PREDICTION AND VALIDATION OF SOIL ELECTROMAGNETIC CHARACTERISTICS FOR APPLICATION IN LANDMINE DETECTION*

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ABSTRACT

Factors controlling the distribution and intensity of soil magnetic susceptibility (MS) and electrical conductivity (EC) were investigated. The purpose was to determine the factors to be considered in predicting MS and EC characteristics of soils in landmine-affected areas and in developing effective landmine detection systems and strategies.

Results indicate that knowledge of bedrock geology, soil weathering and transportation (wind and water) history is essential to predict soil MS and EC characteristics. These factors determine the distribution, concentration and mineral type (e.g., ferromagnetic and clay minerals) in soil. For example, fluctuating water tables in tropical climates could produce soils rich in ferromagnetic minerals at the surface, even though their source (bedrock) may have low iron content. Also, subsequent weathering may change these minerals to high or low MS values. Although high clay concentrations homogeneously distributed may not produce high soil EC values, a low clay content concentrated in a single layer may produce extremely high EC values. These suggest that bedrock geology, agricultural soil, air photo and airborne geophysical survey maps can be used for predicting soil MS and EC characteristics of landmine-affected areas. Laboratory and surficial geophysical surveys are techniques for use in validation.

Keywords: Soil electromagnetic characteristics, landmine detection, ferromagnetic minerals in soil, soil magnetic susceptibility, soil electrical conductivity, weathering history effect, soil electromagnetic property prediction.

1. INTRODUCTION

Landmine detection problems are experienced in many parts of the world. In the case of using metal detectors for the small anti-personnel landmines, normally buried within 30 cm of the surface, the detection problem is due to the electromagnetic (EM) characteristics (magnetic susceptibility [MS] and electrical conductivity [EC]) of the soils. For this reason, the development of a world soil database that is related to the soil electromagnetic characteristics has been proposed.¹² The purpose is to enable the development of efficient and effective detection strategies and systems for use in mine affected areas. A study has been carried out to review information on the source of soil MS and EC characteristics, on the origin of these sources, on the soil MS and EC mechanisms, and on the mechanical and chemical processes that produce these sources. In addition, principles related to prediction of soil EM characteristics and methods for validating these predictions have been investigated. The purpose was to determine the factors to be considered when creating the soil database, which is designed to result in development of new and effective landmine detection strategies and systems.

In this paper, results of these reviews on the sources of EM characteristics and soil EM mechanisms are described.
These are followed by soil structure and its implication on EM source mineral distribution in soil. These include some EM characteristic data on soil and soil-forming minerals. Finally, the methods of soil EM characteristic prediction and validation are discussed. This includes the use of air photographs, airborne and surface geophysical surveys, surficial geological surveys and laboratory analysis.

2. SOURCE OF ELECTROMAGNETISM IN SOILS

The main source of magnetism in soils is ferro-magnetic minerals with strong magnetic susceptibility (MS) characteristics. Examples of such minerals are shown in Table 1. Some non-metallic minerals also show weak to moderate MS values, but will not be discussed here. The main source of electrical conductivity (EC) in soils is moisture, clays and electronically conductive metallic minerals. However, certain clays and metallic minerals are significant contributors to EC only if their grains are interconnected, as will be explained in some detail later. The EC mechanisms will be discussed later. Some representative examples of soil and clay EC characteristics are listed in Table 3.

