in some areas, subsurface materials are the sources for surface materials (in situ weathering), so the soil may be similar in composition to its underlying parent rock. In areas where deposits result from multiple transport media, contrasting soil conditions can occur over short distances. The key to interpreting history is in surface material particle size, shape, and roundness. Given the surface features and spatial (horizontal and vertical) relationships of a site, inferences can be made about the transport medium processes. The changing environments of deposition (facies) within a vertical sediment sequence display an array of lithofacies (sediment units formed under a common environment of deposition). For example, in a section of deltaic sediments, the lithofacies coarsen upward; whereas in a meandering stream sequence, the clasts fine upward.

Soil particle characteristics are important because they provide clues about the depositional energy, transport history, and mineral constituents. Very fine unimodal fractions of sediments are typical of low-energy environments such as lakes (glacial lake sediments of rock flour, river floodplain deposits of silt, etc.). Coarse-grained unimodal sediments may be indicative of an environment of high energy wherein materials have been cleaned of finer fractions (beaches, river channel bottoms, subglacial stream beds). The roundness of clasts is indicative of their mode of transport; beach gravels are usually well rounded; river gravels are less rounded, and glacial gravels may be only subrounded or subangular. Sediment color is caused by the mineralogy of the source material, weathering of the clasts, or deposition of coating material such as iron and manganese.

Magnetic minerals. Magnetic anomalies are caused by the presence of magnetic minerals contained in rocks, sediments, and soils. The magnetic minerals responsible for most magnetic anomalies are classified as ferrimagnetic, antiferromagnetic, or paramagnetic. These mineral types have a measurable positive magnetic susceptibility. Ferrimagnetic minerals are the strongest magnetic minerals and include the iron oxides and iron sulfides such as magnetite, maghaemite, and pyrrhotite. Antiferromagnetic minerals exhibit a magnetic response 2 to 4 orders of magnitude less than the ferrimagnetic minerals, and include hematite and goethite. Paramagnetic minerals have a weak magnetic response and require a high concentration to influence a magnetic survey. Examples of paramagnetic minerals are olivine, siderite, pyrite, and some clays (bentonite, illite, smectite, vermiculite). Table 5 presents the representative rocks of the three rock types with emphasis on the accessory magnetic minerals. Accessory minerals are usually a small percentage of the minerals present in the host rock and are not always present in specific rocks (e.g., granite may not have magnetite). For the ferrimagnetic minerals, only a small percentage present in the soil or rock is required to influence a magnetic survey. Concentrations of magnetic minerals can cause an anomaly that could be mistaken for, or mask, a UXO.

Table 5
Primary and Secondary Minerals of Selected Rocks

Rock	Definition Minerals[1]	Accessory Minerals[1]
Igneous – Granite	Orthoclase feldspar, quartz	**Biotite** (P), hornblende, **magnetite** (Fi), **hematite** (A), tourmaline, **pyrite** (P)
Igneous – Gabbro	Calcic plagioclase, **pyroxenes** (P), **olivine** (P)	**Magnetite** (Fi), **ilmenite** (P), iron, copper sulfides
Metamorphic – Gneiss (variable)	Orthoclase feldspar, quartz, hornblende	Augite, serpentine, **olivine** (P), **biotite** (P)
Metamorphic - Slate	Chlorite, **illite** (P), sericite, and **micas** (P)	Possibly retained from source rock: quartz, feldspar, chlorite, **biotite** (P), **magnetite** (Fi), **hematite** (A), calcite
Sedimentary – Sandstone	Quartz, chert, feldspar, rock particles – occasionally dolomite or calcite grains	Occurrences of **magnetite** (Fi), glauconite, iron oxide sandstones
Sedimentary – Shale	Kaolinite, **illite** (P), **smectite** (P)	Aluminum oxides, ferric iron; possible fragments of quartz, **mica** (P), and feldspar

[1]Bold type indicates magnetic mineral, and letter in () designates class: Fi—ferrimagnetic, A—antiferromagnetic, P—paramagnetic

General soil groups. There are 12 major soil groups throughout the world. Table 6 lists these groups with a description of each (JPL 1995). Each major soil group is comprised of subgroups, but these subgroups differ primarily as a function of climate and moisture. Within the United States there are 36 subgroups of the 12 major soils. A distribution of these soils worldwide and for the U.S. is presented in Figure 22. When little is known of the local soil, a map such as this or regional soils information can be used to infer local soil type and thus physical properties and parameters that may influence the geophysical sensors. However, soil maps are available for most locations in the United States from the U.S. Department of Agricultural (USDA) Natural Resources Conservation Service (NRCS). These maps allow identification of soil types on a local scale and segregate soils into 12 classifications based on texture or particle size. A description of the USDA soil classification system is given in Table 7.

Table 6
Major Soil Groups

Soil Group	Description
Alfisol	Soils commonly found in mild climates. They have a light-colored surface layer that covers a subsurface layer of clay. They are usually moist but during the warm season of the year are dry part of the time.
Andisol	Soils that have formed in volcanic ash or other volcanic ejecta.
Aridisol	Principal soils of deserts and other arid lands. They commonly have a sandy texture and are light colored. They are low in organic matter and are never moist for as long as three consecutive months.
Entisol	New soils that have not been in place long enough to develop layers. These soils are found on recently exposed surfaces such as floodplains and sand hills.
Gelisol	Soils of very cold climates that contain permafrost within 2 m of the surface.
Histosol	Wet organic (peat and muck) soils; they are usually saturated with water and do not drain well. They are soils in which the decomposition of plant residues ranges from highly decomposed to not decomposed and are acidic. They are formed in swamps and marshes.
Inceptisol	Soils that are often found in former valley floodplains and on other stable land surfaces where soil layers are developing. These soils are starting to form a subsurface layer of clay. These soils are usually moist, but, during the warm season of the year, some are dry part of the time.
Mollisol	Most fertile and productive soils, known for their dark, mineral-rich surface layer. This thick layer has large amounts of base nutrients and is full of humus.
Oxisol	Soils that are found mainly on weathered or broken up land surfaces in tropical areas. This kind of soil has a subsurface layer full of iron and aluminum.
Spodosol	Soils are infertile and acidic and do not hold moisture well. They have a pale surface layer and a dark subsurface layer in which humus, iron, and aluminum have accumulated.
Ultisol	Soils that have a light-colored surface layer and a reddish-clay subsurface layer full of iron and aluminum. Although similar to alfisols, ultisols are found in warmer regions. They are usually moist but some are dry part of the time during the warm season.
Vertisol	Contain large amounts of clay. They develop in climates of alternating wet and dry seasons. This kind of soil swells when wet and shrinks when dry, which causes cracking. They have wide, deep cracks when dry.
Note: after JPL 1995	

Table 7
USDA Textural Classification

Soil Class	Description[1]
Sand	Loose and single grained; gritty to the touch and not sticky; grain is of sufficient size that it can easily be seen and felt; cannot be formed into a cast when dry; contains 85-100% sand-sized particles, 0-15% silt-sized particles, and 0-10% clay-sized particles
Loamy Sand	Loose and single grained; most individual grains can be seen and felt; slightly cohesive when moist; forms fragile casts; contains 70-90% sand-sized particles, 0-30% silt-sized particles, and 0-15% clay-sized particles
Sandy Loam	Many of the individual sand grains can be seen and felt; sufficient silt and/or clay to give coherence to soil; casts can be formed but require careful handling without breaking; contains 42-85% sand-sized particles, 0-50% silt-sized particles, and 0-20% clay-sized particles
Loam	Medium textured; slightly gritty feel; slightly sticky and plastic when moist; casts can be handled freely without breaking; contains 25-51% sand-sized particles, 29-50% silt-sized particles, and 8-25% clay-sized particles
Sandy Clay Loam	Exhibits stickiness and plasticity; casts are firm and can be handled roughly without breaking; contains 45-80% sand-sized particles, 0-29% silt-sized particles, and 20-35% clay-sized particles
Clay Loam	Sticky and plastic when wet; forms casts that are firm when moist and hard when dry; contains 20-45% sand-sized particles, 15-55% silt-sized particles, and 25-40% clay-sized particles
Silt	Sand, if present, is fine or very fine and not detectable to the fingers; clay percentage is low so there is little or no stickiness; casts can be formed but require careful handling; contains 0-20% sand-sized particles, 80-100% silt-sized particles, and 0-13% clay-sized particles
Silt Loam	Cloddy when dry but lumps are easily broken between the fingers and the soil feels soft and floury; when moist or dry, casts can be formed which can be handled freely without breaking; contains 0-50% sand-sized particles, 50-87% silt-sized particles, and 0-25% clay-sized particles
Silty Clay Loam	Any sand particles present are quite fine and difficult to detect; sticky and plastic when wet, firm when moist, and forms casts that are hard when dry; contains 0-20% sand-sized particles, 40-75% silt-sized particles, and 25-40% clay-sized particles
Silty Clay	Smooth, nongritty, very sticky and very plastic when wet; forms very hard aggregates when dry; contains 0-20% sand-sized particles, 40-60% silt-sized particles, and 40-60% clay-sized particles
Sandy Clay	Similar to silty clay, but contains more sand and less silt; contains 45-65% sand-sized particles, 0-20% silt-sized particles, and 35-55% clay-sized particles
Clay	Fine textured; forms extremely hard clumps when dry and is extremely sticky and plastic when wet; can be rolled into a long, very thin wire; contains 0-45% sand-sized particles, 0-40% silt-sized particles, and 40-100% clay-sized particles

[1]Fact Sheet SL-29, Soil and Water Science Department, Florida Cooperative Extension Service, Institute of Food and Agricultural Sciences, University of Florida, web site accessed 22 June 2004, http://edis.ifas.ufl.edu

Particle size percentages estimated from USDA textural classification diagram

Particle Size Definitions:
- Sand 2.00 to 0.05 mm
- Silt 0.05 to 0.002 mm
- Clay < 0.002 mm

a.

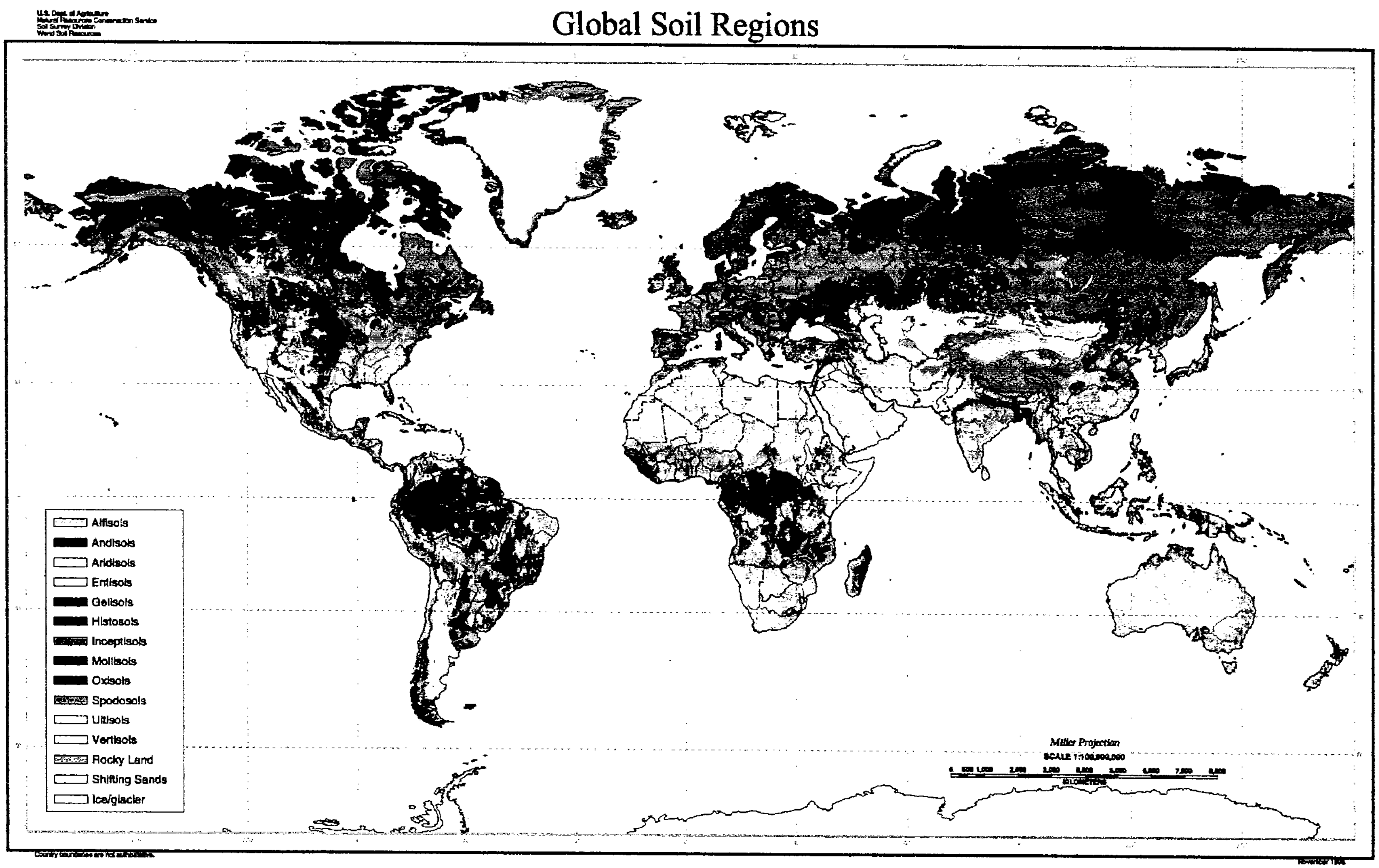


Figure 22. Major soil groups of the world (a) and the United States (b) (U.S. Department of Agricultural, Natural Resources Conservation Services, **http://www.nrcs.usda.gov/technical/worldsoils/mapindex/**, web site accessed 25 March 2004) (Continued)

b.

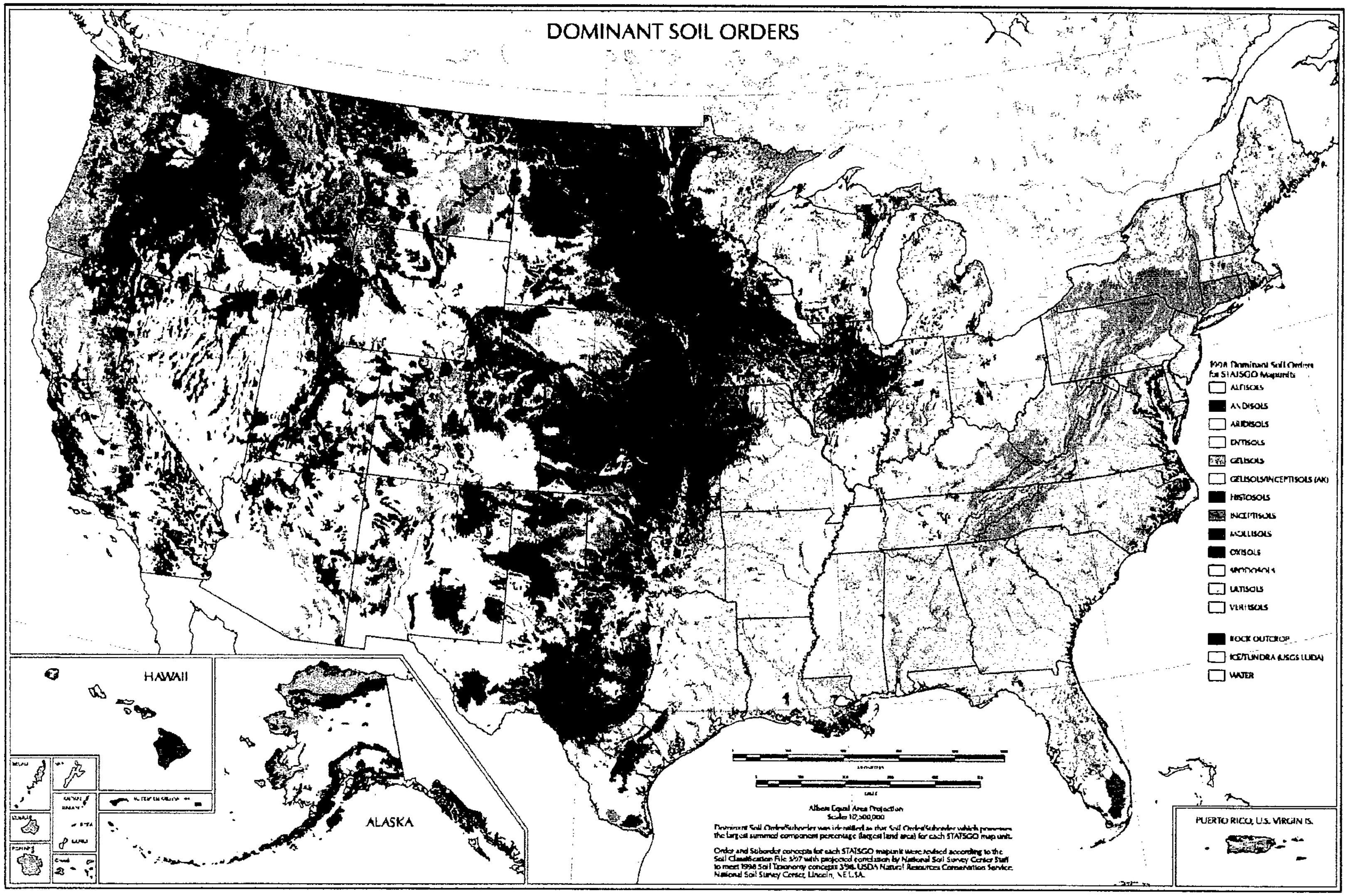


Figure 22. (Concluded)

Analysis of anticipated geophysical survey site conditions. The scale and depth of geologic features to be considered in the analysis of geophysical data will vary for every site. However, given that the fluvial nature of deposits is similar on different scales, the site/anomaly interpretation becomes one of spatial pattern.

The site characterization begins with knowing the rock (mineral) types in the sediment source. Preparation of a site sediment source and geomorphic process checklist is recommended prior to conducting a geophysical survey. The list should include the following to facilitate the interpretation of potential natural anomalies that may interfere with the accurate interpretation of site geophysical data.

- *a.* Surrounding bedrock geology – from maps or reconnaissance
- *b.* Source rock – igneous, metamorphic, or sedimentary
  - *(1)* Igneous – rock type; intrusion or extrusion type features; width and frequency of features such as veins and fractures; magnetic mineral concentrations
  - *(2)* Metamorphic – rock type; significant large mineral assemblages, particularly iron-rich minerals
  - *(3)* Sedimentary – rock type; exposed faults and mineralized veins; fossil beds and fossil replacement mineralization (pyrite, etc.)
- *c.* Rock composition – quartz poor or quartz rich; dark mineral percentages
- *d.* Size of resulting weathered materials – blocks of rock, cobbles, sand, etc.
- *e.* Proximity of survey site to source materials
- *f.* Dynamic process resulting in transport of weathered materials to the survey site - fluvial, aeolian, glacial, gravity, mass slump or slide, etc.
- *g.* Site geology
  - *(1)* Surface sediment materials and spatial distribution
  - *(2)* Fractionation processes in dynamic system – physical sorting processes of
    - *(a)* Streams (meandering, braided, straight channel)
    - *(b)* Aeolian processes (dunes, sheet movement, deposition in low points/areas)
    - *(c)* Glacial processes whereby the sediment depositional environment has not undergone noticeable change since glacial deposition
    - *(d)* Gravitational processes – slumps, slides, mudflows, etc.
    - *(e)* Crosscutting features – fractures, faults, igneous intrusions, etc.
    - *(f)* Voids – if humid conditions and carbonate geology (limestone, dolomite, etc.), caves may be present
- *h.* Mineral concentrations
  - *(1)* Magnetic mineral assemblages
  - *(2)* Fine-grained mineral (clays and silts) accumulations

(a) Surface conductance
(b) Salinity of pore water (fresh versus saline)

Summary. The complexity of the internal evolution of the earth and a multitude of external physical and chemical processes define the bedrock environment and surficial features of an area. The field distribution of bedrock components (mineral content) and their physical nature (folded, faulted, etc.) result from the processes of formation and tectonic history of the respective rock mass. Once exposed, the external processes of weathering alter the rock materials to produce granular and dissolved products. These products are redistributed by transport media (water, ice, and wind) to become soil deposits.

Given the dynamics of erosion, transport, and sediment deposition, fragments too large to transport (exceptions being glacial and mass wasting) will remain in the source area until weathering degrades and decomposes them into moveable sizes or soluble constituents. These large fragments may be anomalous materials and will, by nature of their size and massive nature, decompose slowly in soils.

Moveable materials are fractionated/isolated by shape, size, and density during the erosion, transport, and depositional processes under normal variations in media parameters. These, like large rock fragments, will decompose at rates consistent with their compositions, permeabilities, depth, and climatic conditions. These fractionated sediments may occur in soils as contrasting sediment features (bodies) such as:

a. Irregular masses: stream bottom pothole fillings, abandoned channel fillings, etc.
b. Channel bottom gravels: sinuous bodies reflecting stream channel morphologies
c. Fan-shaped masses: splays of sands beyond natural levees overlying flood plain organic clay deposits
d. Beach and back beach lineaments: magnetite sands, back beach wetland clayey organics
e. Lenses: fluvial deposit remnants buried by contrasting sediments
f. Vertical infill grids: buried sediment desiccation cracks (mud cracks)

The mineral composition, extent to which the vestiges of rock block and sediment bodies have decomposed, and degree of mineral precipitation (grain cement or massive bodies) all determine the influence of a localized soil deposit as an anomaly. For example, a series of individual magnetite-filled potholes in a buried straight stream channel can give a linear array of anomalies. Similarly, in the waning stages of a streambed, settling organic materials in potholes can produce a local environment for mineral replacement (perhaps pyrite) resulting in a possible massive iron-sulfide-induced anomaly.

The distribution of earth materials at any given UXO field site can be complex, and soils will differ from area to area and within a site. To understand the probable scale, distribution, and composition of the soils at a site, information should be gathered from a variety of sources, including soil maps, borings, observations of exposures (streambank, road cuts, etc.), well logs on file with the state agencies, and geologists. The objective is to compile all the information possible from seeing and reading the site geology (geomorphology, composition of soils at the surface, scale and frequency distribution of variations in the transport media). With some data, an understanding of surficial processes, visualization, and imagination, a conceptual model of the soils environment can be constructed. The interpretation will not be in exact detail of the setting but will be an awareness of the probability of concentrations of soil materials (anomalies), their scale, distribution, and influence upon the interpretation of site geophysical data.

Geophysical parameters relevant to UXO detection

Background and definitions. Geophysical methods can be classified broadly based on the nature of the source of the phenomena involved, as seen in Figure 23 where the methods are classed as active (e.g., the EM methods) or passive (e.g., magnetometry). The ability of the geophysical methods to detect UXO depends ultimately on the fact that the UXO has different characteristics and physical properties than the surrounding soil and rock (see Figure 24). All of the UXO characteristics and physical properties, in particular the contrast in physical properties between the UXO and the surrounding geologic media, can be exploited by one or more of the geophysical methods for noninvasive, remote UXO detection (see Figure 25).

Types of Geophysical Methods

Classified by the "Energy" Source

Active -- Require an Artificial Source

- Seismic Methods
- Electrical Resistivity Methods
- Radioactivity Methods
- ➢ Electromagnetic (EM) Methods

Passive – Utilize a Natural Source or Phenomena

- Thermal / Heat Flow Methods
- Natural-Potential Methods
- Magnetotelluric Methods
- Radioactivity Methods
- Gravity Methods
- ➢ Magnetic Methods

➢ ***Indicates methods directly applicable to UXO detection***

Figure 23. A classification of geophysical methods

UXO Characteristics

What is unique or different about buried UXO compared to the surrounding soil and rock ?

- **Compact, elongated shape**
- **Contain metals, most are ferrous**
  - **➧ High electrical conductivity**
    - **-- Typically larger by a factor of > 10^7**
  - **➧ High magnetic susceptibility**
    - **-- Typically larger by a factor of > 10^4**
- **Density**
- **High mechanical wave speeds**
- **Contain explosives**

Figure 24. Distinctive characteristics of UXO relative to surrounding geologic media

Connecting UXO Properties to Geophysical Methods

Characteristic or Fundamental Property		***Geophysical Method***
Magnetic Susceptibility	➡	**Magnetic Methods**
Electrical Conductivity	➡	**Electromagnetic Induction** **Electrical Resistivity**
Dielectric Permittivity	➡	**Ground Penetrating Radar***
Density	➡	**Gravity** **Seismic Methods**
Mechanical Wave Speed	➡	**Seismic Methods**
Compact Elongated Shape	➡	**All**

*** Also magnetic susceptibility and electrical conductivity**

Figure 25. UXO characteristics and physical properties suggest geophysical methods for detection and characterization

As discussed previously, the methods most commonly used for UXO detection surveys are magnetometry and electromagnetic induction. Magnetic susceptibility (permeability) and electrical conductivity are the dominant physical (constitutive) properties that control the magnetic and electromagnetic induction anomaly signatures of UXO, respectively. The large contrasts in these properties relative to the surrounding geologic media explain their applicability (see Figure 25). Another geophysical method that has some applicability to UXO detection is ground penetrating radar (GPR). As indicated in Figure 25, magnetic susceptibility, electrical conductivity, and dielectric permittivity all impact the applicability of GPR. Due to the physics of the phenomena involved and the general, practical requirements for application of the methods, gravity and seismic methods are not broadly applicable to UXO detection; thus density and mechanical properties (e.g., seismic wave speeds) of UXO and surrounding soil are not primary considerations.

The three fundamental EM physical properties appear in the constitutive relations,

$$B = \mu H, \quad (1a)$$
$$J_c = \sigma E, \text{ and} \quad (1b)$$
$$D = \varepsilon E. \quad (1c)$$

B is the magnetic flux in material with magnetic permeability μ and an applied magnetic field H, J_c is the conduction current in material with electrical conductivity σ and applied electric field E, and D is the electric displacement in material with dielectric permittivity ε and applied electric field E. The magnetic susceptibility k, referenced in Figures 24 and 25, and magnetic permeability μ are related by

$$M = k H \text{ and} \quad (2)$$

$$\mu = \mu_o (1 + k), \quad (3)$$

where M is the induced magnetization in the material by the field H, and μ_o is the magnetic permeability of free space. Since B, H, M, J_c , E, and D are vectors, then μ, k, σ, and ε are tensors in the most general case. Also, for the most general case, the physical properties as well as the individual tensor components are frequency-dependent (dispersive), complex quantities. Transforming to principal axes and considering the simplest case of isotropic materials, the tensors all reduce to diagonal form with equal terms along the diagonal that can be represented as:

$$\sigma(\omega) = \sigma'(\omega) + i\,\sigma''(\omega), \quad (4a)$$
$$\varepsilon(\omega) = \varepsilon'(\omega) - i\,\varepsilon''(\omega), \text{ and} \quad (4b)$$
$$\mu(\omega) = \mu'(\omega) - i\,\mu''(\omega), \quad (4c)$$

where $\omega = 2\pi f$ is the circular frequency, indicating the general frequency dependence, and the sign convention is that adopted by Ward and Hohman (1989) and Knight and Endres (2004). Also, the SI system of units is used exclusively in this section; any deviation, such as in figures or tables will be clearly identified and conversion factors provided.

Laboratory or field measurements that determine conductivity and dielectric permittivity are real-valued quantities. It is possible to define real-valued, effective parameters that represent the measured quantities in terms of the fundamental parameters of Equation 4:

$$\sigma_{eff}(\omega) = \sigma'(\omega) + \omega\,\varepsilon''(\omega); \quad (5a)$$
$$\varepsilon_{eff}(\omega) = \varepsilon'(\omega) + \sigma''(\omega)/\omega. \quad (5b)$$

Thus the effective parameters defined in Equation 5 are the real-valued, frequency-dependent quantities actually measured and reported in the literature (unless specifically designated as fundamental parameters). Reported values for the effective parameters should always state the frequency of the measurement. If no measurement frequency is specified, it is often assumed (though sometimes erroneously) to represent a "d.c." or low frequency limit value. For the case of the low frequency limit, $\sigma_{eff}(0) = \sigma'(0) = \sigma_{d.c.}$. Roughly speaking, the effective conductivity and dielectric permittivity represent the energy lost from and energy stored in a material system in an applied electric field. Commonly magnetic losses are assumed small and $\mu_{eff}(\omega) \cong \mu'(\omega)$, but frequency dependence and magnetic losses can be important for materials (soil and rock) with magnetic minerals (e.g., magnetite, hematite, and maghemite).

It is common practice to normalize the magnetic susceptibility and dielectric permittivity to the values of the free space parameters μ_o and ε_o: $\mu_r = \mu / \mu_o$ and $\varepsilon_r = \varepsilon_{eff} / \varepsilon_o$. The normalized or relative dielectric permittivity is often called the dielectric constant (effective) and represented by a separate symbol (commonly κ), although it is not a "constant." If the fundamental parameters are needed for modeling purposes, the fundamental parameters can be defined in terms of the effective, measured parameters in the frequency range of interest (e.g., Knight and Endres 2004). An example of measured effective relative dielectric permittivity and effective conductivity as a function of frequency is shown in Figure 26 for a typical clay-loam soil (King and Smith 1981).

A commonly used model with sound theoretical underpinning that fits the frequency dependence of the EM parameters over a large frequency range is the Cole-Cole model (Cole and Cole 1941), such as for the magnetic permeability (Olhoeft and Strangway 1974):

$$\mu_r(\omega) = \mu_r'(\omega) - i\, \mu_r''(\omega) = (1/\mu_o)\{\mu_\infty + [\mu_{dc} - \mu_\infty] / [1 + (i\omega\tau_\mu)]^{\alpha_\mu}\}. \quad (6)$$

The Cole-Cole model has four adjustable parameters to fit the measured parameter spectrum: μ_{dc} and μ_∞ are the low-frequency and high-frequency limits (asymptotes) of the spectrum; τ_μ is a characteristic relaxation time, corresponding to a relaxation frequency ($f = 1/\tau_\mu$), and α_μ is a distribution parameter that controls the width of the dispersion band about the relaxation frequency (setting $\alpha_\mu = 1$ gives the Debye spectrum). General details of the Cole-Cole model are illustrated in Figure 27 (Golder Associates 1999; Simms et al. 1995). The relationship of the effective parameters to the fundamental parameters over a large frequency range is illustrated in Figure 28, where the fundamental parameter spectra are modeled with typical soil values for the Cole-Cole parameters (with $\alpha_\mu = 1$).

Two additional parameters are commonly used to characterize EM properties of materials, both of which are defined in terms of the fundamental parameters and in turn the effective parameters: the loss tangent ($\tan \delta_T$) and the attenuation (absorption) rate. For example,

$$\tan \delta_E = \sigma_{eff} / (\omega\, \varepsilon_{eff}) = [\sigma'(\omega) + \omega\, \varepsilon''(\omega)] / [\omega\varepsilon'(\omega) + \sigma''(\omega)] \quad (7)$$

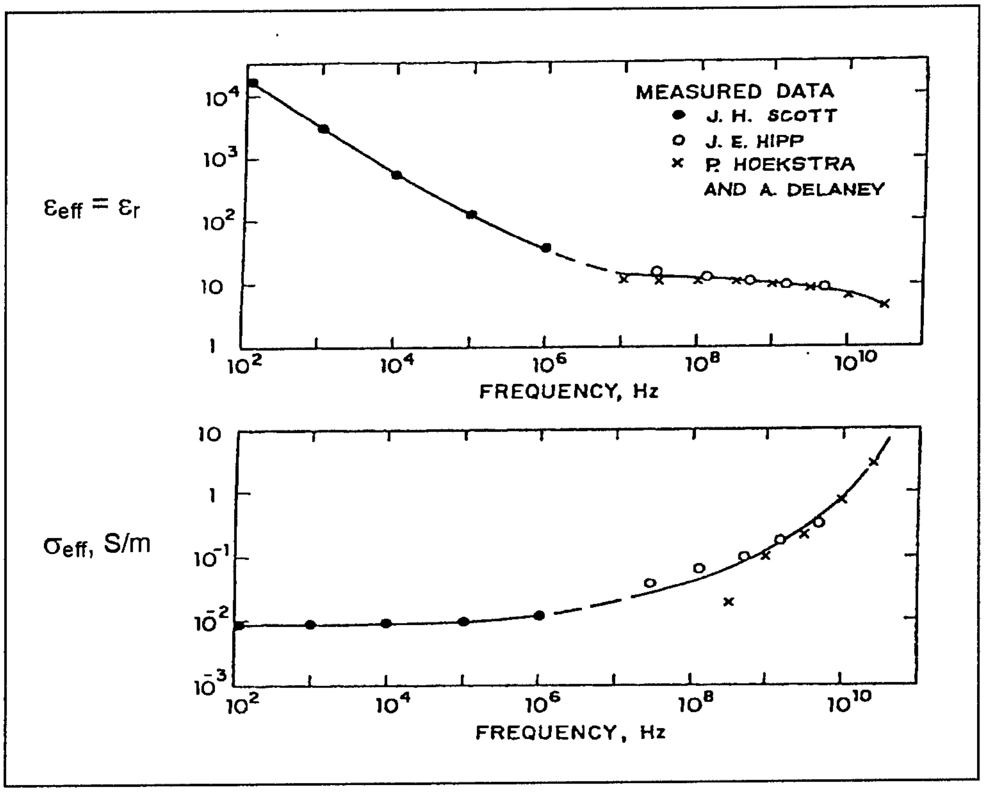


Figure 26. The effective, relative dielectric permittivity and the effective conductivity versus frequency for a typical clay-loam soil with approximately 10 percent water content by weight

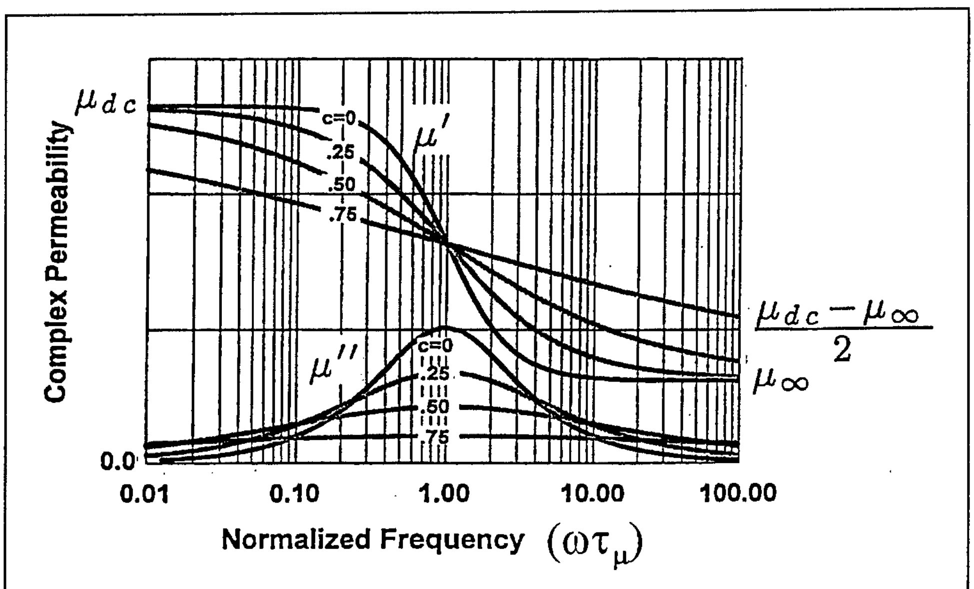


Figure 27. Magnetic permeability dispersion versus normalized frequency for four values of the Cole-Cole distribution parameter, where $c = 1 - \alpha_\mu$; μ_{dc} and μ_∞ are defined by the asymptotic values of μ'

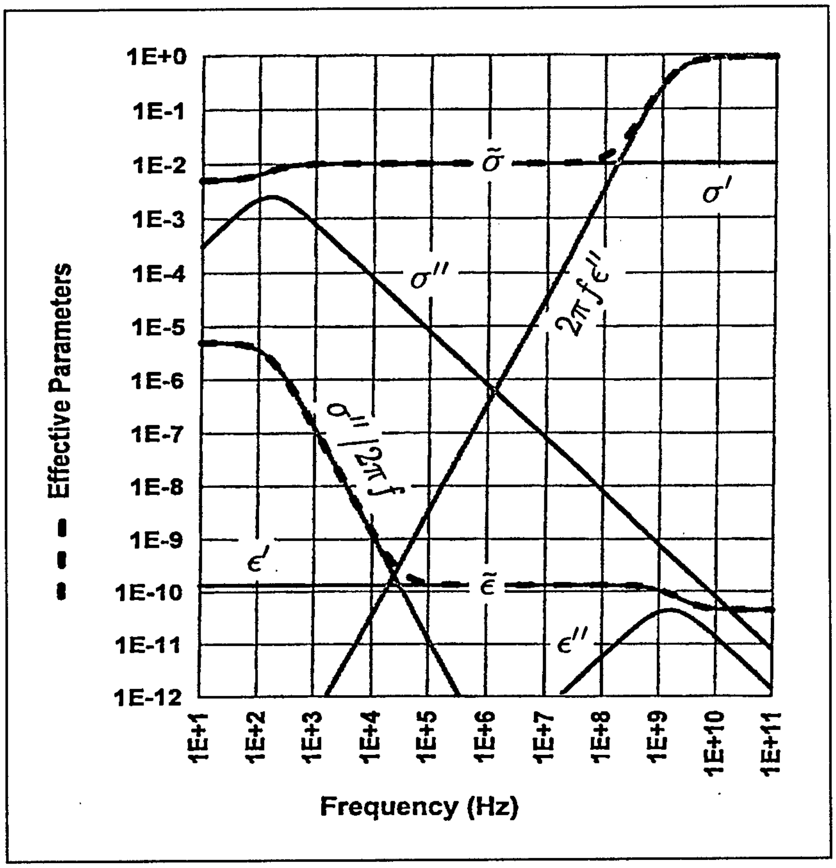


Figure 28. Relation of the effective parameters, $\tilde{\sigma} = \sigma_{eff}$ and $\tilde{\varepsilon} = \varepsilon_{eff}$, and the fundamental parameters σ', σ'', ε', and ε'', using "typical" soil values in the Cole-Cole spectrum (after Golder Associates 1999)

is the electrical loss tangent (physically the phase difference between E and J). Similarly, the magnetic loss tangent is defined as $\tan \delta_M = \mu_r''(\omega) / \mu_r'(\omega)$ (physically the phase difference between B and H), and the total loss tangent is given as

$$\tan \delta_T = \tan [(\delta_E + \delta_M) / 2] = \alpha(\omega) / \beta(\omega) \tag{8}$$

where α and β are the real and imaginary components of the complex "propagation constant" (e.g., Ward and Hohmann 1989; Simms et al. 1995). The parameter α is the attenuation rate, and the propagation velocity is given by $V = \omega / \beta$. Both the attenuation rate and the propagation velocity are conveniently calculated from measured effective parameters or the fundamental parameters and are commonly tabulated or plotted in lieu of or in addition to the effective or fundamental parameters (e.g., Curtis 2001). The attenuation rate can be expressed as an amplitude change of

$$a(\omega) = - 8.686 \, \alpha(\omega) \tag{9}$$

in dB/m due to conductive and dielectric relaxation losses.

Geological materials. The EM properties of geologic materials depend on many factors that are not easy to summarize. Only a select few phenomenological observations, empirical and analytical/theoretical relations, parameter plots, and tabulations are presented for soils and unconsolidated sediments. While many of the general observations hold equally well for rocks, soils are of most interest as the media surrounding buried UXO. Excellent presentations of the physical properties of rocks (including EM properties) are found in Knight and Endres (2004) and Guéguen and Palciauskas (1994). Physical properties of soils are often conveniently summarized in terms of mixing laws or empirical relations (many have a theoretical basis).

Density. Defining ϕ as the volume fraction of a soil occupied by pore space and S_w as the volume fraction of the pore space occupied by fluid (water, with the remainder air-filled), the soil bulk density is given by

$$\rho_{bulk} = (1-S_w)\phi\rho_{air} + S_w\phi\rho_w + (1-\phi)\rho_m \tag{10}$$

where ρ_{air}, ρ_w, and ρ_m are the densities of air, water, and mineral (solids forming the soil matrix). For cases where the solids are composed of minerals with different densities and volume fractions, the last term in Equation 10 is replaced by a sum of products of the form $(1-\phi)\sum_i f_i\, \rho_{mi}$, where f_i and ρ_{mi} are the fraction and density of the i^{th} component of the solid matrix. Equation 10 is an example of a simple mixing formula (law) of individual component properties. The range of densities of geologic materials or geologic components is from 1,000 kg/m^3 for fresh water to 2,000 kg/m^3 for typical soils to 2,650 kg/m^3 for rock (nominal value for crustal rocks, including quartz) to > 3,000 kg/m^3 for the "heavy" minerals. For example, a saturated ($S_w = 1$) quartz sand with 30 percent porosity would have a bulk density of 2,155 kg/m^3, using Equation 10.

Electrical conductivity. Predominant considerations for the EM properties are water content, mineralogy, and structure (particle size gradation, packing, pore shape and interconnectedness, heterogeneity). For sands, silts, and gravels that are predominately quartz, which is a nonconductive mineral, the electrical properties are controlled by the water content, which is a function of the porosity (controlled by particle size gradation and packing). Restricting the consideration for conductivity to very low frequencies (e.g., less than 1 kHz) a useful formulation for the conductivity is given by Archie's law (Archie 1942):

$$\sigma_{eff} = a\,\sigma_w\,\phi^m\,S^n \tag{11}$$

where a, m, and n are empirical constants. Typical ranges for the parameters are: $0.4 \le a \le 2$; $1.3 \le m \le 2.5$; $1.1 \le n \le 2.6$. For unconsolidated sands, $m \sim 1.3$ and $n \approx 2$ is typically assumed, when nothing else is known about the material. The pore fluid conductivity σ_w can range from near zero for very fresh water to > 10 S/m for very salty water (brine). A thorough discussion of studies to characterize the factors that control the parameters a and m and their range of values is found in Edmundson (1988). A practical example is shown in Table 8, for which Equation 11 was used to compute bulk effective electrical conductivity of sands and gravels. Information about clean sand and gravel units in the subsurface at Aberdeen Proving Ground, MD, was gathered from boring logs and monitoring wells for use in the calculations. Types of data used include pore water conductivity, range of saturation, and range of porosity. Conductivity values from interpreted geophysical survey data are consistent with the calculated values in Table 8 (Butler et al. 1996; Sharp et al. 1999).

Table 8
Estimated Effective Conductivity for Clean Sands and Gravels Based on Measured Pore Water Conductivities, Two Saturation Values, and the Observed Range of Porosity for Sands and Gravels

Pore water Conductivity, mS/m	Effective Conductivity, mS/m (S_w = 100%) Porosity		Effective Conductivity, mS/m (S_w = 50%) Porosity	
	20%	50%	20%	50%
High—59	7.2	24	1.8	6.0
Average—20	2.5	8.1	0.6	2.0
Low—4	0.5	1.6	Very Low	0.4

Two additional conduction mechanisms must be considered: (a) conductive minerals in the matrix and (b) minerals that support surface conduction (e.g., clays). Simple mixing laws of electrical conductivity for soils with two or more minerals with different electrical conductivities are not very effective for water-bearing geologic materials. However, the contribution to effective conductivity from surface conduction on clays can be considered as follows:

$$\sigma_{eff} = a\,\sigma_w\,\phi^m\,S^n + \sigma_{eff\,surface} \tag{12}$$

where $\sigma_{eff\,surface}$ is the effective surface conductivity. In many areas with relatively fresh water and/or high clay content, the surface conduction component will be significant and can even dominate the ionic conduction through pore fluid. Numerous detailed studies of surface conduction and the relation of total effective conductivity to clay content, clay types, water content, frequency, and other factors are available (e.g., Knight and Endres 2004; Waxman and Smits 1968; Mualem and Friedman 1991). As emphasized earlier, these simple relations are generally used only for the low-frequency limit (d.c.), although they may be approximately correct with regard to relative effects at other frequencies. Also, as indicated in Figures 26 and 28, the effective conductivity is approximately constant from the low-frequency limit to 100 kHz or more for typical soils.

Electrical conductivity is measured in the laboratory and in the field with multi-electrode (typically four electrodes), low-frequency (typically < 100 Hz) systems; the effective conductivity determined from these measurements is the low frequency or d.c. limit value. Effective conductivity also is determined in the laboratory and in the field with EMI systems; frequency domain EMI systems operate from ~ 1 kHz to < 100 kHz. Effective conductivity can also be calculated from field systems that measure the real and imaginary components of the dielectric constant at microwave frequencies in a coaxial transmission line or time-domain reflectometry (TDR) probe (e.g., 60 MHz) (Everett and Curtis 1996; Siddiqui et al. 2000) or with a laboratory coaxial transmission/reflection network analyzer system (e.g., 45 MHz to 26.5 GHz) (Curtis 2001).

Dielectric permittivity. Similar to the electrical conductivity, the dielectric permittivity is strongly dependent on the water content, but, unlike conductivity, the permittivity does not depend on the pore fluid conductivity (ionic species present). From Figures 26 and 28, the permittivity is seen to be strongly frequency dependent for f < 100 Hz to 1 MHz and is relatively frequency independent for f > 1 MHz to 10 GHz for typical soils. To a first approximation, the dielectric constant (relative dielectric permittivity) can be represented by a mixing law (volume-weighted average of the constituent permittivities, similar to Equation 10). The mixing law is known as the complex refractive index method (CRIM) (Wharton et al. 1980):

$$\sqrt{\kappa(\omega)} = (1-\phi)\sqrt{\kappa_m(\omega)} + \phi S_w\sqrt{\kappa_w(\omega)} + \phi(1-S_w)\sqrt{\kappa_a(\omega)} \qquad (13)$$

where κ_m, κ_w, and κ_a are the complex dielectric constants of the mineral, water, and air constituents of the soil. If it is assumed that the dielectric constants are the effective, real-valued quantities, the CRIM equation simplifies to the time propagation (TP) model (Knight and Endres 2004; Wharton et al. 1980). The effective dielectric constants of water and air are 80 and 1, respectively, and represent the bounding values for geologic materials; Table 9 shows the values for water, air, and typical minerals that make up soils. Considering again the case of a saturated quartz sand with 30 percent porosity, Equation 13 yields an effective dielectric constant of approximately 18, illustrating the dominant effect of the water content.

Applying the CRIM or TP models to predict water content from field measurements of dielectric constant requires the knowledge of five parameters (κ_m, κ_w, κ_a, S_w, and ϕ). While the values of κ_w and κ_a are known, accurate values for κ_m, S_w, and ϕ may not be known and can vary considerably throughout an area of interest. The most common approach to obtain volumetric water content θ_w (= $S_w\,\phi$ = volume of water/total volume) from field measurements of effective dielectric constant κ is to solve the Topp Equation (Topp et al. 1980) for θ_w:

$$\theta_w = -5.3 \times 10^{-2} + 2.92 \times 10^{-2}\,\kappa - 5.5 \times 10^{-4}\,\kappa^2 + 4.3 \times 10^{-6}\,\kappa^3 \qquad (14)$$

The Topp Equation was obtained by fitting data obtained for four different soils with varying water and clay content. Although clearly empirical and subject to error when applied to soils significantly different from the soils used to derive it, the Topp Equation has the advantage of not requiring any specific knowledge about the sampled material. The Topp Equation is often programmed in time-domain reflectometry systems so that a readout or output directly in volumetric water content is available.

Table 9
Values for the Dielectric Constants of Individual Components in Near-Surface Materials

Component	Dielectric Constant
Quartz	4.19-5.00[1]
Orthoclase Feldspar	4.5-5.8[1]
Clay: Kaolinite	9.5-13.7[2]
Calcite	7.8-8.5[1]
Dolomite	6.80-8.00[1]
Water	80
Air (dry)	1

[1]Keller (1989)
[2]Olhoeft (1980)

Field and laboratory systems for measuring effective and real and complex components of the dielectric constant are briefly discussed in the section on electrical conductivity. It is straightforward to determine the complex dielectric constant as a function of frequency with the laboratory systems; sample water content can also be varied (Curtis 2001). An effective dielectric constant can also be determined in the field from analysis of ground-penetrating radar records (e.g., Arcone et al. 2000; Annan 2002).

Magnetic susceptibility. As indicated in Equation 3, $\mu = \mu_o(1 + k)$ or $\mu_r = \mu/\mu_o = (1 + k)$, so that either the magnetic permeability or the magnetic susceptibility can be viewed as the fundamental magnetic property. The natural variation of relative magnetic permeability of soil is typically less than one percent ($\mu_r \sim 1.0 - 1.01$) and depends predominantly on ferrimagnetic minerals and grain size distribution (Walden et al. 1999). However, the magnetic susceptibility of soil varies by several orders of magnitude. The most common ferrimagnetic minerals in soils are haematite and maghaemite, which are weathering products of magnetite. Typical susceptibility ranges of some soil ferrimagnetic minerals are shown in Table 10.

The ranges in Table 10 are only for the specific minerals; in natural soils the minerals may be in various substages of weathering and transformation processes. Also, the susceptibility of the soil assemblage of minerals, organic materials, and water depends critically on the percentages of magnetic minerals present and the grain size distribution of each magnetic mineral. Another issue is the units for magnetic susceptibility. As defined in Equations 2 and 3, susceptibility is dimensionless. Clearly, Equation 2 is a fundamental relationship at a point in space in a material; however, a measurement of susceptibility depends on the volume, density, and geometry of the material of interest. Since M is a volume quantity (= magnetic dipole moment per unit volume), the dimensionless magnetic susceptibility k resulting from most simple laboratory and field measurements is a volume susceptibility. Dividing the volume susceptibility by the sample density yields the mass specific susceptibility that is reported in Table 8. For the most commonly used laboratory magnetic susceptibility measurement system (Bartington MS2) (Dearing 1994), the system is calibrated to a specific volume standard, so all measurements on soil samples of the same volume will be automatically corrected volume magnetic susceptibilities (dimensionless). The MS2 system measures an effective or real-valued susceptibility.

Table 10
Typical Magnetic Susceptibility Ranges for Some Common Ferrimagnetic Minerals Found in Soils

Mineral	Mass Specific Susceptibility[1] 10^{-6} m^3/kg
Magnetite (Fe_3O_4)	400 to 1000
Maghaemite (γFe_2O_3)	250 to 450
Haematite (αFe_2O_3)	0.3 to 2.0
Goethite ($\alpha FeOOH$)	0.3 to 1.3

[1] Walden et al. (1999)

The Bartington MS2 system measures the susceptibility at two frequencies with the laboratory configuration (0.46 and 4.6 kHz). Determination of susceptibilities at two frequencies allows calculation of a measure of frequency dependence, commonly known as the percent frequency effect (difference in the two values normalized by the low frequency value). Theoretical ranges for the percent frequency effect range from 14.6 to 16.9 percent for magnetite and 11.6 to 14.3 percent for maghaemite, with the range resulting from different assumptions about grain sizes. There is considerable observational evidence that the percent frequency effect value can be used to classify soils in terms of grain size and grain size distribution (Walden et al. 1999). Only rarely will the percent frequency effect exceed 12 percent, with most topsoils lying in the range 2 to 12 percent. Samples with percent frequency effect < 2 percent can be assumed to have zero to very small mass percentages of ferrimagnetic minerals and virtually no superparamagnetic grains (Walden et al. 1999).

Laboratory measurements of magnetic susceptibility on soil samples from three distinctly different geologic settings are given in Tables 11 through 13 for JPG, IN, Kaho'olawe, HI, and former Fort Ord, CA, respectively. The percent frequency effect for the three locations is comparable in value and variation, however, the susceptibility magnitudes for Kaho'olawe samples (Table 12) are nominally an order of magnitude larger than either Fort Ord or JPG. The high susceptibility magnitudes at Kaho'olawe are attributed to the magnetic minerals present in the volcanic Hawaiian soils. The effect of frequency-dependent susceptibility on detectability of buried UXO is dependent on the overall background susceptibility value (Pasion et al. 2002) and primarily affects the EMI methods. Pasion et al. (2002) demonstrate fitting the susceptibility measurements at two frequencies for Kaho'olawe (Table 12) to a Cole-Cole model for analysis of the impacts of the frequency dependence on detection and discrimination of UXO. However, for the magnetic methods, the frequency dependence of the susceptibility is not a significant factor, and it is the overall background susceptibility level and short wavelength susceptibility variations that can impact UXO detectability (e.g., Butler 2003; Khadr et al. 1997).

Table 11
Volume Magnetic Susceptibilities for Site at Jefferson Proving Ground, Indiana, 40-Acre UXO Technology Demonstration Site

Sample		Volume Magnetic Susceptibility $\times 10^{-5}$ SI		% Frequency Effect
Location	Depth, m	465 Hz	4, 650 Hz	
K1	0.1	73.6	67.3	8.6
	0.5	32.5	30.6	5.8
	1.0	17.2	16.4	4.6
K7	0.1	20.5	19.3	5.8
	0.5	15.1	13.8	8.6
K13	0.1	10.7	10.7	0
	0.5	14.8	14.6	1.4
	1.0	13.3	12.6	5.3
G1	0.1	62.9	58.7	6.7
	0.5	27.2	25.5	6.2
	1.0	28.2	26.7	5.3
G7	0.1	13.1	12.7	3.0
	0.5	7.1	6.9	2.8
G13	0.1	11.6	11.2	3.4
	0.5	8.8	8.1	8.6
	1.0	13.6	13.5	0.7
C1	0.1	65.3	62.1	4.9
	0.5	25.0	23.9	4.4
	1.0	31.5	30.3	3.8
C7	0.1	11.6	11.2	3.4
	0.5	9.0	8.8	2.2
	1.0	22.7	21.8	4.0
C13	0.1	19.9	19.1	4.0
	0.5	17.6	16.6	5.7
	1.0	21.5	20.9	2.8

While there are published magnetic susceptibility mixing formulas for soils (e.g., Walden et al. 1999; Klein and Santamarina 2000), the issue is considerably more complicated than for density, conductivity, and permittivity, in that susceptibility depends not only on the susceptibilities and percentages of the magnetic constituents, but also critically on the distribution of grain sizes of the constituents. The discussion above applies to susceptibility and induced magnetization; the issue of remanent or permanent magnetization is not considered. For some situations, rock inclusions in the soil or soils with large ferrimagnetic mineral grain sizes (e.g., > 0.07 μm) may have a permanent magnetization component. Also, burned soils and sites of lightning strikes may have permanent magnetization as well as increased susceptibility relative to the normal state.

Table 12
Volume Magnetic Susceptibilities from Selected Locations at Two Sites on Kaho'olawe Island, Hawaii

Sample		Volume Magnetic Susceptibility $\times 10^{-5}$ SI		% Frequency Effect
Location	Depth, m	465 Hz	4, 650 Hz	
Site Seagull				
7462 - 2728 A	0.15	3554	3311	7.0
	0.61	3022	2771	8.2
7462 - 2728 B	0.15	1046	1001	4.3
7468 - 2734 A -P	0.15	1726	1630	5.6
	0.46	1529	1448	5.3
7468 - 2734 B -P	0.30	2807	2634	6.2
	0.46	1920	1807	5.9
7468 - 2734 A -B	0.15	845	805	4.6
7468 - 2734 B -B	0.20	1795	1707	4.9
Site Lua Makika				
7537 - 2754 A -P	0.20	2355	2249	4.5
	0.46	2227	2134	4.2
7537 - 2754 B -P	0.15	1461	1383	5.4
	0.30	1497	1411	5.8
7537 - 2754 A -B	0.15	2475	2431	1.8
7537 - 2754 B (Back)	0.30	1394	1334	4.3

Table 13
Volume Magnetic Susceptibilities from Seven Locations at Former Fort Ord, California, Seven Distinct Soil Types

Sample		Volume Magnetic Susceptibility $\times 10^{-5}$ SI		% Frequency Effect
Location	Depth, m	465 Hz	4, 650 Hz	
Toropark between OE-62 and OE-63	0.10	41.66	40.74	2.2
OE-27 Oil Well Rd Clay Site	0.10	16.96	16.6	2.1
OE-32 C Oil Well Rd	0.10	12.14	11.8	2.8
OE-46 York School	0.10	15.76	14.86	5.7
Del Ray Oaks Firing Range 26	Surface	108.52	98.46	9.3
OE-14 Lookout Ridge	Surface	18.84	17.76	5.7
OE-15 BLM	Surface	21.10	23.78	1.3

Heterogeneity. As already suggested by Tables 11 through 13, a fundamental characteristic of geologic environments is heterogeneity. Heterogeneity exists from microscale to mesoscale; even within a relatively homogeneous soil, fundamental physical properties can vary in all directions (i.e., vertically and horizontally). The heterogeneity manifests itself at all measurement scales from laboratory measurements on small samples (or field measurements that are essentially point sample measurements) to measurements with systems that are volume-weighted averages. For example, the MS2 field measurement loop system produces a volume-weighted average susceptibility of the upper 15 to 20 cm below the loop. In a homogeneous soil, the physical property (e.g., electrical conductivity) will often be normally (Gaussian) or log-normally distributed. Everett and Weiss (2002) observed that electrical conductivity of a geologic medium is a fractional Brownian motion behavior that is nonstationary, self-similar, and has long-range correlations (fractal). That is, the fundamental properties of geologic materials are not the commonly assumed piecewise, smoothly varying functions superimposed on random, uncorrelated background noise, but have spatial correlations at different scales that are generally self-similar (e.g., Knight et al. 1997).

Not surprisingly, the general variation of physical properties over a site will correlate to the variation in soil type (see Figure 29, Table 13, and Figure 30) (Butler et al. 1999). The physical properties also correlate to the topography, even in an area with a single soil type, since the soil water content and even mineral constituents will correlate to topography. A simple topographical cause of mineral constituent variation is just differential deposition of minerals with differing densities, such as erosional deposition of heavy minerals with higher magnetic susceptibilities along slopes and in topographic lows. Another source of physical property variation related to topography occurs when an erosional or drainage feature downcuts through a soil horizon with differing properties from the sediments above it. The example of magnetic susceptibility measurements and elevation along a profile at JPG, shown in Figure 31, weakly supports this second correlation mechanism of physical property versus topography because the high susceptibility values seem to occur on the slopes of drainage features (Butler et al. 1999). Electrical conductivity and dielectric constant vary seasonally with wet and dry seasons and also as a function of time after the most recent rainfall and rainfall amount. The variation of water with depth for dry and wet (just after rainfall) site conditions for a location at JPG is shown in Figure 32. The heterogeneity of soil hydraulic conductivity leads directly to heterogeneity in electrical conductivity and dielectric permittivity that is time dependent.

Selected Parameter Tabulations and Plots. Many texts and references give tabular listings of physical properties of soils and rocks. About the only commonality is a general correlation of the ranges of parameters and different nomenclature, terminology, and units. Most of the differences in physical property tabulations are due to disciplinary/experience background of the authors, the application area (soil science, geotechnical engineering, mining, petroleum, etc.), depths of interest (related to the application area), and the extreme site-, area-, regional-, and environmental-dependence of the physical properties. Also, since the physical properties depend on mineralogy, temperature, water content, and other factors, it is difficult to specify or even account for all the variables in any tabulation.

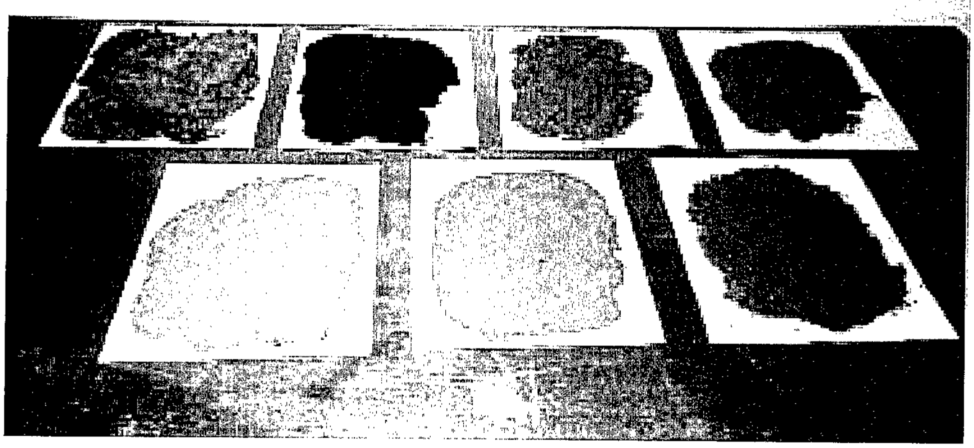


Figure 29. Seven soil types from former Fort Ord, California (see Table 13)

Some parameter values, tabulations, and plots have been presented in the preceding discussion with considerable explanation and caveat. The following tabulations and plots are presented without detailed explanation to convey general concepts, trends, ranges, and dependencies. While not discussed previously, some of the physical properties are functions of temperature. Figure 33 illustrates the temperature dependence of electrical resistivity, which is the reciprocal of electrical conductivity. For temperatures above freezing, the variation in conductivity over a typical 24-hr temperature cycle is nominally a factor of two or less (Butler et al. 1999).

Physical properties are frequency dependent as discussed previously. The specific example of JPG is continued in Figure 34, where laboratory measurements of dielectric permittivity are shown as a function of frequency. The measured real and imaginary components of the dielectric constant and the calculated effective conductivity, attenuation, loss tangent, and normalized phase velocity are indicated.

As discussed previously, electrical conductivity and dielectric constant are strongly dependent on soil water content (volumetric moisture). The results of laboratory dielectric constant measurements at 200 MHz (a typical ground penetrating radar center frequency) for all samples from the two large JPG sites are shown in Figure 35. The spread in values at a given water content is due to the different soil types, topography, and physical locations of the samples.

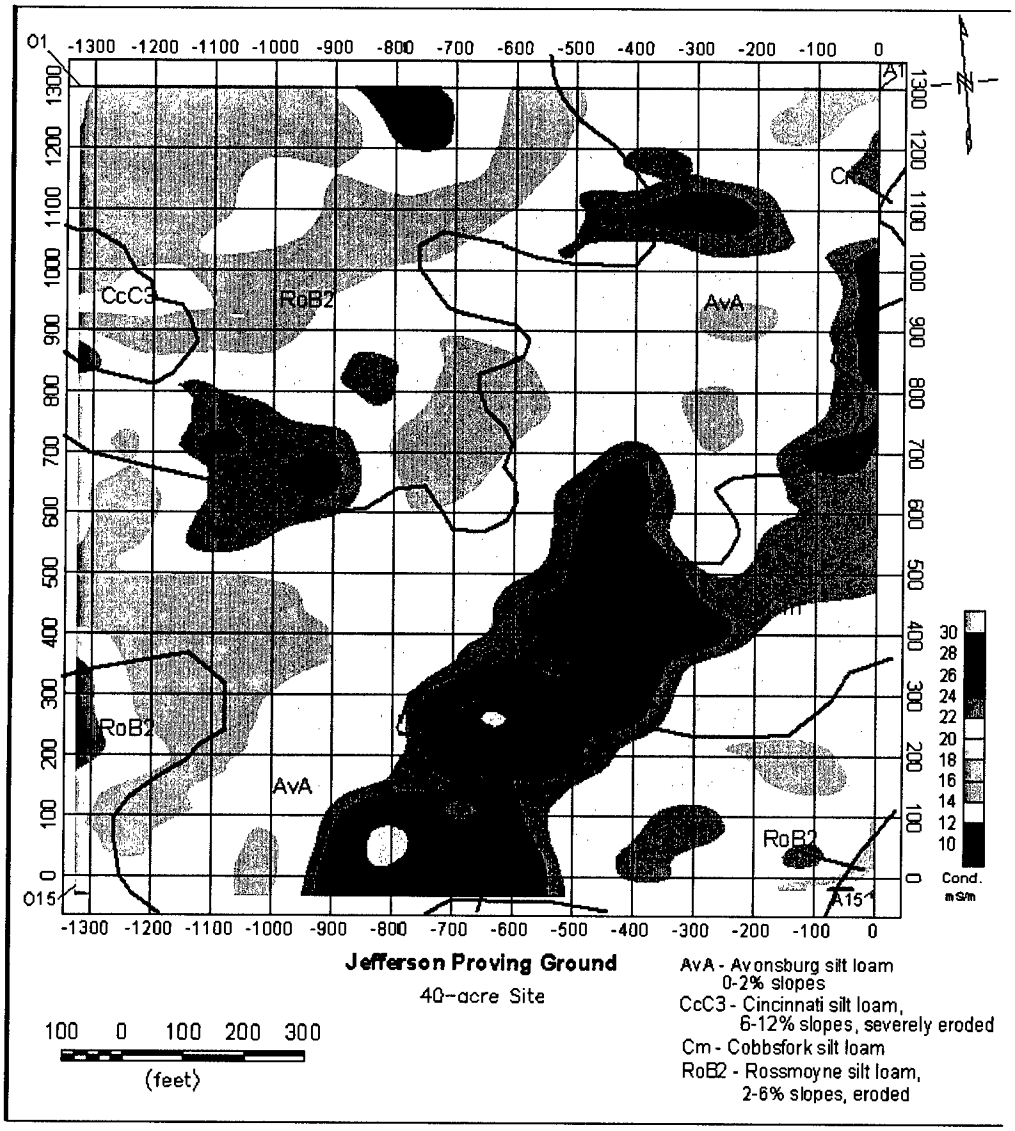


Figure 30. Electrical conductivity determined with EMI system (9.8 kHz) that determines a volume-weighted conductivity of approximately the upper 5 m of the subsurface; the irregular black lines delineate soil units from a soils map; the conductivity generally correlates to the soil type, with the factual caveats that (1) the effective measurement depth exceeds the soil thickness and (2) the soil unit boundaries that were digitized from a 1985 soils map may not be accurate

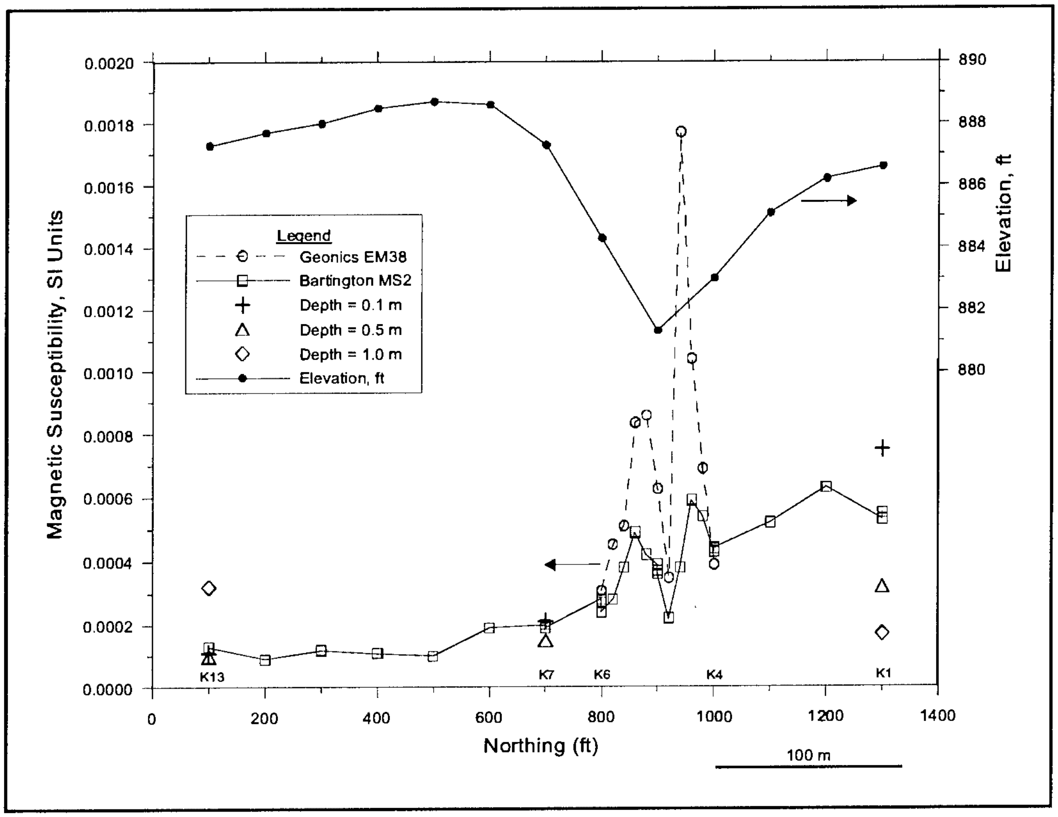


Figure 31. Correlation of laboratory and field magnetic susceptibility values with topography along a N-S profile line at a JPG UXO demonstration site

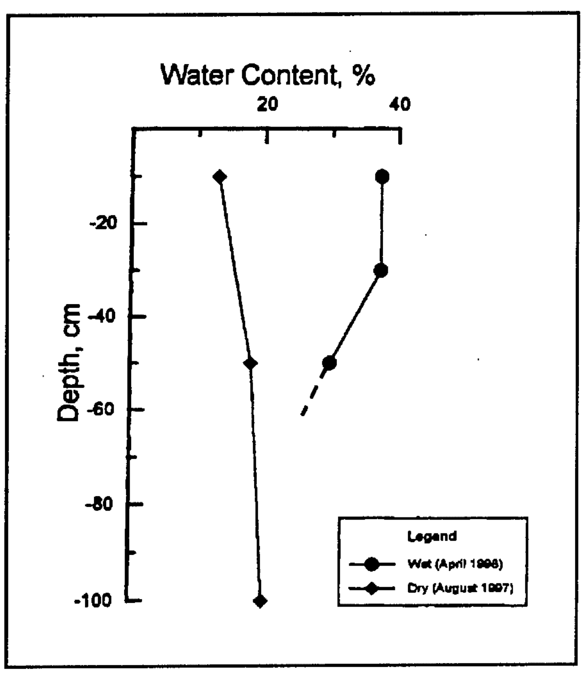


Figure 32. Volumetric water content as a function of depth for dry and wet ground conditions

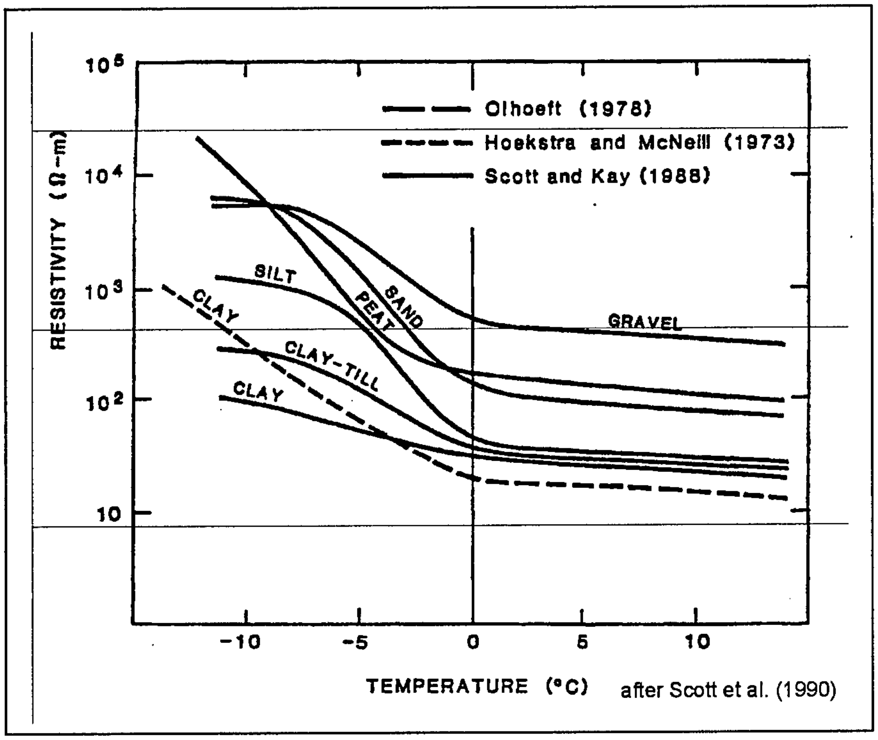


Figure 33. Resistivity variation with temperature for selected soil types

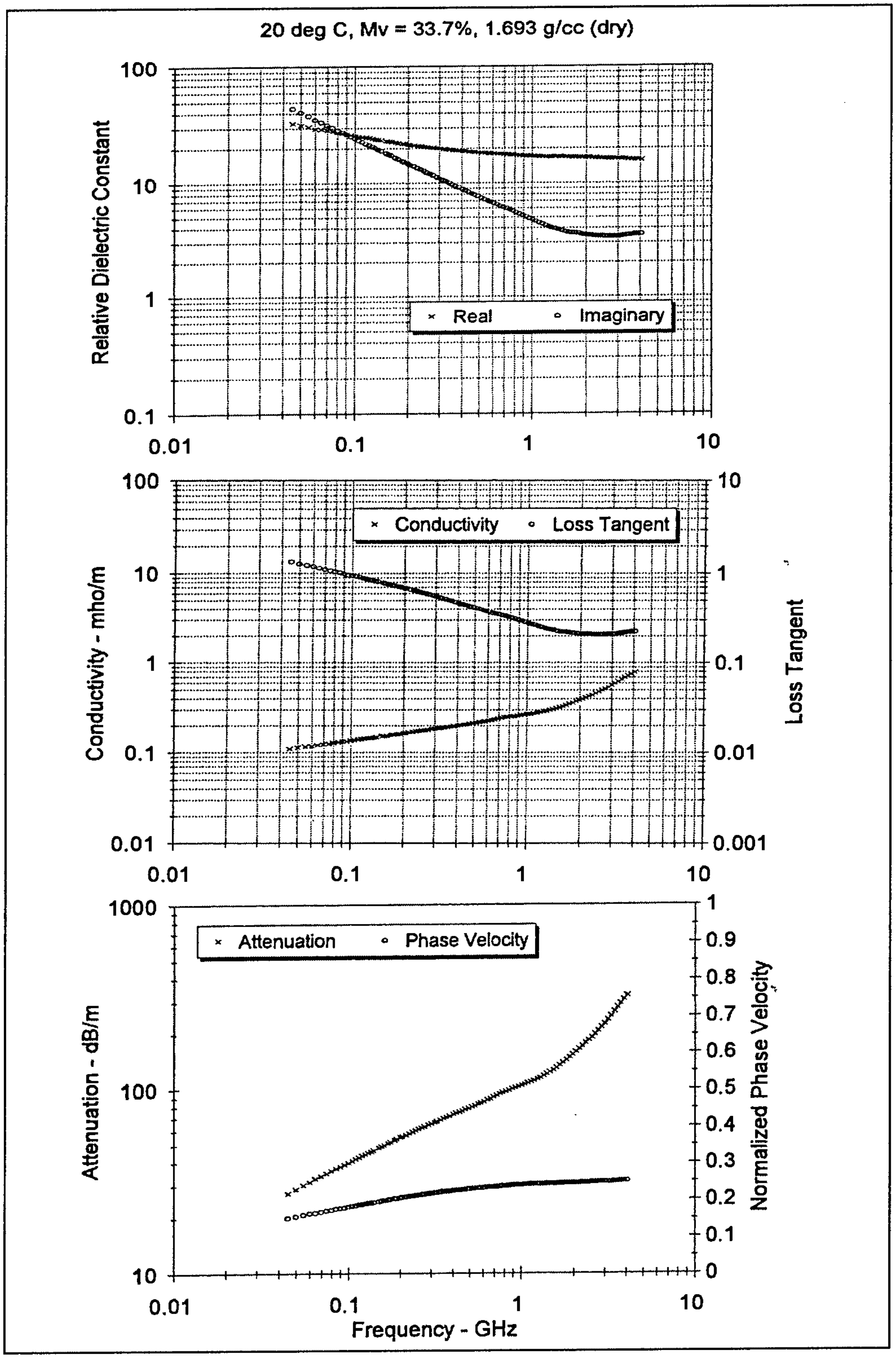


Figure 34. Dielectric constant, effective conductivity, loss tangent, attenuation, and normalized phase velocity as a function of frequency of a JPG soil sample at ~ 33 percent volumetric water content

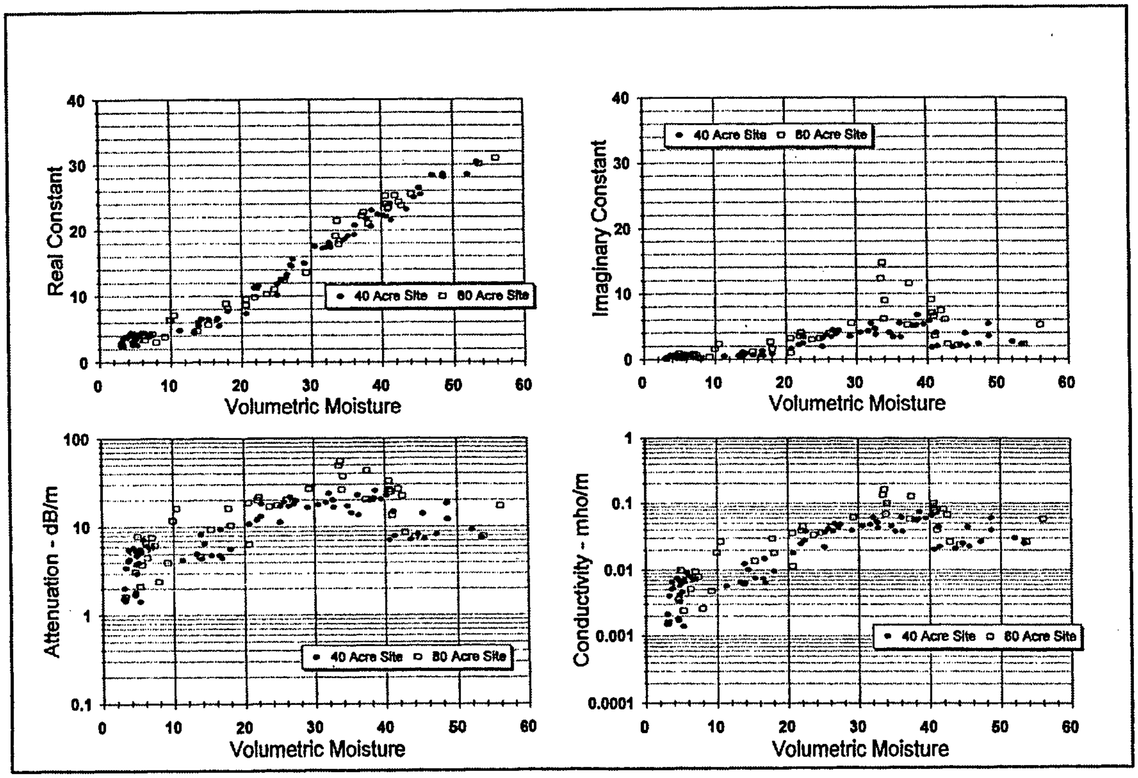


Figure 35. Real and imaginary components of the dielectric constant, attenuation, and conductivity for all samples from the two large JPG UXO test sites as a function of volumetric water (moisture) content

Tabulations of generic ranges of physical properties of typical geological materials are extremely useful for modeling and prediction applications and in cases when only a material or soil type classification is known. Tables 14 and 15 are examples of tabulations that include unconsolidated sediments and soils. Tabulations of physical properties in geophysics texts and references often are heavily slanted to rocks, mineral mining, and petroleum applications and are not useful for UXO surveys in soils.

Table 14
Typical Effective Dielectric Constant, Effective Electrical Conductivity, Phase Velocity, and Attenuation Observed in Common Geologic Materials

MATERIAL	K	σ mS/m	v m/ns	a dB/m
Air	1	0	0.30	0
Distilled Water	80	0.01	0.033	2×10^{-3}
"Fresh" Water	80	0.5 to 100	0.033	0.1
Sea Water	80	3000	0.01	103
"Dry" Sand	3 to 5	0.1 to 5	0.15	0.01
Saturated Sand	20 to 30	0.1 to 50	0.06	0.03 to 0.3
Limestone	4 to 8	0.5 to 2	0.12	0.4 to 1
Shales	5 to 15	1 to 100	0.09	1 to 100
Silts	5 to 30	1 to 100	0.07	1 to 100
Clays	5 to 40	2 to 1000	0.06	1 to 300
Granite	4 to 6	0.01 to 1	0.13	0.01 to 1
Dry Salt	5 to 6	0.01 to 1	0.13	0.01 to 1
Ice	3 to 4	0.01	0.16	0.01

Note: after Annan 2002 and Palacky 1989

Table 15
Typical Ranges of Physical Properties for Soils

	Electrical Conductivity mS/m	Mass Magnetic Susceptibility 10^{-6} m^3/kg	Relative Dielectric Permittivity
Classification by Soil Grain Size and Mineralogy			
Silty Sand	0.1 to 25	0.01 to 15	5 to 20
Sandy Silt	1 to 50	0.01 to 15	1 to 30
Silt	1 to 100	0.01 to 15	5 to 30
Clay	2 to 2000	-0.01 to +0.15	5 to 40
Classification by Generic Soil Moisture Content Condition			
Dry	0.01 to 1	NA	3 to 5
Moist	1 to 100	NA	5 to 30
Wet	< 1000	NA	20 to 40

Noise

In geophysics, the term "noise" has different definitions, depending on the depth of investigation and application. For example, the shallow subsurface (< 100 m) in the petroleum industry is considered noise, whereas it is the signal of interest in near-surface geophysics studies. In UXO geophysical surveys, there are both geological and cultural noise sources. Geological sources include natural environments that interfere with geophysical detection surveys (e.g. high magnetic backgrounds) and lightning strikes. Cultural noise sources can be more problematic because they affect all sensor types. Examples of cultural noise include buildings, fences, utility/pipe lines, transmitting towers, and smaller sources such as cans, foil-lined cigarette wrappers, and other man-made debris. If possible, removal of cultural influences is the most effective means of optimizing geophysical survey results. Removal can be done when dealing with surface debris and is also a possibility with fences and abandoned utility/pipe lines and buildings. For sources that cannot be removed, then avoidance is recommended to reduce contamination of the data. A standoff distance of 3 to 7 m from fences and buildings is generally sufficient to eliminate an overwhelming influence of the structure. The TDEM instruments tend to be less affected by fences and large structures than do magnetometers. Table 16 gives approximate magnetic responses to a variety of cultural items. If it is not possible to collect acceptable-quality geophysical data near a cultural feature, then it will be necessary to use some other means to determine if the area contains UXO.

Small-scale subsurface cultural debris cannot be avoided and can cause major interference during UXO detection surveys (see Figure 11). Under these circumstances, a sophisticated discrimination algorithm is likely required to differentiate debris from possible UXO.

Table 16
Magnetic Anomalies of Common Objects

Object	Near Distance		Far Distance	
	m	nT	m	nT
Automobile (1 ton)	9	40	30	1
File (10 in./25.4 cm)	1.5	50 to 100	3	5 to 10
Screwdriver (5 in./12.7 cm)	1.5	5 to 10	3	0.5 to 1
Revolver (38 special or 45 automatic)	1.5	10 to 20	3	1 to 2
Rifle	1.5	10 to 50	3	2 to 10
Ball Bearing (2 mm)	0.1	4	0.1	0.5
Fence line	3	15	7	1 to 2
Pipeline	7	50 to 200	15	12 to 50
"Cow" magnet (1/2 in. W, 3 in. L / 1.3 cm W, 7.6 cm L)	3	20	6	2
Well casing and wellhead	15	200 to 500	150	2 to 5

Note: Anomalies are only representative and may vary by a factor of 5 or even 10 depending on object orientation, remanent magnetization, sensor orientation, metallurgy, etc.
after Breiner 1973

Phenomenological Evaluation

The set of dashed boxes in Figure 18 shows how the guidelines describing the Phenomenological Evaluation fit into the standard Footprint Analysis framework. The Phenomenological Evaluation is positioned between the two stages Adjust Boundaries and Conduct Field Investigations and consists of five data-gathering tasks and one GIS task.

The first task involves gathering data relative to the site geology, topography, hydrogeology, vegetation, and climate that could influence the transmitted and received signal of the geophysical sensor. To a lesser degree, some of this effort may have been accomplished under the second level of the Footprint Analysis, Document Current Conditions. The goal at this point is not to duplicate prior efforts but to provide greater detail so the spatial variability of parameters at different scales can be identified. Task 2 includes dividing the site into areas having similar physical attributes for each data source, such as topography, slope, soil type, vegetation, and moisture regime. The degree of subdivision will be dictated by the level of information available on a site. These data will then be overlaid to obtain intersecting layers of soil-moisture, topography-vegetation, and topography-moisture. Task 3 involves determining the geophysical parameters relevant to each sub-area identified in Task 2 and estimating their range of variation. Under Task 4 the maximum depth of ordnance penetration is identified for the types of ordnance suspected to be at the site. Task 5 uses the information from the previous four tasks to select the sensor or combination of sensors to employ during the geophysical survey, platform to carry the sensors (hand-held, cart, vehicle towed, airborne), and spatial sampling required to optimize target detection. Task 6 involves estimating the anomalous field response caused by the targets given the background conditions specified in Tasks 3 and 4. A more thorough description of each task follows, with an example of how the phenomenological information can be used.

Task 1: Geo-environmental information

Most information and maps can be obtained through resources on the installation. However, there are many sources of geological and geotechnical information that can help with characterizing an area of interest.

Published geotechnical information about sites within the United States is available through Federal, state, local, and private agencies and organizations. Geotechnical data are in the form of geologic reports, maps, boring logs, in situ and laboratory test results, reports of geophysical investigations, remote imagery, and supplemental topographic maps. Much information is now available in digital format for viewing and processing on a personal computer and can be downloaded directly from a World Wide Web (www) Internet site, often at no charge to the viewer. Other data must be collected in hard copy or in digital format through request or by personal visit to the source provider. The information provided here is a guide to finding and obtaining geologic and supplemental data and provides information on points of contact (POCs), addresses, telephone numbers, data formats, and data characteristics of the sources. Today's Internet www services offer a quick and inexpensive first step in obtaining geologic data for a site or for determining through an Internet search what data are available and where and from whom they may be obtained.

Federal agencies, such as the U.S. Geological Survey (USGS), the U.S. Department of Agriculture (USDA), the Federal Department of Transportation (FDOT), and their affiliated offices have a wealth of published information pertaining to sites throughout the United States. Much of the Federally funded and published information is available at standard scale and format, making it applicable nationwide. However, geographic coverage is limited or incomplete for some kinds of Federally produced data. Data more pertinent to a specific site might be obtained through state or local agencies.

State geological surveys, which are sometimes embedded in departments of natural resources (DNR), departments of environmental quality (DEQ), or state universities, are often good sources of more site-specific geologic data. State DOTs maintain boring logs and some geological reports on the miles of highway projects and bridge sites within a state. Most of these agencies maintain web pages with POCs for obtaining information and with some viewable or downloadable information, including published reports and maps. Interested parties may also visit these agencies and review published and unpublished reports and other data in hard copy.

Private industry (e.g., engineering and geotechnical firms) maintains data files of foundation and other investigations containing geologic and engineering boring logs, surface and subsurface geophysical investigations, laboratory and in situ engineering tests of soil and rock, and other geotechnical information that may be pertinent. Private businesses may not be willing to release information for legal, proprietary, or other reasons but are a potential source worth pursuing if other sources of data do not produce results.

The types of data pertinent to UXO survey sites include rock type and engineering properties; soil types, thickness, and properties; geologic stratigraphy and structure; groundwater data; and potential geologic hazards. The rock should be described from the surface to a depth encompassing the depth of investigation. Soil characteristics should include surface distribution and thickness or depth of soil cover. Geologic structure and stratigraphy are characterized from surface geologic maps and subsurface data including logs of borings, trenches, and tunneling.

Geophysical investigations provide information on remotely sensed rock and soil properties, including depth to groundwater and top-of-rock, lateral and vertical changes in soil and rock properties, and the presence of anomalous bodies of rock, soil, or cavities within the subsurface. Surface topographic maps describe the morphology of the land surface, which may be important in site access and assessment of subsurface geologic conditions. Surface topography may provide a clue to conditions in the subsurface because topography often is a result of and reflects characteristics of the underlying geology.

Published topographic maps also commonly display roads, buildings, bridges, and streams in the vicinity of the site. Satellite and aerial photography and other imagery provide wide coverage of the earth's surface for determining general site conditions. These kinds of geotechnical information are commonly available in the sources listed.

A table included in Appendix A summarizes information about data sources in state agencies and is listed alphabetically by state. The kinds of information listed under "Data Description" are not necessarily viewable via the web site but are held by the agency listed under "Source." State agencies that acquire and store geologic and soils information include the geological surveys, the divisions of oil and gas, the divisions of mining, the departments of transportation, and others. Appendix B lists additional sources and explanations and provides some examples of data that can be obtained at some of the larger Internet-accessible sources that cannot be fully described in a table.

Task 2: Subdivide site based on physical characteristics

Once the available geo-environmental information has been gathered, a GIS system can be used to subdivide each dataset into areas having similar characteristics. The boundary of the data is the same as that identified as the area of interest in the Footprint Analysis. Four primary datasets are utilized: topography/slope, vegetation, soil type, and moisture regime. The subdivision is performed on each dataset individually, therefore the division boundaries of the various datasets generally will not coincide, and the number of subdivisions between datasets may vary. The resolution of the various data types is likely to vary also. For example, the topographic data could be at 1-m resolution, whereas the spatial distribution of soils may be based on samples collected hundreds of meters apart. For some sites, measurement data will not be available for a given parameter, so the information must be inferred from other physical characteristics of the site. Soil moisture is often a parameter for which limited, if any, data are available. However, general assumptions based on relative elevation, types of vegetation, and soil type can assist in determining if a soil is likely to be dry, moist, or wet. In most cases, the soil moisture layer will strongly correlate to one of the other primary datasets (topography/slope, vegetation, soil type).

A single GIS layer will contain information detailing the slope and topographic features of a site. A digital elevation model (DEM) or digital terrain elevation data (DTED) and topographic map can be used to divide the site based on degrees of slope and topographic conditions. Slope is categorized as Gentle (slope < 2 deg), Moderate (slope 2 to 5 deg), and Steep (slope > 5 deg). The topography categories include Flat, Hilly, Rolling, and Mountainous. The topography/slope layer is combined with the vegetation and moisture layers to aid in generating a list of possible geophysical sensors and platforms for each subdivision.

The vegetation within a site is categorized based on general descriptions rather than specific vegetation types. The categories include None/Minimal, Short Grass/Brush (height ≤ 0.3 m), Moderate Grass/Brush (height 0.3 to 0.6 m), Tall Grass/Heavy Brush (height > 0.6 m), Thin Woods (trees > 1 m separation), and Thick Woods (trees ≤ 1 m separation). The tree spacing for the woods categories is based on the coil size of the Geonics EM-61.

The USDA Textural System was chosen for the soil descriptors since the majority of soil surveys utilize this system. It can be considered a regional system and defines a soil based on particle size. This system differs from the classification described in Chapter 6, which provides a continuity of soil types on a global scale based on soil unit characteristics rather than particle size. The USDA system defines a soil based on the quantity of sand-, silt-, and clay-size particles. There are 12 soil classifications: sand, loamy sand, sandy loam, sandy clay loam, sandy clay, clay, clay loam, loam, silty clay, silty clay loam, silt loam, and silt. The soils layer is used in conjunction with the moisture layer to estimate values of the geophysical parameters within each subdivision.

Consider the hypothetical scenario depicted in Figure 36. The topography/slope, moisture regime, and distribution of soils and vegetation are shown. Note that the number of subdivisions and their extent varies between datasets. The topography is divided into three regions: moderately steep depression, steep high point, and flat to gently sloping. Associated with these regions are short grasses in the higher elevations, tall grasses in the lower elevations, and both thin woods and moderate height grasses and brush cover the flatter land. Four general soil types are identified within the near-surface. A loamy sand is found in the highest elevations and extends into the flat/gently sloping area. The flat/gently sloping area is predominantly sandy loam and loam. The low area and a small region surrounding it contain clay. The soil moisture generally follows the topography with the high region considered dry, the low region and area immediately surrounding it classified as wet, and the flat to gently sloping region having a moderate moisture content. By utilizing the GIS capabilities, intersecting layers are constructed that contain the soil-moisture, topography/slope-vegetation, and topography/slope-moisture information. These layers are the basis for the phenomenological evaluation. The next step in the process is to estimate values for the geophysical parameters given the physical attributes of the site.

Task 3: Estimate geophysical parameters

After the physical characteristics of a site have been identified and subdivided into areas of similar features, magnetic and EM parameters can be estimated based on the combined characteristics of the soil type and moisture layers. Ideally, field or laboratory measurements of the requisite geophysical parameters are made (see preceding section on geophysical properties). The GIS output can be used as a guide to optimize sampling of preliminary field measurements. Each subdivided area has a unique set of physical characteristics so the geophysical parameters within each subdivision are likely to differ. When no measurement data are available, however, it is necessary to make a best estimate of the geophysical parameters based on a compilation of available sources of both laboratory and field measurements. Table 17 provides a range of property values for the 12 soil types and 3 moisture conditions. Note that there is generally a wide range of parameter values for a given soil type and the values overlap between the different types of soil. Figure 37 shows values assigned to the three geophysical parameters for the soil type and moisture conditions described in Figure 36. This information will aid in determining which geophysical sensors are most applicable for surveying the areas identified as having different physical characteristics.

Task 4: Ordnance types

It is necessary to have a cursory knowledge of the range of ordnance sizes expected at a site because ordnance size and depth of burial are among two factors considered when selecting an appropriate geophysical sensor. Chapter 2 addresses ordnance penetration, and Chapter 4 provides several examples showing how sensor response varies with target type and position. It is important to anticipate the smallest ordnance type expected at a site to ensure the proper sensor and spatial sampling are selected to optimize the chance of detection and minimize the number of UXO remaining in the subsurface.

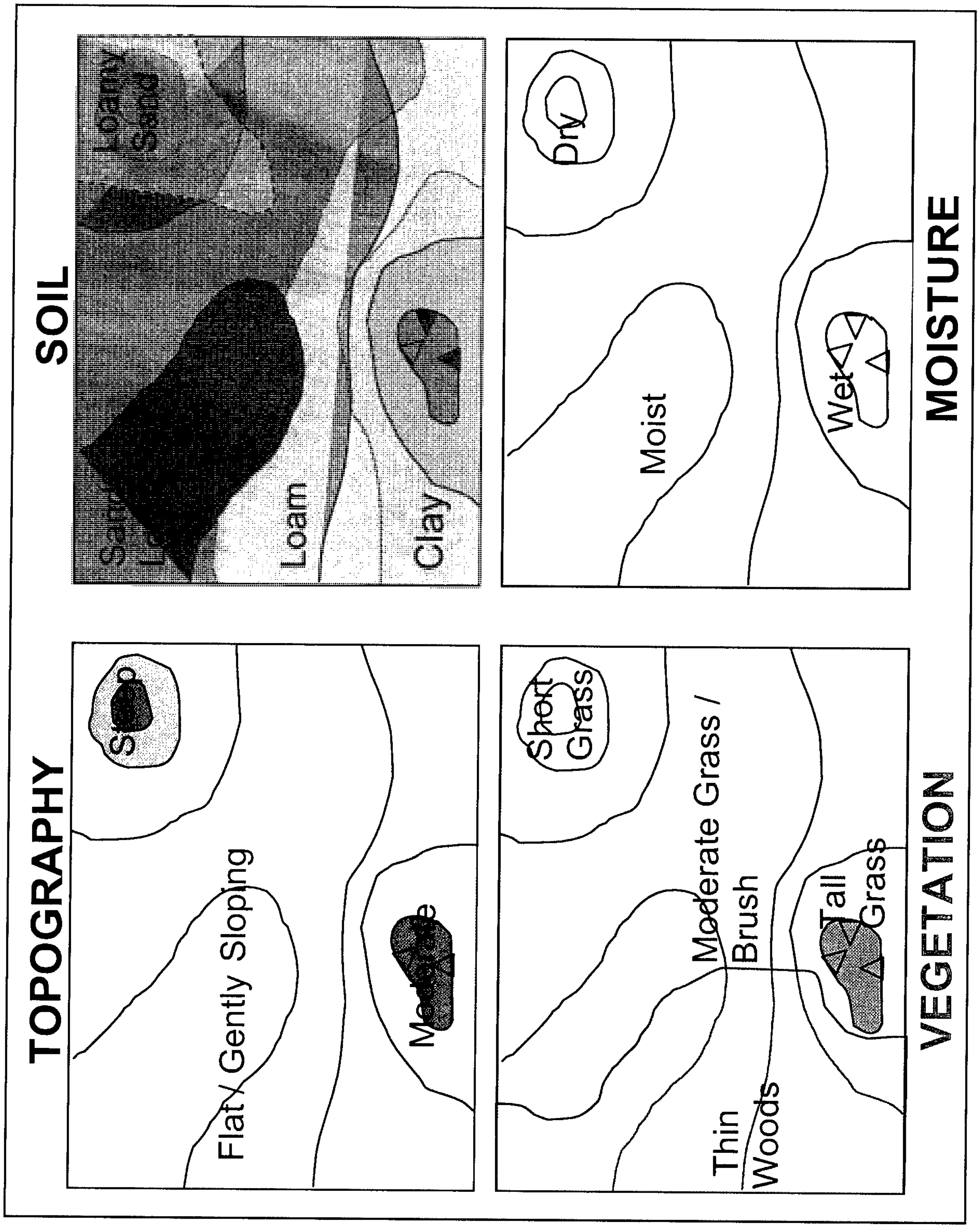


Figure 36. Hypothetical scenario used to illustrate phenomenological evaluation

Table 17
Representative Values of Geophysical Parameters for Different Soil Types and Moisture Conditions

USDA Soil Type	Electrical Conductivity mS/m	Mass Magnetic Susceptibility 10^{-6} m^3/kg	Relative Dielectric Permittivity
Clay	2 to 1000	-0.1 to +0.15	5 to 40
Silt	1 to 100	0.01 to 20	5 to 30
Loam	1 to 75	0.01 to 20	5 to 20
Sand	0.1 to 50	0.01 to 20	3 to 5
Silty clay	1 to 500	0.01 to 20	5 to 35
Silty clay loam	1 to 300	0.01 to 20	5 to 25
Silty loam	1 to 75	0.01 to 20	5 to 20
Clayey loam	1 to 200	0.01 to 20	5 to 30
Sandy clay	1 to 200	0.01 to 20	5 to 25
Sandy clay loam	1 to 150	0.01 to 20	5 to 20
Sandy loam	1 to 75	0.01 to 20	5 to 15
Loamy sand	1 to 75	0.01 to 20	5 to 10
Moisture State			
Dry	0.01 to 1	NA	3 to 5
Moist	1 to 100	NA	5 to 30
Wet	<1000	NA	20 to 40

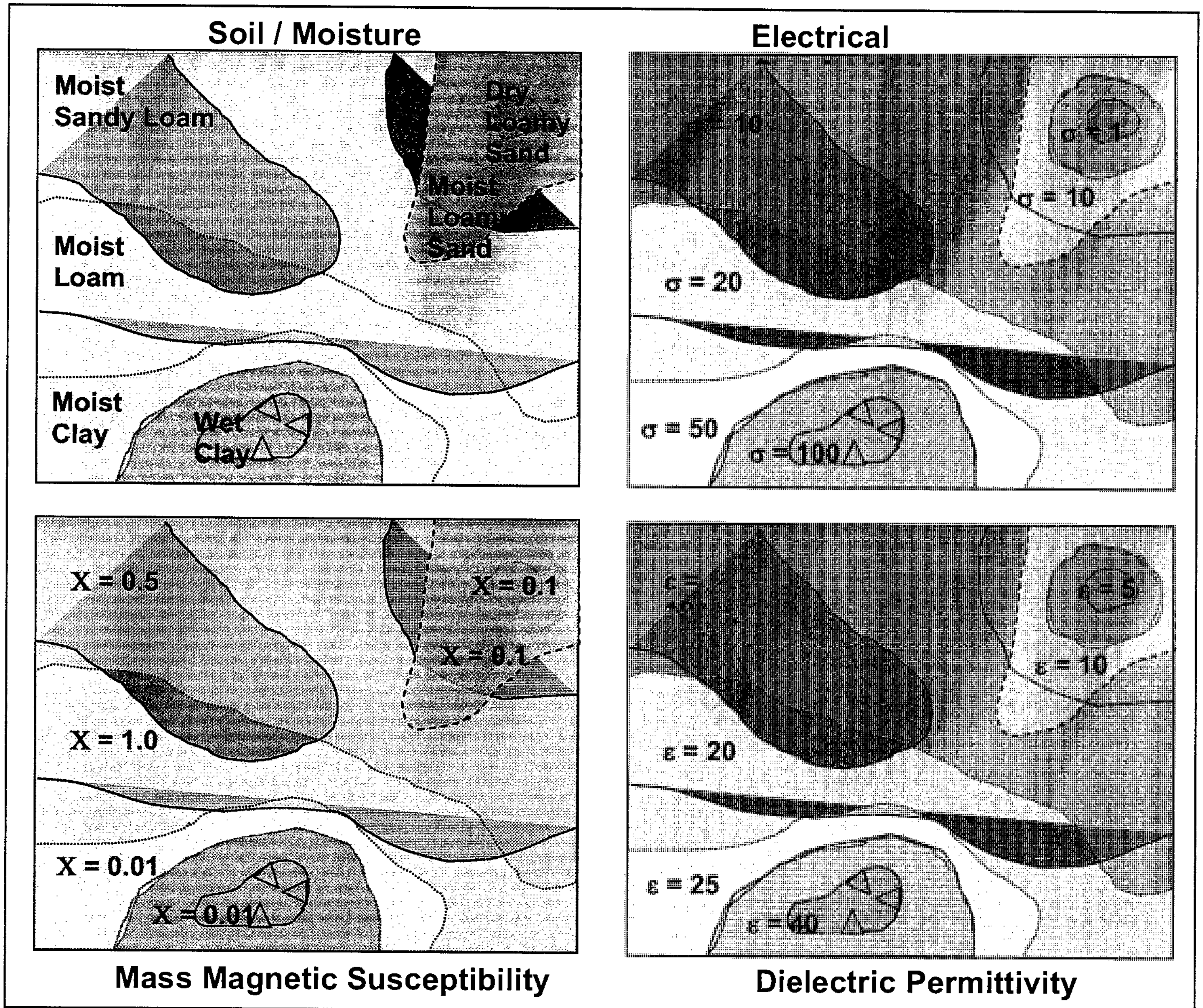


Figure 37. Geophysical parameters assigned to areas having different soil types and moisture conditions

Task 5: Determine sensor type, platform, spatial sampling

Sensor and platform selection. Once the geo-environmental background has been identified, the selection of geophysical sensors and platforms can proceed. Table 18 indicates which sensor and platform are applicable for the different vegetative and topographical conditions. This table incorporates results of the former Fort Ord Ordnance Detection and Discrimination Study (ODDS) effort (USA Environmental, Inc. 2000) which developed guides for sensor selection given the ordnance size, maximum suspected depth of burial, and site obstacles (e.g. trees, terrain).

The specific type of instrument is listed for the EM sensors in Table 18 because there is a limited number of manufacturers of EM geophysical equipment that supply tools for UXO surveying, and these are the instruments commonly employed in UXO detection surveys. There are several manufacturers of magnetometers that are suitable for UXO surveys. Examples of quasi-continuous measuring magnetometers are G-858, GSM-19, SMARTMAG, and DIMADS; sweep mode magnetometers include GA-52/Cx and generally the quasi-continuous measuring magnetometers.

Figure 38 shows the topography/vegetation overlay for the example in Figure 36. The information in this overlay is used to extract a listing of the sensors and platforms that have possible application in each individual area. For example, in the area identified as having moderate slope and thin woods, all hand-held or cart/wheeled EM and magnetometer instruments listed could be used.

Application of Table 18 selects sensors without consideration of the geophysical parameter characteristics of a soil. The next step is to utilize the information in Figure 37, containing the estimated values for the three primary physical parameters that influence the sensor measurement, to further refine the sensor selection for the site-specific conditions. The background magnetic susceptibility values within each area are low and should not cause any interference; therefore, a magnetometer is suitable for all areas. The electrical conductivity will not pose a problem over the majority of the site. However, in the regions where the conductivity exhibits values greater than 50 mS/m, the EM instruments will be influenced to some degree. In particular, the frequency domain EM (FDEM) will be affected more than the time domain EM systems. The FDEM system may compensate for some of the interference by judicious selection of measurement frequencies. In the wet area, where the conductivity is 100 mS/m, all EM systems will have difficulty in achieving sufficient depth of investigation for general UXO detection.

Table 18
Geophysical Sensor Selection

Sensor	Ordnance Size		Ordnance Depth		Vegetation Density					
	Small	Large	Shallow	Deep	None/Minimal	Short Grass/Brush, height ≤ 0.3 m	Moderate Grass/Brush, height 0.3 to 0.6 m	Tall Grass/Heavy Brush, height ≥ 0.6 m	Thin Woods, trees > 1 m separation	Thick Woods, trees < 1 m separation
Magnetometer--quasi-continuous measurement	X	X	X	X	X	X	X	X	X	X
Magnetometer--sweep	X	X	X	X	X	X	X	X	X	X
EM-61		X	X	X	X	X	X[1]		X	
EM-61HH	X	X	X		X	X			X	X
NanoTEM (prototype)	X	X	X		X	X			X	
GEM-3 (prototype)	X	X	X		X	X	X	X	X	X
Airborne Magnetometer		X	X	X	X	X	X	X		
Airborne EM		X	X	X	X	X	X	X		
GPR	X	X	X	X	X	X			X	
Platform										
Hand-held					X	X	X	X	X	X
Cart/Wheeled					X	X			X	
Vehicle Towed					X	X				
Airborne					X	X	X	X		

(Continued)

[1]no wheels mode

Table 18 (Concluded)

Sensor	Ordnance Size		Ordnance Depth		Topography					
	Small	Large	Shallow	Deep	Flat/Gently Sloping, < 2 deg	Moderate Slope, 2 to 5 deg	Steep Slope, > 5 deg	Rolling	Hilly	Mountainous
Magnetometer--quasi-continuous measurement	X	X	X	X	X	X	X	X	X	X
Magnetometer--sweep	X	X	X	X	X	X	X	X	X	X
EM-61		X	X	X	X	X		X		
EM-61HH	X	X	X		X	X		X		
NanoTEM (prototype)	X	X	X		X	X		X		
GEM-3 (prototype)	X	X	X		X	X	X	X		X
Airborne Magnetometer		X	X	X	X	X	X	X	X	X
Airborne EM		X	X	X	X	X	X	X	X	X
GPR	X	X	X	X	X	X		X	X	
Platform										
Hand-held					X	X	X	X	X	X
Cart/Wheeled					X	X		X		
Vehicle Towed					X	X		X		
Airborne					X	X	X	X	X	X

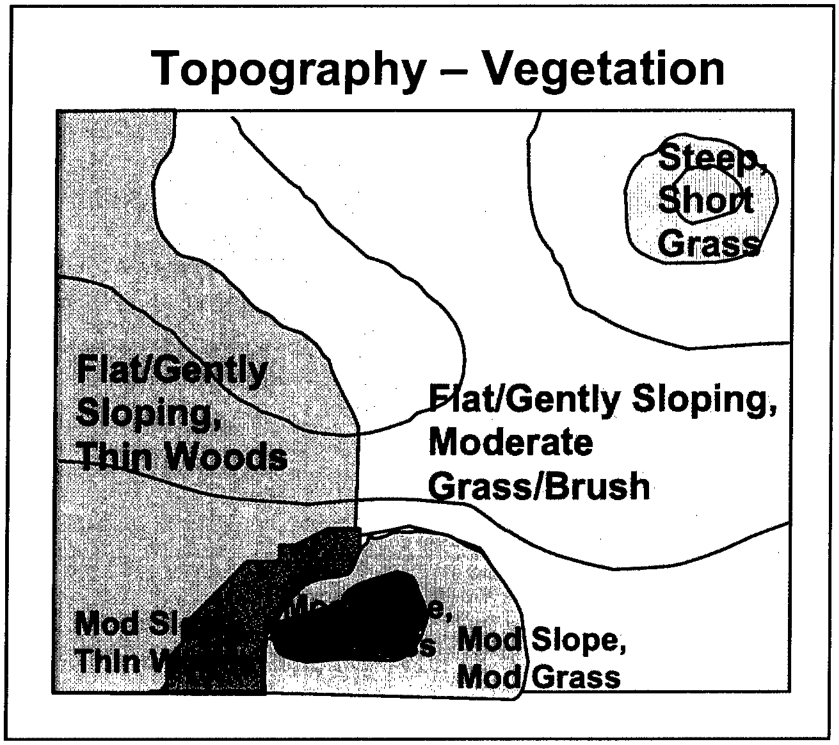


Figure 38. Overlay showing intersection of topography and vegetation layers for scenario in Figure 36

Spatial sampling. The spatial sampling recommendations provided in these guidelines are based on ordnance size, suspected burial depth, and spatial wavelength. The general guidelines are based on field studies, and no attempt is made to provide sampling scenarios using statistical methods. Efforts by others, such as Doll et al. (2003b) and Pulsipher et al. (2002a, b), address techniques for obtaining statistically relevant sampling and search schemes.

The basic selection process for determining nominal survey line spacing is presented in Table 19. The line spacing chosen should be based on the smallest ordnance to be detected within an area. If using a magnetometer in sweep mode, then the line spacing can generally be increased since the sensor is swept across an area rather than advanced along a given path. Also, vehicle and airborne platforms generally have an array of sensors so their line spacing is dictated by the array configuration. Figure 39a illustrates the importance of selecting an appropriate line spacing. Plotted in the figure are three curves showing the maximum anomaly response over a 20-mm projectile at different offset distances from the projectile. These curves show that, for a given sensor-target separation, as the distance the sensor is offset from the target center increases, the anomaly response decreases. For example, at a sensor-target separation distance of 25 cm, the peak anomaly response is 25 nT at zero offset, 17 nT at 10-cm offset, and 2.5 nT at an offset of 25-cm. This emphasizes the need to have some knowledge of the types of UXO that may be encountered and to use a line spacing that will maximize target response.

Table 19
Nominal Survey Line Spacing

Line Spacing	Ordnance Size		Ordnance Depth	
	Small, ≤ 37 mm	Large, > 37 mm	Shallow, ≤ 0.6 m	Deep, > 0.6 m
≤ 0.5 m	X			
≥ 0.5 m		X	X	
≥ 1 m		X		X

The majority of magnetometer and EM instruments used in UXO detection surveys are capable of acquiring several measurements per second. To resolve a target, at least two samples per spatial wavelength are required, regardless of background influences. The spatial wavelength can be defined as the width of the anomaly at half the maximum response. Profile plots for a 20-mm projectile are shown in Figure 39b for survey paths passing directly over the projectile and a half-meter offset. Note that for a given ordnance type, the spatial wavelength will vary with sensor-target separation distance, lateral offset, and orientation.

Task 6: Forward modeling of field response

It is advantageous to have a feel for the magnetic and EM response of an ordnance prior to any field activities, even in a minimum-noise environment. A forward modeling routine can provide estimated responses over a target at different depths and orientations within the subsurface. Target response can be viewed at minimum and maximum response orientations to aid in identifying noise levels that may hinder the UXO detection efforts. Another helpful exercise is to model the ordnance for all possible sensor choices to determine if a particular sensor may provide greater sensitivity to a target. This can aid in the final sensor selection process. The forward modeling capabilities can also be utilized to generate theoretical response curves to compare with profiles gathered over ordnance during the geophysical prove-out. Such a comparison provides insight on the true geo-environmental influence of the site.

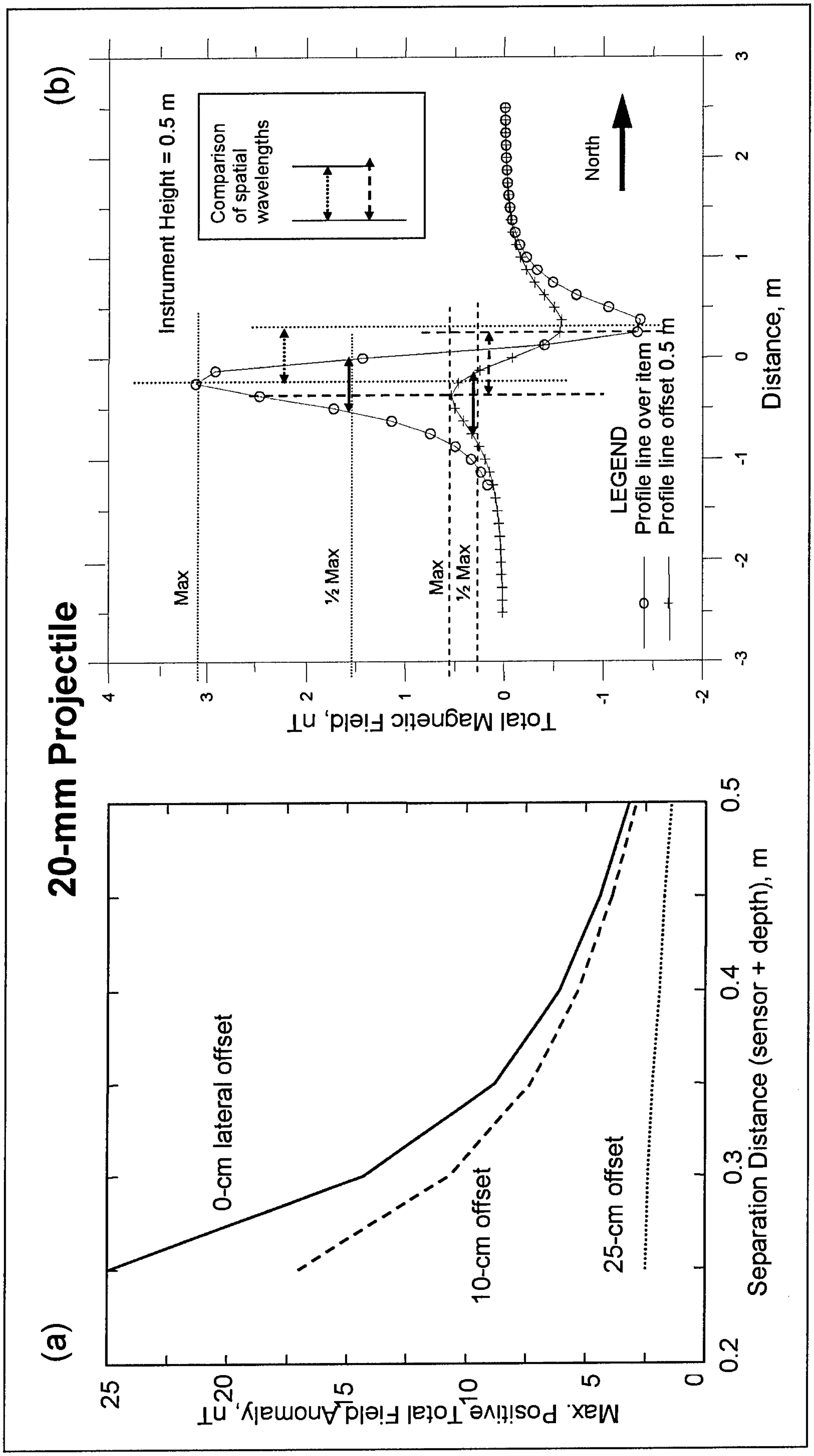


Figure 39. Plots illustrating the importance of selecting a suitable line spacing (a) and along-line sampling interval (b)

Phenomenological summary

A summary of the phenomenological evaluation is provided in Figure 40 and Table 20. Ordnance type and depth of burial are not addressed in the summary. Figure 40 shows the 11 areas that result from the intersection of the topography, vegetation, soil, and moisture layers for the scenario in Figure 36. Table 20 summarizes the physical characteristics, geophysical parameters, and possible sensors and platforms for each area determined using the phenomenological approach. The summary provides the UXO site manager with a listing of site factors that influence the detection of UXO. It can be used as an initial guide for estimating survey costs and planning the geophysical prove-out. In addition, it provides supplemental information for methods that statistically determine optimal search and sampling plans.

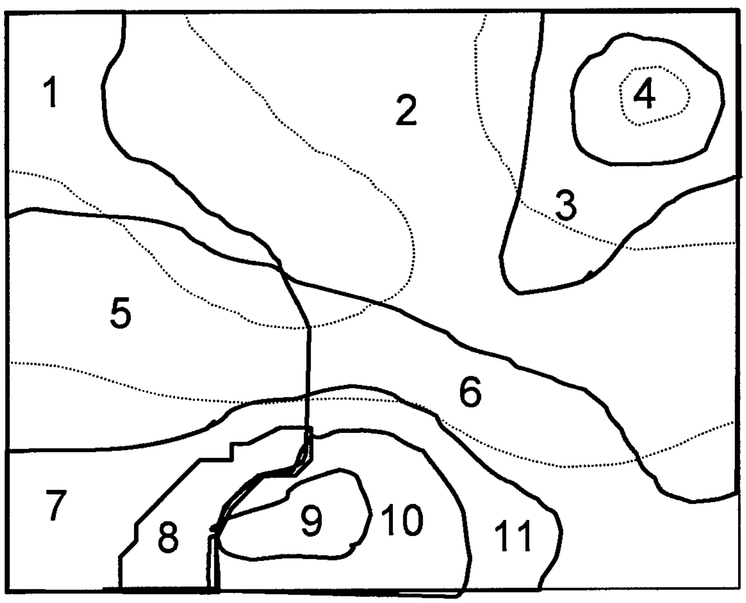


Figure 40. Areas having different topography, vegetation, soil, and moisture characteristics for the scenario in Figure 36. Refer to Table 20 for a description of each area.

Table 20
Phenomenology Example Summary[1]

Polygon	Topography	Soil Type	Vegetation	Moisture	Electrical Conductivity, mS/m	Mass Magnetic Susceptibility, 10^6 m^3/kg	Dielectric Permittivity	Sensor	Platform
1	Flat/Gently Sloping	Sandy Loam	Thin Woods	Moist	10	0.5	10	Magnetometer, EM-61, EM-61HH,NanoTEM,GEM-3	Hand-held, Cart/Wheeled
2	Flat/Gently Sloping	Sandy Loam	Moderate Grass/Brush	Moist	10	0.5	10	Magnetometer, EM-61, GEM-3, Airborne Mag, Airborne EM	Hand-held, Airborne
3	Flat/Gently Sloping	Loamy Sand	Moderate Grass/Brush	Moist	10	0.1	10	Magnetometer, EM-61, GEM-3, Airborne Mag, Airborne EM	Hand-held, Airborne
4	Steep Slope	Loamy Sand	Short Grass	Dry	1	0.1	5	Magnetometer, GEM-3, Airborne Mag, Airborne EM	Hand-held, Airborne
5	Flat/Gently Sloping	Loam	Thin Woods	Moist	20	1	20	Magnetometer, EM-61, EM-61HH,NanoTEM,GEM-3	Hand-held, Cart/Wheeled
6	Flat/Gently Sloping	Loam	Moderate Grass/Brush	Moist	20	1	20	Magnetometer, EM-61, GEM-3, Airborne Mag, Airborne EM	Hand-held, Airborne
7	Flat/Gently Sloping	Clay	Thin Woods	Moist	50	0.01	25	Magnetometer, EM-61, EM-61HH,NanoTEM,GEM-3	Hand-held, Cart/Wheeled
8	Moderate Slope	Clay	Thin Woods	Wet	100	0.01	40	Magnetometer	Hand-held, Cart/Wheeled
9	Moderate Slope	Clay	Tall Grass	Wet	100	0.01	40	Magnetometer, Airborne Mag	Hand-held, Airborne
10	Moderate Slope	Clay	Moderate Grass/Brush	Wet	100	0.01	40	Magnetometer, Airborne Mag	Hand-held, Airborne
11	Flat/Gently Sloping	Clay	Moderate Grass/Brush	Moist	50	0.01	25	Magnetometer, EM-61, GEM-3, Airborne Mag, Airborne EM	Hand-held, Airborne

[1]Does not consider ordnance factors

7 Summary

The success of a UXO detection survey is dependent, in part, on the appropriate selection of geophysical sensors used to perform the survey. The conceptual site model (CSM) is a document developed when evaluating a UXO-contaminated site and provides basic information for guiding the sensor selection process. Improvements in the CSM can be achieved through the incorporation of phenomenological information prior to executing the geophysical prove-out. The basic premise for considering site phenomenology is that the geologic and cultural makeup of a site is a primary influence on what the geophysical sensor measures. The Phenomenological Evaluation process evaluates a variety of factors that should be considered during the sensor selection process, including physical characteristics of a site, geophysical properties of the soil/rock, ordnance types, and depth of burial.

The Phenomenological Evaluation is a six-step process. The first step involves gathering geologic information to supplement that in the CSM. In step 2 the site is subdivided into areas that have similar physical characteristics based on topography, vegetation, soil type, and moisture regime. During the third step, values are assigned to the three geophysical parameters (electrical conductivity, magnetic susceptibility, dielectric permittivity) relevant to the geophysical sensors. The type of ordnance and expected depth of burial are addressed in step 4. In step 5 the type of sensor, platform, and nominal spatial sampling suitable for use in each subdivision are determined based on the four physical characteristics (topography, vegetation, soil type, and moisture). The final step allows forward modeling of senor response to targets at different orientations and burial depths.

The resultant of the Phenomenological Evaluation is a table summarizing, for each subdivision, the area's physical characteristics, representative values of electrical conductivity, magnetic susceptibility, and dielectric permittivity and a listing of geophysical sensors and platforms that could be employed.

References

Adley, M.D., Berger, R.P., Cargile, J.D., White, H.G., and Creighton, D.C. (1997). "Three-dimensional projectile penetration into curvilinear geologic/structural targets: User's guide for PENCRV3D," Technical Report SL-97-1, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Annan, P. (2002). "*Ground penetrating radar workshop notes*," Sensors and Software, Inc., Mississauga, Ontario, Canada.

Archie, G.R. (1942). "The electrical resistivity log as an aid in determining some reservoir characteristics." *Petrology Transactions of the AIME* 146, 54-62.

Arcone, S.A., O'Neill, K., Delaney, A.J., and Sellmann, P. (2000). "UXO detection at Jefferson Proving Ground using ground-penetrating radar," ERDC/CRREL Technical Report TR-00-5, Hanover, NH.

Briener, S. (1973). "Applications manual for portable magnetometers," GeoMetrics, Sunnyvale, CA.

Butler, Dwain K. (2003). "Magnetic background implications for UXO detection," *Journal of Applied Geophysics* (accepted for publication).

Butler, D.K, Sharp, M.K., Sjostrom, K.J., Simms, J.E., Llopis, J.L., and Fitterman, D.V. (1996). "Assessment of geophysical methods for subsurface geologic mapping, Cluster 13, Edgewood Area, Aberdeen Proving Ground, Maryland," Technical Report GL-96-17, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Butler, D.K., Cespedes, E.R., Cox, C.B., and Wolfe, P.J. (1998). "Multisensor methods for buried unexploded ordnance detection, discrimination, and identification," Technical Report SERDP-98-10, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Butler, D.K., Llopis, J.L., and Simms, J.E. (1999). "Phenomenological investigations of the Jefferson Proving Ground UXO Technology Demonstrations," Technical Report GL-99-7, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Cole, K.S., and Cole, R.H. (1941). "Dispersion and absorption in dielectrics," *Journal of Chemical Physics* 9, 341-51.

Crull, M., Taylor, L., and Tipton, J. (1999). "Estimating ordnance penetration into earth," *Proceedings of the UXO Forum 99*. Atlanta, Georgia, 25-27 May 1999.

Curtis, J.O. (2001). "Moisture effects on the dielectric properties of soils," *IEEE Transactions on Geoscience and Remote Sensing* 39, 125-28.

Dearing, J. (1994). *Environmental magnetic susceptibility: Using the Bartington MS2 system*. Chi Publishing, Kenilworth, UK.

Doll, W.E., Gamey, T.J., Beard, L.P., Bell, D.T., and Holladay, J.S. (2003a). "Recent advances in airborne survey technology yield performance approaching ground-based surveys," *The Leading Edge* 22(5), 420-25.

Doll, W. E., Wolf, D.A., Morris, M., and Butler, D.K. (2003b). "Spatial statistical model and optimal survey design for rapid geophysical characterization of UXO sites," Final Report, SERDP Project CU-1201.

Durrett, R.E. and Matuska, D.A. (1972). "HULL." Air Force Weapons Laboratory.

Edmundson, H.N. (1988). "Archie's Law: Electrical conduction in clear, water-bearing rock," *The Technical Review* 36, 4-13.

Everett, J.B., and Curtis, J.O. (1996). "A prototype microwave probe and reflectometer for in situ measurement of soil electrical properties," Miscellaneous Paper EL-96-1, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Everett, M., and Weiss, C. (2001). "Near-surface electromagnetic responses: Geological noise or fractal signals?" *Expanded Abstracts*. 71st Annual Internation Meeting, Society of Exploration Geophysicists, 1427-30.

Golder Associates. (1999). "Soil properties and GPR detection of landmines: A basis for forecasting and evaluation of GPR performance," Contract Report DRES CR 2000-091, Defense Research Establishment Suffield, Canada.

Guéguen, Y., and Palciauskas, V. (1994). *Introduction to the physics of rocks*. Princeton University Press, Princeton, NJ.

Hoekstra, P., and McNeill, D. (1973). "Electromagnetic probing of permafrost," *Proceedings Second International Conference On Permafrost*. National Academy of Sciences, Washington, DC, 517-26.

Jet Propulsion Laboratory. (1995). "Sensor technology assessment for ordnance and explosive waste detection and location," JPL D-11367 Revision B, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA.

Keller, G.V. (1989). "Section V: Electrical properties," *CRC practical handbook of physical properties of rocks and minerals.* R.S. Carmichael, ed., CRC Press, 361-427.

Khadr, N. (1997). "Maui subsurface geophysical test results," AETC Report VA-072-96-TR, February 25, 1997, AETC, Inc., Arlington, VA.

Khadr, N., Bell, T., Williams, S., and Bacon, W.B. (1997). "UXO detection in highly magnetic soils," *Proceedings of the UXO forum 97.* Anaheim, CA, 222-28.

King, R.W.P., and Smith, G.S. (1981). *Antennas in matter: Fundamentals, theory and applications.* MIT Press, Cambridge, MA.

Klein, K., and Santamarina, J. C. (2000). "Ferromagnetic inclusions in geomaterials – implications," *ASCE Geotechnical Journal* 162, 167-79.

Knight, R., Tercier, P., and Jol, H. (1997). "The role of ground-penetrating radar and geostatistics in reservoir description," *The Leading Edge* 16(11), 1576-82.

Knight, R.J., and Endres, A.L. (2004). "An introduction to rock physics principles for near-surface geophysics." *Near-surface geophysics: Volume 1, concepts and fundamentals.* D.K. Butler, ed., Society of Exploration Geophysicists, Tulsa, OK.

Kuenen, P.H. (1956). "Experimental abrasion of pebbles: 2. Rolling by current," *Journal of Geology* 64, 336-68.

McDonald, J.R., and Nelson, H.H. (1999). "Results of the MTADS technology demonstration #3," NRL/PU/6110-99-375, Naval Research Laboratory, Washington, DC.

McFee, J.E., and Das, Y. (1990). "A multipole expansion model for compact ferrous object detection." *Proceedings of the NATEM Symposium on Antenna Technology and Applied Electromagnetics.* Manitoba, Canada, 633-38.

Mualem, Y., and Friedman, S.P. (1991). "Theoretical prediction of electrical conductivity in saturated and unsaturated soil," *Journal of Water Resources Research* 27, 2771-77.

NDCEE. (2003). "Unexploded Ordnance (UXO) Task 307; Subtask 4: UXO Recovery Database" (Computer Software), Limited-access database visited September 24th, 2003. http://uxords.ctcgsc.org.

Olhoeft, G.R. (1978). "Electrical properties of permafrost," *Proceedings Third International Conference on Permafrost.* Edmonton, Canada, Ottawa, National Research Council, July, 1978. Vol. 1, 127-31.

Olhoeft, G.R. (1980). "Electrical properties of rocks." *Physical properties of rocks and minerals*. Y.S. Touloukian, W.R. Judd, and R.F. Roy, ed., Hemisphere Publishing Corp., 257-329.

Olhoeft, G.R., and Strangway, D.W. (1974). "Magnetic relaxation and the electromagnetic response parameter," *Geophysics* 39(3), 302-11.

O'Neill, K., Sun, K., Shubitidze, F., Shamatava, I., Curtis, J.O., and Simms, J.E. (2002). "UXO discrimination: Near field, heterogeneous, and multiple objects," UXO/Countermine Forum 2002 Proceedings, 3-6 September 2002, Orlando, FL.

Palacky, G.J. (1989). "Characteristics of geologic targets." *Electromagnetic theory in applied geophysics*. M. N. Nabighian, ed., Society of Exploration Geophysicists, Tulsa, OK.

Pasion, L.R., Billings, S., and Oldenburg, D.W. (2002). "Evaluating the effects of magnetic susceptibility in UXO discrimination problems," *Proceedings of the symposium on the application of geophysics to engineering and environmental problems (SAGEEP)*. Las Vegas, Nevada, 12 February 2002.

Pulsipher, B.A., Wilson, J.E., Gilbert, R.O., and Hassig, N.L. (2002a). "Sequential and adaptive sampling approaches within Visual Sample Plan (VSP) in support of dynamic field activities." 21st Annual National Conference on Managing Environmental Quality Systems, Environmental Protection Agency, Washington, DC, 173-78.

Pulsipher, B.A., Gilbert, R.O., and Wilson, J.E. (2002b). "Statistical tools for designing initial and post-removal UXO characterization surveys," *The UXO/Countermine Forum*, The UXO/Countermine Forum, Orlando, FL.

Scott, W.J., and Kay, A.E. (1988). "Earth resistivities of Canadian soils," Project Number: 143 T 250, Canadian Electric Association, Montreal, Vol. 1.

Scott, J.H., Sellmann, P.V., and Hunter, J.A. (1990). "Geophysics in the study of permafrost," *Geotechnical and environmental geophysics*, S. Ward, ed., Society of Exploration Geophysicists, Tulsa, OK.

Sharp, M.K., Butler, D.K., and Sjostrom, K.J. (1999). "Integrated geophysical methods for subsurface geologic mapping utilizing high-resolution transient electromagnetic soundings," *Journal of Environmental and Engineering Geophysics* 4, 57-70.

Siddiqui, S.I., Drnevich, V.P., and Deschamps, R.J. (2000). "Time domain reflectometry development for use in geotechnical engineering," *Geotechnical Testing Journal* GTJODJ 23, 9-20.

Simms, J.E., Butler, D.K., and Powers, M.H. (1995). "Full waveform inverse modeling of ground penetrating radar data: An initial approach," Miscellaneous Paper GL-95-4, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Thiel, G.A. (1941). "The relative resistance to abrasion of mineral grains of sand size," *Journal of SedimentaryPetrology* 10, 103-24.

Topp, G.C., Davis, J.L., and Annan, A.P. (1980). "Electromagnetic determination of soil water content: Measurement in coaxial transmission lines," *Water Resources Research* 16, 574-82.

USA Environmental, Inc. 2000. "Ordnance and explosives remedial investigation/feasibility study (RI/FS) former Fort Ord, ordnance detection and discrimination study, static test technical memorandum," 27 July 2000.

U.S. Army Corps of Engineers. (2000). "Ordnance and explosives response," Engineer Manual EM 1110-1-4009, 23 June 2000.

U.S. Army Engineering and Support Center, Huntsville. (2002). "Technical manual for footprint analysis," Draft Report.

U.S. Department of the Army. (1986). "Fundamentals of protective design for conventional weapons," Technical Manual TM 5-855-1, 3 November 1986.

U.S. Environmental Protection Agency. (2002). "Handbook on the management of ordnance and explosive at closed, transferring, and transferred ranges and other sites (Interim Final)," February 2002.

Walden, J., Oldfield, F., and Smith, J.P., eds. (1999). "Environmental magnetism: A practical guide," Technical Guide No. 6, Quaternary Research Association, London.

Ward, S.H., and Hohmann, G.W. (1989). "Electromagnetic theory for geophysical applications." *Electromagnetic methods in applied geophysics*. M. N. Nabighian, ed., Society of Exploration Geophysicists, Tulsa, OK.

Waxman, M.H., and Smits, L.J.M. (1968). "Electrical conductivities in oil-bearing shaly sands," *Journal of the Society of Petroleum Engineers* 8, 107-22.

Wharton, R.P., Hazen, G.A., Rau, R.N., and Best, D.L. (1980). "Electromagnetic propagation logging: Advances in technique and interpretation," Society of Petroleum Engineers, Paper 9267.

Appendix A
Summary of Data Source Information

SOURCE	CONTACT	DATA DESCRIPTION
Geological Survey of Alabama P.O. Box 0 Tuscaloosa, AL 35486-9780	205-349-2852 gsa@ogb.gsa.state.al.us http://www.gsa.state.al.us/	Geologic map of Alabama, publication list, GIS data, interactive maps, downloadable data
Alabama Department of Transportation 1409 Coliseum Blvd Montgomery, AL	334-242-6358 http://www.dot.state.al.us/	Geological and engineering boring logs, geological maps and cross-sections, groundwater tests, physical and engineering properties of soils and rocks
Alabama State Conservationist (NRCS) 3381 Skyway Dr, P.O. Box 311 Auburn, AL 36830-0311	334-887-4517 http://www.al.nrcs.usda.gov	Soil surveys/soil data
Alaska Division of Geological and Geophysical Surveys 794 University Ave Suite 200 Fairbanks, AK 99709	907-451-5000 dggs@dnr.state.ak.us http://www.dggs.dnr.state.ak.us/	Geologic map of Alaska, publication list, geophysical information, some electronic data available, geochemical data, mineral industry publication on-line
Department of Natural Resources **Alaska Division of Oil and Gas** 550 West 7th Ave, Suite 800 Anchorage, AK 99501	907-269-8800 http://www.dog.dnr.state.ak.us/oil/	Geology, surface and ground water, soil science, earthquake engineering, and mineral and energy resources oil and gas leases, and publications
Department of Natural Resources **Alaska Division of Mining and Water Management** Robert A. Atwood Building, 550 West 7th Ave, Anchorage, AK 99501	http://www.dnr.state.ak.us/mine_wat/index.htm	Mining regulations, lease offerings, mine permits, information on the Alaska hydrologic survey
Alaska Department of Transportation and Public Facilities 3132 Channel Dr. Juneau AK 99801-7898	907-465-3900 http://www.dot.state.ak.us/	Geological and engineering boring logs, geological maps and cross-sections, groundwater tests, physical and engineering properties of soils and rocks
Alaska State Conservationist (NRCS) 800 West Evergreen, Atrium Building, Suite 100 Palmer, AK 99645-6539	907-761-7700 http://www.ak.nrcs.usda.gov	Soil surveys/soil data
Arizona Geological Survey 416 West Congress, #100 Tucson, AZ 85701	520 770-3500 http://www.azgs.state.az.us/	Geological maps (digital), on-line publications
Arizona Department of Transportation **ADOT Construction Group** Ron Williams, Assistant State Engineer 206 South 17th Ave, MD 172A Phoenix, AZ 85007	602-712-7323 http://www.dot.state.az.us/index.html	Geological and engineering boring logs, geological maps and cross-sections, groundwater tests, physical and engineering properties of soils and rocks

SOURCE	CONTACT	DATA DESCRIPTION
USDA, Arizona Natural Resources Conservation Service (NRCS) 3003 North Central Ave, Suite 800 Phoenix, AZ 85012-2945	602-280-8801 http://www.az.nrcs.usda.gov	Soil surveys/soil data
Arkansas Geological Commission Vardelle Parham Geology Center 815 West Roosevelt Rd Little Rock, AR 72204	501-296-1877 agc@mail.state.ar.us http://www.state.ar.us/agc/	Geology, surface and groundwater, and mineral and energy resources
Arkansas State Highway and Transportation Department 10324 Interstate 30 Little Rock, Arkansas 72211	501-569-2000 http://www.ahtd.state.ar.us/AHTD.htm	Geological and engineering boring logs, geological maps and cross-sections, groundwater tests, physical and engineering properties of soils and rocks
Arkansas State Conservationist (NRCS) Federal Building, Room 3416, 700 West Capitol Ave, Little Rock, AR 72201-3228	501-301-3100 http://www.ar.nrcs.usda.gov/	Soil surveys/soil data
California Environmental Protection Agency 555 Capitol Mall, Suites 235 and 525 Sacramento, CA 95814	916-445-3846 http://www.calepa.ca.gov/	Regulations, hot topics, publications
California State Water Resources Control Board P.O. Box 100 Sacramento, CA 95814	916-657-2390 http://www.swrcb.ca.gov/	Surface and groundwater quality
California Resources Agency	http://ceres.ca.gov/cra/	
California Department of Conservation 801 K St, MS 24-01 Sacramento, CA 95814-3501	916-322-1080 http://www.consrv.ca.gov/	Soil surveys/soil data
California Division of Mines and Geology 801 K St, MS 14-33 Sacramento, CA 95814-3533	916-445-5716 http://www.consrv.ca.gov/dmg/	Geology, mineral resources, seismic hazards, and earthquake engineering
California Division of Oil, Gas, and Geothermal Resources 801 K St, MS 20-20 Sacramento, CA 95814-3520	916-323-1777 http://www.consrv.ca.gov/dog/	Petroleum and geothermal resources
California Office of Mine Reclamation 801 K St, MS 09-06 Sacramento, CA 95814-3506	916-323-9198 http://www.consrv.ca.gov/omr/	Reclamation of mined land
California State Mining and Geology Board 801 K St, MS 09-06 Sacramento, CA 95814-3506	916-322-1082 http://www.consrv.ca.gov/smgb/	Mining and geological policy; advisory and regulatory responsibilities related to the Division of Mines and Geology and the Office of Mine Reclamation

SOURCE	CONTACT	DATA DESCRIPTION
California Department of Water Resources P.O. Box 942836 Sacramento, CA 94236-0001	916-653-5791 http://wwwdwr.water.ca.gov/	Groundwater, flood control, and surface water supply
California Seismic Safety Commission 1900 K St, Suite 100, Sacramento, CA 95814	916-322-4917 http://www.seismic.ca.gov/	Earthquake-related policy
California Department of Transportation 1120 N St, Sacramento, CA	916-654-5266 http://www.dot.ca.gov/	Geological and engineering boring logs, geological maps and cross-sections, groundwater tests, physical and engineering properties of soils and rocks
California State Conservationist (NRCS) 430 G St #4164, Davis, CA 95616-4164	530-792-5600 http://www.ca.nrcs.usda.gov	Soil surveys/soil data
Department of Natural Resources **Colorado Geological Survey** 1313 Sherman Street, Rm 715 Denver. CO 80203	303-866-2611 http://geosurvey.state.co.us	Geology, surface and ground water, mineral and energy resources, avalanche forecasting, and waste disposal
Colorado State Conservationist (NRCS) 655 Parfet St, Room E200C, Lakewood, CO 80215-5517	720 544-2810 http://www.co.nrcs.usda.gov	Soil surveys/soil data
Connecticut Department of Environmental Protection 79 Elm St, Hartford, CT 06106-5127	860-424-3540 http://dep.state.ct.us/cgnhs/	
Connecticut Department of Environmental Protection **Connecticut Natural Resources Center**	http://dep.state.ct.us/cgnhs/index.htm	
Connecticut Department of Environmental Protection **Connecticut Geological and Natural History Survey**	http://dep.state.ct.us/cgnhs/index.htm	Geology, surface and ground water, soil science, biology, and mineral and energy resources
Connecticut Department of Transportation 2800 Berlin Turnpike, Newington, CT 06131-7546	860-594-2000 http://www.dot.state.ct.us/	Geological and engineering boring logs, geological maps and cross-sections, groundwater tests, physical and engineering properties of soils and rocks
Connecticut State Conservationist (NRCS) 344 Merrow Road Suite A Tolland, CT 06084-3917	860-871-4011 http://www.ct.nrcs.usda.gov/	Soil surveys/soil data
University of Delaware **Delaware Geological Survey** Delaware Geological Survey Building, Newark, DE 19716-7501	302-831-2833 http://www.udel.edu/dgs/	Geology, hydrology, geophysics

SOURCE	CONTACT	DATA DESCRIPTION
Delaware Department of Transportation P.O. Box 778, Dover, DE 19903	302-760-2080 http://www.state.de.us/deldot/	Geological and engineering boring logs, geological maps and cross-sections, groundwater tests, physical and engineering properties of soils and rocks
Delaware State Conservationist (NRCS) 1203 College Park Dr, Suite 101, Dover, DE 19904-8713	302-678-4160 http://www.de.nrcs.usda.gov	Soil surveys/soil data
District of Columbia State Conservationist John Hanson Business Center, 339 Busch's Frontage Rd, Suite 301E, Annapolis, MD 21401	410-757-0861 see http://www.md.nrcs.usda.gov	Soil surveys/soil data
Florida Department of Natural Resources **Florida Geological Survey** **Gunter Bldg MS #720** 903 West Tennessee St, Tallahassee, FL 32304-7700	850-488-4191 http://www.dep.state.fl.us/geo/	Geology, groundwater, mineral and petroleum resources
Florida Department of Transportation 605 Suwannee St, MS-69, Tallahassee, FL 32399-0450	850-414-4364 http://www.dot.state.fl.us/	Geological and engineering boring logs, geological maps and cross-sections, groundwater tests, physical and engineering properties of soils and rocks
Florida State Conservationist (NRCS) 2614 NW 43rd St, P.O. Box 141510, Gainesville, FL 32614-1510	352-338-9500 http://www.fl.nrcs.usda.gov	Soil surveys/soil data
Georgia Department of Natural Resources	http://www.ganet.org/dnr/	
Georgia Department of Natural Resources **Environmental Protection Division**	http://www.ganet.org/dnr/environ/	
Georgia Department of Natural Resources **Environmental Protection Division** **Georgia Geologic Survey** 19 Martin Luther King, Jr., Dr, SW, Room 400, Atlanta, GA 30334	404-656-3214 http://ggsstore.dnr.state.ga.us/	Geology, minerals, surface and ground water
Georgia Department of Natural Resources **Land Protection Branch**	http://www.ganet.org/dnr/environ/	
Georgia Department of Natural Resources **Water Protection Branch**	http://www.ganet.org/dnr/environ/	

SOURCE	CONTACT	DATA DESCRIPTION
Georgia Department of Natural Resources **Water Resources Branch**	http://www.ganet.org/dnr/environ/	
Georgia Department of Transportation	404-656-5187 http://www.dot.state.ga.us/	Geological and engineering boring logs, geological maps and cross-sections, groundwater tests, physical and engineering properties of soils and rocks
Georgia State Conservationist (NRCS) **Robert G. Stephens** Federal Building, Stop 200, 355 East Hancock Ave, Athens, GA 30601-2769	706-546-2272 http://www.ga.nrcs.usda.gov/	Soil surveys/soil data
USGS state representative to Hawaii **677 Ala Moana Blv, Suite 415** **Honolulu, HI, 96813**	http://www.hawaii.gov/dlnr/	
Hawaii Department of Land and Natural Resources **Division of Water and Land Development** P.O. Box 373, Honolulu, HI 96809	808-587-2400 http://geology.wr.usgs.gov/docs/stateinfo/HI.html	Geologic mapping data
Hawaii Department of Transportation 869 Punchbowl St, Honolulu, HI 96813	808-587-2160, Public Affairs Office dotpao@exec.state.hi.us http://www.state.hi.us/dot/index.htm	Geological and engineering boring logs, geological maps and cross-sections, groundwater tests, physical and engineering properties of soils and rocks
Hawaii State Conservationist P.O. Box 50004, Room 4-118, 300 Ala Moana Blvd, Honolulu, HI 96850-0002	808-541-2600	Soil surveys/soil data
University of Idaho **Idaho Geological Survey** **Morrill Hall, Third Floor** **P.O. Box 443014** Moscow, ID 83844-3014	208-885-7991 http://www.idahogeology.org/	Geology and mineral resources
Idaho Transportation Department **Division of Highways** 3311 W. State St, P.O. Box 7129, Boise, ID 83707-1129	208-334-8803 http://www2.state.id.us/itd/about.htm	Geological and engineering boring logs, geological maps and cross-sections, groundwater tests, physical and engineering properties of soils and rocks
Idaho State Conservationist (NRCS) 9173 West Barnes Dr, Suite C, Boise, ID 83709-1574	208-378-5700 http://www.id.nrcs.usda.gov/	Soil surveys/soil data

SOURCE	CONTACT	DATA DESCRIPTION
Illinois Department of Energy and Natural Resources **Illinois State Geological Survey** 615 East Peabody Dr, Champaign, IL 61820	217-333-4747 http://www.isgs.uiuc.edu/isgshome.html	Geology, groundwater, and mineral and energy resources
Illinois Department of Energy and Natural Resources **Illinois State Water Survey**	http://www.sws.uiuc.edu	
Illinois Department of Energy and Natural Resources **Illinois State Water Survey** **Hydrology Division**	http://www.sws.uiuc.edu/hydro/	
Illinois Department of Transportation **2300 S. Dirksen Parkway** **Springfield, IL 62764**	217 782-7820 http://www.dot.state.il.us/	Geological and engineering boring logs, geological maps and cross-sections, groundwater tests, physical and engineering properties of soils and rocks
Illinois State Conservationist (NRCS) 2118 W Park Court Champaign, IL 61821	217-353-6600 http://www.il.nrcs.usda.gov/	Soil surveys/soil data
Indiana Department of Natural Resources	http://www.state.in.us/dnr/	
Indiana Department of Natural Resources **Division of Oil and Gas**	http://www.state.in.us/dnroil/	
Indiana Department of Natural Resources **Division of Reclamation**	http://www.state.in.us/dnr/reclamation/	
Indiana Department of Natural Resources **Division of Soil Conservation**	http://www.state.in.us/dnr/soilcons/	
Indiana Department of Natural Resources **Division of Water**	http://www.state.in.us/dnr/water/	
Indiana Department of Natural Resources **Natural Resources Commission**	http://www.ai.org/nrc/	Water, soil, and mine land reclamation
Indiana Geological Survey 611 North Walnut Grove, Bloomington, IN 47405	812-855-7636 igsinfo@indiana.edu http://adamite.igs.indiana.edu/	Geology, mineral and petroleum resources
Indiana Department of Transportation 100 N. Senate Ave, Room IGCN 755 Indianapolis, IN 46204	317-232-5533 indot@ai.org http://www.ai.org/dot/	Geological and engineering boring logs, geological maps and cross-sections, groundwater tests, physical and engineering properties of soils and rocks

SOURCE	CONTACT	DATA DESCRIPTION
Indiana State Conservationist (NRCS) 6013 Lakeside Blvd, Indianapolis, IN 46278	317-290-3200 http://www.in.nrcs.usda.gov/	Soil surveys/soil data
Iowa Department of Natural Resources **Energy and Geological Resources Division** **Geological Survey Bureau** 109 Trowbridge Hall, Iowa City, IA 52242-1319	319-335-1575 webmanager@igsb.uiowa.edu http://www.igsb.uiowa.edu/	Geology, mineral and water resources
Iowa Department of Transportation 800 Lincoln Way, Ames, IA 50010	515-239-1101 http://www.dot.state.ia.us/	Geological and engineering boring logs, geological maps and cross-sections, groundwater tests, physical and engineering properties of soils and rocks
Iowa State Conservationist (NRCS) 210 Walnut St, 693 Federal Building, Des Moines, IA 50309-2180	515-284-4260 http://www.ia.nrcs.usda.gov/	Soil surveys/soil data
University of Kansas **Kansas Geological Survey** 1930 Constant Ave, West Campus, Lawrence, KS 66047-3726	785 864-3965 http://www.kgs.ukans.edu/kgs.html	Geology, ground water, mineral resources; seismicity
Kansas Department of Transportation 915 Harrison, Room 754, Docking State Office Building Topeka, KS 66612-1568	785-296-3585 http://www.ink.org/public/kdot/	Geological and engineering boring logs, geological maps and cross-sections, groundwater tests, physical and engineering properties of soils and rocks
Kansas State Conservationist (NRCS) 760 South Broadway, Salina, KS 67401-4642	785 823-4500 http://www.ks.nrcs.usda.gov/	Soil surveys/soil data
University of Kentucky **Kentucky Geological Survey** 228 Mining and Mineral Resources Building, Lexington, KY 40506-0107	606-257-5500 http://www.uky.edu/KGS/home.htm	Geology, mineral and energy resources, and surface and ground water
Kentucky Transportation Cabinet State Office Building, 501 High St, Frankfort, KY 40622	502-564-4890, Main Office http://www.kytc.state.ky.us/	Geological and engineering boring logs, geological maps and cross-sections, groundwater tests, physical and engineering properties of soils and rocks
Kentucky State Conservationist (NRCS) 771 Corporate Dr, Suite 110, Lexington, KY 40503-5479	859 224-7350 http://www.ky.nrcs.usda.gov/	Soil surveys/soil data
Louisiana Department of Natural Resources P.O. Box 94396, Baton Rouge, LA 70804-9396	225-342-4500 http://www.dnr.state.la.us/	Geology, publications

SOURCE	CONTACT	DATA DESCRIPTION
Louisiana State University **Department of Natural Resources** **208 Howe-Russell** Baton Rouge, LA 70803	225 578-5320 http://www.lgs.lsu.edu/index1.htm/	Geology, mineral and energy resources, flood control, water resources, and soil conservation.
Louisiana Department of Transportation and Development P.O. Box 94245, 1201 Capitol Access Rd, Baton Rouge, LA 70802	225-379-1100 http://www.dotd.state.la.us/	Geological and engineering boring logs, geological maps and cross-sections, groundwater tests, physical and engineering properties of soils and rocks
Louisiana State Conservationist (NRCS) 3737 Government St, Alexandria, LA 71302-3727	318-473-7751 http://www.la.nrcs.usda.gov/	Soil surveys/soil data
Maine Department of Conservation **Maine Geological Survey** 22 State House Station, Augusta, ME 04333	207-287-2801 nrimc@state.me.us http://www.state.me.us/doc/nrimc/mgs/mgs.htm	Geology, groundwater
Maine Department of Transportation 16 State House Station, Augusta, ME 04333	207-287-2551 http://www.state.me.us/	Geological and engineering boring logs, geological maps and cross-sections, groundwater tests, physical and engineering properties of soils and rocks
Maine State Conservationist (NRCS) 967 Illinois Ave, Suite 3, Bangor, ME 04401	207-990-9100, ext 3 http://www.me.nrcs.usda.gov/	Soil surveys/soil data
Maryland Department of Natural Resources	http://www.dnr.state.md.us/	
Maryland Department of Natural Resources **Maryland Geological Survey** 2300 St. Paul Street, Baltimore, MD 21218	410-554-5500 http://mgs.md.gov/	Geology; mineral, energy, surface and ground water resources; archaeology
Maryland Department of Transportation P.O. Box 8755, BWI Airport, MD 21240	888-713-1414 http://www.mdot.state.md.us/	Geological and engineering boring logs, geological maps and cross-sections, groundwater tests, physical and engineering properties of soils and rocks
Maryland State Conservationist (NRCS) J. Hanson Business Center, Ste 301E, 339 Busch's Frontage Rd, Annapolis, MD 21401-5534	410-757-0861 http://www.md.nrcs.usda.gov/	Soil surveys/soil data
Massachusetts Executive Office of Environmental Affairs 251 Causeway Street, 9th floor Boston, MA 02202	617-727-9800 http://www.magnet.state.ma.us/envir/eoea.htm	Geology, groundwater

SOURCE	CONTACT	DATA DESCRIPTION
Massachusetts Highway Department Boston Headquarters, 10 Park Plaza, Suite 3510, Boston, MA 02116	617-973-7800 http://www.magnet.state.ma.us/	Geological and engineering boring logs, geological maps and cross-sections, groundwater tests, physical and engineering properties of soils and rocks
Massachussetts State Conservationist (NRCS) 451 West St, Amherst, MA 01002-2995	413-253-4350 http://www.ma.nrcs.usda.gov/	Soil surveys/soil data
Michigan Department of Environmental Quality **Geological Survey Division** **Constitution Hall** **525 W. Allegan** P.O. Box 30256, Lansing, MI 48909-7756	517-241-1515 http://www.michian.gov.deq/ (see DEQ Division)	Geology, mineral and energy resources
Michigan Department of Transportation State Transportation Building, 425 West Ottawa St, P.O. Box 30050, Lansing, MI 48909	517-373-2090 http://www.mdot.state.mi.us/	Geological and engineering boring logs, geological maps and cross-sections, groundwater tests, physical and engineering properties of soils and rocks
Michigan State Conservationist (NRCS) 3001 Coolidge Rd, Suite 250, East Lansing, MI 48823-6350	517-324-5270 http://www.mi.nrcs.usda.gov/	Soil surveys/soil data
Minnesota Department of Natural Resources	http://www.dnr.state.mn.us/	
Minnesota Department of Natural Resources **Minerals Division** 500 Lafayette Rd, St. Paul, MN 55155-4045	612-296-4807 http://www.dnr.state.mn.us/minerals/	Mineral Resources
University of Minnesota **School of Earth Sciences** **Minnesota Geological Survey** 2642 University Avenue, St. Paul, MN 55114-1057	612-627-4780 mgs@gold.tc.umn.edu http://www.geo.umn.edu/mgs/	Geology, mineral and groundwater resources
Minnesota Department of Transportation Transportation Building, 395 John Ireland Blvd, St. Paul, MN 55155	651-296-3000 http://www.dot.state.mn.us/	Geological and engineering boring logs, geological maps and cross-sections, groundwater tests, physical and engineering properties of soils and rocks
Minnesota State Conservationist (NRCS) Farm Credit Building, Suite 600, 375 Jackson St, St. Paul, MN 55101-1854	651-602-7900 http://www.mn.nrcs.usda.gov/	Soil surveys/soil data
Mississippi Department of Environmental Quality	http://www.deq.state.ms.us/newweb/homepages.nsf	

SOURCE	CONTACT	DATA DESCRIPTION
Mississippi Department of Environmental Quality **Office of Geology** **2380 HiWay 80 West** P.O. Box 20307, Jackson, MS 39289-1307	601-961-5500 http://www.deq.state.ms.us/newweb/homepages.nsf	Geology, groundwater, mineral and energy resources
Mississippi Department of Transportation 401 North West St, Jackson, MS 39201	601-359-7004, Chief Engineer http://www.mdot.state.ms.us/	Geological and engineering boring logs, geological maps and cross-sections, groundwater tests, physical and engineering properties of soils and rocks
Mississippi State Conservationist (NRCS) Federal Building, Suite 1321, 100 West Capitol St, Jackson, MS 39269-1399	601-965-4940 http://www.ms.nrcs.usda.gov/	Soil surveys/soil data
Missouri Department of Natural Resources	http://www.dnr.state.mo.us/	
Missouri Department of Natural Resources **Division of Geology and Land Survey** **Geological Survey and Resources Division** P.O. Box 176, Jeffferson City, MO 65102	1-800-361-4827 or 573 368-2100 dnrdgls@mail.dnr.state.mo.us http://www.dnr.state.mo.us/dgls/geology/homegsrad.htm	Geology; mineral, energy, ground and surface water resources; land surveying
Missouri State Emergency Management Agency P.O. Box 116, Jefferson City, MO 65102	573-526-9100	
Missouri State Emergency Management Agency **Natural and Technological Hazards Branch** **Missouri Seismic Safety Commission**	http://www.eas.slu.edu/SeismicSafety/ http://www.state.mo.us/sema/seismic.htm	
Missouri Department of Transportation 105 West Capitol Ave, P.O. Box 270, Jefferson City, MO 65102	888-ASK-MODOT http://www.modot.state.mo.us/	Geological and engineering boring logs, geological maps and cross-sections, groundwater tests, physical and engineering properties of soils and rocks
Missouri State Conservationist (NRCS) Parkade Center, Suite 250, 601 Business Loop 70 West Columbia, MO 65203-2546	573-876-0901 http://www.mo.nrcs.usda.gov/	Soil surveys/soil data
Montana Tech **Montana Bureau of Mines and Geology** 1300 West Park St, Butte, MT 59701-8997	406-496-4167 http://mbmg.mtech.edu/	Geology; mineral, energy, and groundwater resources
Montana Department of Transportation P.O. Box 201001, 2701 Prospect Ave, Helena, MT 59620-1001	406-444-6200 http://www.mdt.state.mt.us/	Geological and engineering boring logs, geological maps and cross-sections, groundwater tests, physical and engineering properties of soils and rocks

SOURCE	CONTACT	DATA DESCRIPTION
Montana State Conservationist (NRCS) Federal Building, Room 443, 10 East Babcock St, Bozeman, MT 59715-4704	406-587-6868 http://www.mt.nrcs.usda.gov/	Soil surveys/soil data
University of Nebraska-Lincoln **Institute of Agriculture & Natural Resources** **Conservation and Survey Division** 113 Nebraska Hall, Lincoln, NE 68588-0517	402-472-3471 http://csd.unl.edu/csd.html	Geology; mineral, petroleum, soil, and water resources
Nebraska Department of Roads P.O. Box 94759, Lincoln, NE 68509-4759 1500 Highway 2, Lincoln, NE 68502	402-471-4567 http://www.dor.state.ne.us/	Geological and engineering boring logs, geological maps and cross-sections, groundwater tests, physical and engineering properties of soils and rocks
Nebraska State Conservationist (NRCS) Federal Building, Room 152, 100 Centennial Mall North Lincoln, NE 68508-3866	402-437-5300 http://www.ne.nrcs.usda.gov/	Soil surveys/soil data
University of Nevada-Reno **Nevada Bureau of Mines and Geology** **Mail Stop 178** Reno, NV 89557-0088	755-784-6691 http://www.nbmg.unr.edu/	Geology; mineral resources
Nevada Department of Transportation 1263 South Stewart St, Carson City, NV 89712	775-888-7000 info@nevadadot.com http://www.nevadadot.com/	Geological and engineering boring logs, geological maps and cross-sections, groundwater tests, physical and engineering properties of soils and rocks
Nevada State Conservationist (NRCS) 5301 Longley Lane, Bldg F, Suite 201, Reno, NV 89511-1805	702-784-5863 http://www.nv.nrcs.usda.gov/	Soil surveys/soil data
New Hampshire Department of Environmental Services P.O. Box 2008, Concord, NH 03302-2008	603-271-3406 http://www.state.nh.us/des/descover.htm	Air, waste, and water
New Hampshire Department of Transportation John O. Morton Building, 1 Hazen Dr, Concord, NH 03302-0483	603-271-3734 http://www.des.state.nh.us/	Geological and engineering boring logs, geological maps and cross-sections, groundwater tests, physical and engineering properties of soils and rocks
New Hampshire State Conservationist (NRCS) Federal Building, 2 Madbury Rd, Durham, NH 03824-2043	603-868-7581 http://www.nh.nrcs.usda.gov/	Soil surveys/soil data

SOURCE	CONTACT	DATA DESCRIPTION
New Jersey Department of Environmental Protection **Division of Science, Research and Technology** **New Jersey Geological Survey** PO Box 427, 29 Arctic Parkway, Trenton, NJ 08625-0427	609-292-1185 http://www.state.nj.us/dep/njgs/	Geology, ground and surface water
New Jersey Department of Transportation **Administrative Offices** 1035 Parkway Ave, Trenton, NJ 08625	973-770-5170, North Region 732-409-3263, Central Region 856-222-2090, South Region	Geological and engineering boring logs, geological maps and cross-sections, groundwater tests, physical and engineering properties of soils and rocks
New Jersey State Conservationist (NRCS) 1370 Hamilton St, Somerset, NJ 08873-3341	732 246-2358 http://www.nj.nrcs.usda.gov/	Soil surveys/soil data
New Mexico Tech **The New Mexico Bureau of Mines and Mineral Resources** 801 Leroy Place Socorro, NM 87801-4796	505-835-5420 http://geoinfo.nmt.edu/	Geology, mineral and energy resources, groundwater
New Mexico State Highway and Transportation Department 1120 Cerrillos Rd, P.O. Box 1149, Santa Fe, NM 87504-1149	505-827-5100 http://www.nmshtd.state.nm.us/	Geological and engineering boring logs, geological maps and cross-sections, groundwater tests, physical and engineering properties of soils and rocks
New Mexico State Conservationist (NRCS) 6200 Jefferson, NE, Suite 305, Albuquerque, NM 87109-3734	505-761-4401or 1 800 410-2067 http://www.nm.nrcs.usda.gov/	Soil surveys/soil data
New York State Geological Survey 3136 Cultural Education Center, Room 3023, Albany, NY 12230	518-474-5877 http://www.nysm.nysed.gov/geology.html	Geology, mineral resources
New York Department of Transportation Governor Harriman State Campus, Building 5, Albany, NY 12232	518-457-4422, Main Office 518-457-4712, Geotechnical Engineering Bureau http://www.dot.state.ny.us/	Geological and engineering boring logs, geological maps and cross-sections, groundwater tests, physical and engineering properties of soils and rocks
New York State Conservationist (NRCS) 441 S. Salina St, Suite 354, Syracuse, NY 13202-2450	315-477-6504 http://www.ny.nrcs.usda.gov/	Soil surveys/soil data
North Carolina Department of Environment and Natural Resources 512 North Salisbury St, P.O. Box 27687 Raleigh, NC 27611-7687	919-733-4984 http://www.ehnr.state.nc.us/EHNR/	

SOURCE	CONTACT	DATA DESCRIPTION
North Carolina Department of Environment and Natural Resources Division of Land Resources	http://www.ehnr.state.nc.us/EHNR/DLR/scr0.htm	
North Carolina Department of Environment and Natural Resources Division of Land Resources North Carolina Geological Survey 1612 Mail Service Center P.O. Box 27687, Raleigh, NC 27699-1612	919-733-2423 http://www.geology.enr.state.nc.us/	Geology; mineral and groundwater resources
North Carolina Department of Environment and Natural Resources Division of Water Quality	http://h2o.ehnr.state.nc.us/	Ground and surface water protection
North Carolina Department of Environment and Natural Resources Division of Water Resources	http://www.dwr.ehnr.state.nc.us/	Water supply, river basin management, flood control, and beach protection
North Carolina Department of Transportation 1536 Mail Service Center, Raleigh, NC 27699-1536 (MAIL) 1 S Wilmington St, Raleigh, NC 27611 (DELIVERY)	919-733-7384 State Highway Administrator lsanderson@dot.state.nc.us http://www/doh.dot.state.nc.us/	Geological and engineering boring logs, geological maps and cross-sections, groundwater tests, physical and engineering properties of soils and rocks
North Carolina State Soil Scientist (NRCS) 4405 Bland Rd, Suite 205 Raleigh, NC 27609-6293	919-873-2101 http://www.nc.nrcs.usda.gov/	Soil surveys/soil data
North Dakota Industrial Commission	http://www.state.nd.us/ndic/	
North Dakota Industrial Commission Oil and Gas Division 600 East Boulevard Ave Dept 405, Bismarck, ND 58505-0840	701-328-8020 http://explorer.ndic.state.nd.us/	Petroleum resources; oil and gas development
North Dakota Geological Survey 1016 E. Calgary Ave. Bismarck, ND 58503	701-328-8000 http://www.state.nd.us/ndgs/	Geology, mineral and petroleum resources
North Dakota State Water Commission 900 East Blvd, Bismarck, ND 58505	701-328-2750 http://www.swc.state.nd.us/	Water resources

SOURCE	CONTACT	DATA DESCRIPTION
North Dakota Department of Transportation 608 East Boulevard Ave, Dismarck, ND 58505-0700	701-328-2500, Information 701-328-4444, Infrastructure Support http://www.state.nd.us/	Geological and engineering boring logs, geological maps and cross-sections, groundwater tests, physical and engineering properties of soils and rocks
North Dakota State Conservationist (NRCS) Federal Building, P.O. Box 1458, 220 E. Rosser Ave, Room 278 Bismarck, ND 58502-1458	701-530-2000 http://www.nd.nrcs.usda.gov/	Soil surveys/soil data
Ohio Department of Natural Resources	http://www.dnr.state.oh.us/	
Ohio Department of Natural Resources **Division of Geological Survey** 4383 Fountain Square Dr, Columbus, OH 43224-1362	614-265-6576 geo.survey@dnr.state.oh.us http://www.ohiodnr..com/geo_survey/	Geology; mineral resources
Ohio Department of Natural Resources **Division of Soil and Water Conservation**	http://www.dnr.state.oh.us/odnr/soil+water/	
Ohio Department of Transportation 1980 West Broad St, Columbus, OH 43223	419-222-9055, District 1 http://www.dot.state.oh.us/	Geological and engineering boring logs, geological maps and cross-sections, groundwater tests, physical and engineering properties of soils and rocks
Ohio State Conservationist 200 North High St, Room 522, Columbus, OH 43215-2478	614-255-2500	Soil surveys/soil data
Oklahoma Conservation Commission	http://www.state.ok.us/~conscom/	Mine land reclamation and water quality
University of Oklahoma **Oklahoma Geological Survey** 100 E. Boyd, Rm N-131 Norman, OK 73019-0628	405-360-2886 http://www.ou.edu/special/ogs-pttc/	Geology; mineral and energy resources; seismicity
Oklahoma Department of Transportation	405-521-2688, Chief Engineer http://www.okladot.state.ok.us/	Geological and engineering boring logs, geological maps and cross-sections, groundwater tests, physical and engineering properties of soils and rocks
Oklahoma State Conservationist (NRCS) 100 USDA, Suite 203, Stillwater, OK 74074-2655	405-742-1248 http://www.ok.nrcs.usda.gov/	Soil surveys/soil data
Oregon Department of Geology and Mineral Industries 910 State Office Building, 1400 SW Fifth Ave Portland, OR 97201	503-229-5580 http://sarvis.dogami.state.or.us/homepage/	Geology; mineral and energy resources; earthquake hazards

SOURCE	CONTACT	DATA DESCRIPTION
Oregon Transportation Commission 355 Capitol NE St, Room 101, Salem, OR 97301-3871	503-986-3450 http://www.odot.state.or.us/	Geological and engineering boring logs, geological maps and cross-sections, groundwater tests, physical and engineering properties of soils and rocks
Oregon State Conservationist (NRCS) 101 SW Main St, Suite 1300, Portland, OR 97204-3221	503-414-3200 http://www.or.nrcs.usda.gov/	Soil surveys/soil data
Pennsylvania Department of Conservation and Natural Resources	http://www.dcnr.state.pa.us/	
Pennsylvania Department of Conservation and Natural Resources **Pennsylvania Geological Survey** **3240 Schoolhouse Rd** Middletown, PA 17057	717-702-2017 http://www.dcnr.state.pa.us/topogeo/	Geology; groundwater; fossil fuels; topographic mapping
Pennsylvania Department of Transportation **Central Office** Forum Place, 555 Walnut St, Harrisburg, PA 17101-1900 **Engineering District 8**, 2140 Herr St, Harrisburg, PA 17120-1699	717-787-6653, Engineering District 8 http://www.dot.state.pa.us/	Geological and engineering boring logs, geological maps and cross-sections, groundwater tests, physical and engineering properties of soils and rocks
Pennsylvania State Conservationist (NRCS) 1 Credit Union Place, Suite 340, Harrisburg, PA 17110-2993	717-237-2100 http://www.pa.nrcs.usda.gov/	Soil surveys/soil data
University of Rhode Island **Department of Geology** **Rhode Island Geological Survey** 9 East Alumni Ave 314 Woodward Hall Kingston, RI 02881	401-874-2191/2265 http://www.uri.edu/cels/gel/ri_geological_survey.htm/	Geology
Rhode Island State Conservationist 60 Quaker Lane, Suite 46, Warwick, RI 02886-0111	401-828-1300	Soil surveys/soil data
South Carolina Department of Natural Resources	http://www.dnr.state.sc.us/	
South Carolina Department of Natural Resources **South Carolina Geological Survey** 5 Geology Rd, Columbia, SC 29212	803-896-7708 http://www.dnr.state.sc.us/geology/geohome.html	Geology and mineral resources
South Carolina Department of Natural Resources **Water Resources Division**	http://water.dnr.state.sc.us/water/	

SOURCE	CONTACT	DATA DESCRIPTION
South Carolina Department of Transportation 955 Park St, P.O. Box 191, Columbia, SC 29202-0191	803-737-2314 http://www.dot.state.sc.us/	Geological and engineering boring logs, geological maps and cross-sections, groundwater tests, physical and engineering properties of soils and rocks
South Carolina State Conservationist Strom Thormond Federal Building, Room 950 1835 Assembly St, Columbia, SC 29201-2489	803-253-3935	Soil surveys/soil data
South Dakota Department of Environment and Natural Resources	http://www.state.sd.us/denr/	
South Dakota Department of Environment and Natural Resources **South Dakota Geological Survey** **Akeley-Lawrence Service Center, USD** **414 E. Clark Street** Vermillion, SD 57069-2391	605-677-5227 http://www.sdgs.usd.edu/	Geology; hydrology; mineral resources
South Dakota Department of Transportation **Divison of Planning/Engineering**	605-773-3174 http://www.state.sd.us/	Geological and engineering boring logs, geological maps and cross-sections, groundwater tests, physical and engineering properties of soils and rocks
South Dakota State Conservationist (NRCS) Federal Building, 200 4th St. SW, Huron, SD 57350-2475	605-352-1200 http://www.sd.nrcs.usda.gov/	Soil surveys/soil data
Tennessee Department of Environment and Conservation	http://www.state.tn.us/environment/	
Tennessee Department of Environment and Conservation **Geology Division** 401 Church St, Nashville, TN 37243-0445	615-532-1500 http://www.state.tn.us/environment/tdg/	Geology; mineral and groundwater resources
Tennessee Department of Transportation Suite 700, James K. Polk Building Nashville, TN 37243	615-741-0791, Chief Engineer http://www.tdot.state.tn.us/	Geological and engineering boring logs, geological maps and cross-sections, groundwater tests, physical and engineering properties of soils and rocks
Tennessee State Conservationist (NRCS) 675 U.S. Courthouse, 801 Broadway, Nashville, TN 37203-3878	615-277-2531 http://www.tn.nrcs.usda.gov/	Soil surveys/soil data

SOURCE	CONTACT	DATA DESCRIPTION
University of Texas at Austin **Texas Bureau of Economic Geology** University Station, Box X, 10100 Burnet Rd, Bldg 130 Austin, TX 78758-4497	512-471-1534/7721 begmail@begv.beg.utexas.edu http://www.beg.utexas.edu/	Geology; mineral, petroleum, surface and ground water resources
Texas Department of Transportation **Dallas District** 125 East 11th St, Austin, TX 78701-2483	214-320-6100, District Engineer http://www.dot.state.tx.us/	Geological and engineering boring logs, geological maps and cross-sections, groundwater tests, physical and engineering properties of soils and rocks
Texas State Conservationist (NRCS) W.R. Poage Building, 101 South Main St, Temple, TX 76501-7682	254-742-9800 http://www.tx.nrcs.usda.gov/	Soil surveys/soil data
Utah Department of Natural Resources **Utah Geological and Mineral Survey** 1594 West North Temple, P.O. Box 146100 Salt Lake City, UT 84114-6100	801-537-3300 http://geology.utah.gov/	Geology; mineral resources; and earthquake engineering
Utah Department of Transportation **Region 1** 169 North Wall Ave, P.O. Box 12580, Ogden, UT 84412-2580	801-399-5921 http://www.dot.state.ut.us/	Geological and engineering boring logs, geological maps and cross-sections, groundwater tests, physical and engineering properties of soils and rocks
Utah State Conservationist (NRCS) P.O. Box 11350, Salt Lake City, UT 84147-0350 125 South State St, Room 4402, Salt Lake City, UT 84138	801-524-4550 http://www.ut.nrcs.usda.gov/	Soil surveys/soil data
Vermont Agency of Natural Resources	http://www.anr.state.vt.us/	
Vermont Agency of Natural Resources **Vermont Geological Survey** 103 S. Main St, Laundry Building Waterbury, VT 05671-0301	802-241-3496 http://www.anr.state.vt.us/geology/vgshmpg.htm	Geologic reports, maps
Vermont Agency of Transportation 1 National Life Dr, Drawer 33, Montpelier, VT 05633	802-828-2169 Director of Technical Services Division, http://www.aot.state.vt.us/	Geological and engineering boring logs, geological maps and cross-sections, groundwater tests, physical and engineering properties of soils and rocks

SOURCE	CONTACT	DATA DESCRIPTION
Vermont State Conservationist (NRCS) **356 Mountain View Drive** Suite 105 Colchester, VT 05446	802-951-6795 http://www.vt.nrcs.usda.gov/	Soil surveys/soil data
Virginia Department of Mines, Minerals, and Energy	http://www.mme.state.va.us/	
Virginia Department of Mines, Minerals, and Energy **Virginia Division of Mineral Resources** P.O. Box 3667, Charlottesville, VA 22903	434 951-6342 http://www.mme.state.va.us/DMR/home.dmr.html	Geology; mineral resources
Virginia Department of Transportation **Public Affairs, Central Office** 1401 East Broad St, Richmond, VA 23219	804-786-2716 vdotinfo@vdot.state.va.us http://www.vdot.state.va.us/	Geological and engineering boring logs, geological maps and cross-sections, groundwater tests, physical and engineering properties of soils and rocks
Virginia State Conservationist (NRCS) Culpepper Building, Suite 209, 1606 Santa Rosa Rd, Richmond, VA 23229-5014	804-287-1646 http://www.va.nrcs.usda.gov/	Soil surveys/soil data
Washington Department of Natural Resources **Division of Geology and Earth Resources** **1111 Washington Street, Rm 148** **P.O. Box 47007** **Olympia, WA 98504-7007**	360 902-1450 http://www.wa.gov/dnr/htdocs/ger/	
Washington Department of Natural Resources 1111 Washington St SE, Room 148 P.O. Box 47007, Olympia, WA 98504-7007	360-902-1450 geology@wadnr.gov http://www.wa.gov/dnr/htdocs/ger/ger.html	Geology, mineral and energy resources
Washington State Department of Transportation **Highways and Local Programs Service Center** P.O. Box 47390, 310 Maple Park Dr, Olympia, WA 98504-7390	360-705-7871 http://www.wsdot.wa.gov/	Geological and engineering boring logs, geological maps and cross-sections, groundwater tests, physical and engineering properties of soils and rocks
Washington State Conservationist (NRCS) W. 316 Boone Ave, Suite 450, Spokane, WA 99201-2348	509-323-2900 http://www.wa.nrcs.usda.gov/	Soil surveys/soil data
West Virginia Geological and Economic Survey **Mont Chateau Research Center** **1 Mont Chateau Rd** P.O. Box 879, Morgantown, WV 26507-0879	304-594-2331 or 1 800 984-3656 http://www.wvgs.wvnet.edu/	Geology; mineral, energy, and water resources

SOURCE	CONTACT	DATA DESCRIPTION
West Virginia Department of Transportation **Division of Highways** Building 5, Room A-110, 1900 Kanawha East Charelston, WV 25305-0430	304-558-3505 304-558-0191, Joseph T. Deneault, State Highway Engineer http://www.wvdot.com/	Geological and engineering boring logs, geological maps and cross-sections, groundwater tests, physical and engineering properties of soils and rocks
West Virginia State Conservationist (NRCS) 75 High St, Room 301, Morgantown, WV 26505-7558	304-284-7540 http://www.wv.nrcs.usda.gov/	Soil surveys/soil data
Wisconsin Department of Natural Resources	http://www.dnr.state.wi.us/	
Wisconsin Department of Natural Resources **Bureau of Drinking Water and Groundwater**	http://www.dnr.state.wi.us/org/water/dwg/	Water resources
Wisconsin Department of Natural Resources **Bureau of Waste Management**	http://www.dnr.state.wi.us/org/aw/wm/mining/	Metallic mining
University of Wisconsin-Extension **Wisconsin Geological and Natural History Survey** 3817 Mineral Point Road, Madison, WI 53705-5100	608-262-1705 http://www.uwex.edu/wgnhs/	Geology, mineral resources, water resources, climatology
Wisconsin State Conservationist (NRCS) 6515 Watts Rd, Suite 200, Madison, WI 53719-2726	608-276-8732 http://www.wi.nrcs.usda.gov/	Soil surveys/soil data
Geological Survey of Wyoming Box 3008, University Station, Laramie, WY 82071	307-766-2286 wsgs@wsgs.uwyo.edu http://www.wsgsweb.uwyo.edu/	Geology; mineral resources
Wyoming Department of Transportation 5300 Bishop Blvd, Cheyenne, WY 82009-3340	307-777-4375 http://wydotweb.state.wy.us/	Geological and engineering boring logs, geological maps and cross-sections, groundwater tests, physical and engineering properties of soils and rocks
Wyoming State Conservationist (NRCS) Federal Office Building, Room 3124, 100 East B St, Casper, WY 82601-1911	307-261-6453 http://www.wy.nrcs.usda.gov/	Soil surveys/soil data

Appendix B
Additional Internet Sources

Publications of the USGS, http://usgs-georef.cos.com. The USGS has for years produced professional geologic and hydrologic reports of specific sites, areas, or regions throughout the country. This web site is a search and download engine for online publications of the USGS. For example, selecting the online publication category *Geology* returns a page of USGS books and reports that are directly downloadable to the user. Highlighting the choice *Bulletins* returns a list of all freely downloadable USGS bulletins. USGS bulletins provide information on a wide variety of geological subjects in a broad geographic area. The web site also provides a search engine for reviewing lists of reports published by other agencies and organizations on a user-selectable subject, author, or keyword. The latter are not downloadable, but publication information is provided. Other USGS report series in addition to Bulletins include Professional Papers (comprehensive scientific reports of wide interest to professional scientists and engineers), Water-supply Papers (comprehensive reports of the results of hydrologic investigations of wide interest to geologists, hydrologists, and engineers), and Water-resources Investigation Reports (papers of an interpretive nature). Many university libraries retain hard copies of these USGS publications for review.

National Geologic Map Database, http://ngmdb.usgs.gov. The USGS and its state affiliates produce high-quality geologic maps and accompanying reports for much of the United States and its territories. The most common scale for production of geologic maps is 1:24,000 (1 in. = 2000 ft, prepared on a base consisting of a 7 ½ minute topographic quadrangle). This is a page maintained by the USGS. It provides a search engine for maps and related data pertaining to geology, hazards, earth resources, geophysics, geochemistry, geochronology, and marine geology. Selecting the link *Geologic Maps* brings up a page of searchable geologic themes and a menu of options for selecting a geographic area in which to conduct the data search. As an example, selecting the theme *Geology* and the area *Arkansas* in the menu brings up a list and full reference of over 150 published geologic reports by various agencies for the state of Arkansas. Selecting the link for *Digital Geologic Map of the Murfreesboro Quadrangle...* under *Scale 1:24,000* produces information about the publication (map scale, areal coverage, format, etc.) and provides an address and POC for obtaining the report.

This site provides the latest information on the status of mapping and geologic reporting for a particular geographic region. It is a rapid way to determine whether a state or Federally prepared map or report is available and how to obtain it. The publications listed in this database are generally not directly downloadable over the Internet. Product availability is listed for each selected reference. Most must be obtained by contacting the USGS in Denver, CO, at (303)202-4700 or 1-888-ASK-USGS.

State Geological Surveys. Each state maintains a staff of geologists for investigating and evaluating geological resources and hazards. Many state surveys reside at a major university within the state. Others are a governmental agency located at the state capital. The survey may be included in the state's Department of Environmental Quality or Department of Environmental Management. Appendix A lists addresses and contacts for all state geological surveys. Geological surveys publish technical reports and other information pertaining to local, regional, and statewide areas of investigation. A site listing addresses, phone numbers, and web links for all 50 state geological surveys and Puerto Rico is accessible at **http://www.consrv.ca.gov/cgs/information/other_surveys/index.htm**. Some publications and other data are available in digital format and can be downloaded at a state survey's web site. The web site listed above provides links to every survey's web site. Once within an individual web site, the user has access to all services provided by the state survey via the Internet. Services include POCs, personnel directory, list of publications, on-line (downloadable) publications, and, usually, a state geologic map that shows the type of rock or soil to be expected in a particular part of the state. Downloads are commonly in .PDF format (requiring the *Adobe Acrobat* reader to view). State geological surveys maintain excellent libraries of published and unpublished reports, maps containing a variety of detailed geologic information, and maps of areas within the state.

State Departments of Transportation and Highway Administrations. State highway departments collect and store geotechnical and geological information statewide. Most bridge crossings require borings for design and construction. Borings are commonly sampled and logged for geological interpretation and engineering design considerations. Stretches of highway susceptible to subsidence or landsliding problems may be geologically mapped and may have required the placement of borings during site investigation. Utility crossings at bridge locations may provide additional geologic and engineering data from boring, sampling, testing, and mapping programs. The Internet provides a web site through the Federal Highway Administration for accessing state transportation and highway departments. The web address is **http://www.fhwa.dot.gov/webstate.htm**. This site provides links to all state departments of transportation and lists telephone numbers, addresses, and email addresses of key personnel, including district or division highway engineers, for each state. Appendix A provides contacts for all state transportation or highway departments. Telephone numbers for Chief Engineers are listed in the table where available. Inquiries should be directed to the engineering department if only an information number is provided.

U.S. Army Corps of Engineers Commands (USCEC), **http://www.usace.army.mil/where.html#state**. This page presents a list of addresses and links to all USCEC districts, divisions, and research labs. The Corps has accumulated extensive and detailed geotechnical data from many projects nationwide including dam and levee construction, military base construction and environmental monitoring, river and harbor dredging, and others. Data include geological and engineering boring logs, geologic evaluation, maps, and cross sections, groundwater tests, laboratory tests for physical and engineering properties of soil and rock, and in situ tests of engineering properties of soil and rock. Corps offices may be able to provide copies of reports or raw data pertinent to a site near a Corps project. In some cases, actual soil and rock core obtained for a Corps project may be available for examination. The web site provides links to all Corps offices, with POCs for each office.

Publications of the Headquarters, U.S. Army Corps of Engineers, http://www.usace.army.mil/inet/usace-docs. This site provides a list of all Corps publications originating from Army Corps Headquarters (HQUSACE), , most of which are downloadable. All publications are accessible through links and include engineering regulations, circulars, manuals, pamphlets, and publications by the Corps' research offices.

The National Soil Survey Center (NSSC). The NSSC is a division of the U.S. Department of Agriculture's Natural Resources Conservation Service (formerly Soil Conservation Service). The NSSC produces and makes available published reports of the distribution (maps) and properties of soils for each county of every state. County soil survey reports present detailed and medium-scale (usually 1:20,000) maps and classification of surface soils and often provide engineering characteristics and properties and engineering test data for the various soil classifications. Soil survey reports give the thickness of soils (depth to rock), which can be of great importance in HDD projects. Some soil survey reports also discuss the relationship of soils to underlying geologic units, thus providing important information on local geology. A web site is available for NSSC at www.statlab.iastate.edu/soils/nssc/. The site provides links to sites describing soil survey standards, soil geography (offering, for a fee, digital versions of selected county soil survey maps), and a list of published soil surveys and maps for every state. The lists of published soil surveys provide a POC for the state (usually the state soil conservationist), and an alphabetical list of soil surveys by county showing date prepared. The more recent soil surveys are more likely to contain data on engineering properties of soils. Appendix A lists addresses and contacts for obtaining soil surveys and maps through the State Conservationist in each state.

EROS Data Center, Sioux Falls, SD site, http://edc.usgs.gov. The Earth Resources Observation Systems (EROS) Data Center is an agency of the USGS. EROS Data Center stores and distributes cartographic data, satellite imagery, and aircraft imagery. The web site provides a search engine to locate imagery and maps for any location within the United States. The home page provides links to pages describing the various products and to other searches. For ordering and additional information, contact the EROS Data Center at Customer Services, USGS, 47914 252nd Street, Sioux Falls, SD 57198-0001, Telephone 1-800-252-4547.

USGS Data Download, http://edc.usgs.gov/geodata. This is a USGS web page for downloading free digital USGS topographic map data, including digital elevation models (DEM) and digital line graphs (DLG). DEMs are regular grids of topographic elevations extracted from paper maps. DEMs permit the user to reconstruct topographic contour maps and pseudo 3D (surface or wireframe) maps from the digital grid. This web site redirects the user to commercial sites for downloading DEM data. DLGs contain line information extracted from topographic maps and include roads, lakes and streams, cultural features, and contours. These freely downloadable DEMs are provided at scales of 1:250,000 and 1:24,000. DLGs are provided at scales of 1:2,000,000 and 1:100,000. The files are sent compressed and must be decompressed using readily available software, such as WinZip Version 7 or 8.

USGS Global Land Information System (GLIS), http://edcwww.cr.usgs.gov. This site is being replaced by EarthExplorer (http://earthexplorer.usgs.gov). The site provides links to maps and other data about climate, geology, hydrology, land cover, aerial photography, satellite imagery, digital line graphs, and elevation models worldwide. A search engine permits the user to review databases and imagery for a variety of topics. Data are primarily in the form of maps and imagery. The site is very good for viewing satellite and aerial imagery by a user-selected field of view (latitude/longitude), data acquisition date, image quality, and other characteristics prior to ordering or purchasing. The web page provides a full description of data characteristics, such as spatial resolution, format, extent of coverage, and data availability. Products are not directly downloadable, except in a reduced resolution version for reviewing. Ordering and purchasing information is provided.

Geology of Conterminous United States at 1:2,500,000 – A digital representation of the 1974 P. B. King and H. M. Beikman map, http://minerals.usgs.gov/kb. This is a free, downloadable digital version of the geological map of the United States. The 16-megabyte (MB) file is in ArcInfo and ArcView formats. Each mapped geologic unit is in a separate layer (shape file), allowing a map of any combination of layers for any selected area to be produced in ArcInfo or ArcView GIS software. The resolution of this map is about 1 km, so it is usable only for regional geologic investigations or for preliminary determination of rock types to be expected at a site.

USGS Digital Raster Graphics, http://mcmcweb.er.usgs. A digital raster graphic (DRG) is a scanned image of a USGS standard series topographic map, including all map collar information. The image inside the neatline is georeferenced (tied to geographic coordinates) and is presented in the Universal Transverse Mercator (UTM) projection. A DRG can be combined with other georeferenced data, such as aerial images, GPS or other surveyed positions, DEMs, and DLGs. The site provides samples of the data but does not permit downloading of files. The site provides links to sources of DRGs and other map products. Many states provide free downloads of DRGs for their respective regions. See http://mcmcweb.er.usgs.gov/drg/free_drg.html for a list of free downloads.

Other sites. Other web sites offering free or purchase-required digital geologic, topographic, and/or imaging data include:

a. MapMart at http://www.mapmart.com/

b. TopoZone.com at http://www.topozone.com/

c. The GIS Data Depot at http://www.gisdatadepot.com/

d. GIS data site at http://www.pipeline.com/~rking/gobb.htm

e. National Geophysical Data Center at http://www.ngdc.noaa.gov/

f. National Imagery and Mapping Agency (NIMA) at http://www.nima.mil/

Appendix C
Acronym List

AOPCs	Areas of Potential Concern
ASR	Archive Search Reports
CRIM	Complex Refractive Index Method
CSM	Conceptual Site Model
d.c.	Direct Current
DEM	Digital Elevation Model
DoD	Department of Defense
DTED	Digital Terrain Elevation Data
EM	Electromagnetic
EMI	Electromagnetic Induction
ERDC	Engineer Research and Development Center
EQT	Environmental Quality and Technology
EOD	Explosive Ordnance Disposal
FA	Footprint Analysis
FDEM	Frequency Domain Electromagnetic
GHz	Gigahertz
GIS	Geographical Information System
GPR	Ground Penetrating Radar
GPS	Global Positioning System
HEAT	High-Explosive Anti-Tank
JPG	Jefferson Proving Ground, IN
JPL	Jet Propulsion Laboratory
kHz	Kilohertz
MHz	Megahertz
NDCEE	National Defense Center for Environmental Excellence

NDRC	National Defense Research Committee
NRCS	Natural Resources Conservation Service
nT	Nanotesla
ODDS	Ordnance Detection and Discrimination Study
OE	Ordnance and Explosive
POC	Point of Contact
TDR	Time Domain Reflectometry
TDEM	Time Domain Electromagnetic
TMF	Total Magnetic Field
TP	Time Propagation (model)
USDA	U.S. Department of Agriculture
UXO	Unexploded Ordnance
WES	Waterways Experiment Station

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
August 2004

2. REPORT TYPE
Final report

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
Guidelines for Planning Unexploded Ordnance (UXO) Detection Surveys

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Janet E. Simms, Robert J. Larson, William L. Murphy, and Dwain K. Butler

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Engineer Research and Development Center, Geotechnical and Structures Laboratory, 3909 Halls Ferry Road, Vicksburg, MS 39180-6199;
Alion Science and Technology Corportation, 3909 Halls Ferry Road, Vicksburg, MS 39180-6199

8. PERFORMING ORGANIZATION REPORT NUMBER
ERDC/GSL TR-04-8

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Corps of Engineers
Washington, DC 20314-1000

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

This report represents guidelines for planning UXO detection surveys based on a phenomenological approach. The phenomenological evaluation considers the physical characteristics (topography, vegetation, soil type, and moisture) of a site and subdivides the site into areas that have a unique classification for the set of four physical characteristics. Values for three geophysical parameters (electrical conductivity, dielectric permittivity, and magnetic susceptibility) are assigned to each area based on the physical characteristics of that area. Given the physical characteristics, geophysical parameters, and ordnance usage history, a selection of geophysical sensors and platforms are identified that would be appropriate for conducting a UXO detection survey within each area of the site.

15. SUBJECT TERMS
Geophysics
Geophysical survey
Phenomenology
Unexploded ordnance
UXO

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON James C. Ray
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			**19b. TELEPHONE NUMBER** *(include area code)*
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED		126	(601) 634-3265