<table>
<thead>
<tr>
<th>Minerals</th>
<th>Composition</th>
<th>MS (x10^-8 SI/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetite</td>
<td>Fe₃O₄</td>
<td>100 - 4000</td>
</tr>
<tr>
<td>Hematite</td>
<td>αFe₂O₃</td>
<td>0.04 - 25</td>
</tr>
<tr>
<td>Ilmenite</td>
<td>FeTiO₃</td>
<td>25 - 300</td>
</tr>
<tr>
<td>Pyrrhotite</td>
<td>Fe₁₋ₓS</td>
<td>0.1 - 500</td>
</tr>
<tr>
<td>Maghemite</td>
<td>γFe₂O₃</td>
<td>500 - 750</td>
</tr>
</tbody>
</table>

3. ELECTRICAL CONDUCTIVITY (EC) MECHANISMS OF SOILS

3.1 Basic soil electrical conductivity concepts

Soil generally consists of grains of insulating material and pore space. The electrical conducting media in soil is usually pore water. Pores consist of storage pores and connecting pores, with only the connecting pores contributing to electrical conductivity (EC). Effective porosity (φₑ) represents the total inter-connected porosity of a soil:

\[ φₑ = φₛ + φₓ \]  

where \( φₛ \) and \( φₓ \) are the storage and connecting porosities\(^3\), respectively. The electrical resistivity of soil (\( ρᵣ \)) is a function of the pore water resistivity (\( ρₚ \)):

\[ ρᵣ = Fρₚ \]  

where F is the formation factor. An electrical conductivity model\(^4,5\) used to explain the relationship between these parameters is presented in Figure 1.

3.2 Grain or pore surface conductivity mechanism

All mineral grains have adsorbed water layers on their surfaces\(^6\) which are relatively electrically conductive (Figure 2). For a soil texture with large grains and pores, these adsorbed water layers are insignificant. However, for fine grained material with small pores (e.g., clays) the effect of these adsorbed water layers can be significant. In Figure 3, an example is shown where \( 1/ρᵣ \) decreases with pore fluid conductivity (\( 1/ρₚ \)) decrease, until the point (\( ~2 \) S/m) where the grain surface conductivity takes over and the \( 1/ρᵣ \) values level off. As the soil dries due to pore water evaporation, only the free water evaporates and the adsorbed water layers remain. A soil temperature above 106 °C is required to eliminate all of the adsorbed
water layers. Accordingly, the $\rho_f$ of the soil increases as the free water evaporates\(^6\), as shown in Figure 4. The moisture content (0.06-0.16 gm/cc) at which the $\rho_f$ values start to show a rapid increase with decreasing moisture content is the wilting point (WP). It implies that the free water that bridged the conductivity between the grains has disappeared or evaporated.

$$
\rho_c = F \rho_w \\
\phi_e = \phi_s + \phi_c \\
\phi_e = \phi_s + \tau^2 \left( \frac{1}{F} \right) \\
\tau = \frac{1}{\rho} \\
F = \frac{\tau^2}{\phi_e} \\
\phi_c = nd\tau
$$

**Figure 1:** Electrical conductivity model of rocks and soil consisting of insulating material and electrically conducting fluid\(^4,1\). The $\rho_b$, $F$ and $\rho_w$ are the soil bulk resistivity, formation factor and pore fluid resistivity, respectively. The $\phi_e$, $\phi_s$ and $\phi_c$ are the effective, storage and connecting porosities, respectively. The $\tau$, $1/\rho$, $n$ and $d$ are the tortuosity, length of connecting pore, dimension of a unit cube of rock or soil and sheet-like connecting pore width, respectively.

**Figure 2:** A soil with mineral grains having adsorbed water surfaces\(^6\) which are relatively electrically conductive.

**Figure 3:** An example where the electrical conductivity of a rock ($1/\rho_c$) decreases with pore fluid conductivity ($1/\rho_w$) decrease, until the point (~2 S/m) where grain surface conductivity takes over and the $1/\rho_c$ values level off\(^16\).
3.3 Effect of soil texture

A typical example of a soil grain-size distribution (Clay < 2 μm, silt = 2-63 μm, fine sand = 63-250 μm, medium-coarse sand = 0.25-2.0 mm) is shown in Figure 5 for a Cambodian soil. In the case of a sand framework (Figure 6: top), pore-fluid between the grains would provide the main electrical conductive paths. In the case of a matrix (clay) framework (Figure 6: bottom), the multiple adsorbed water layers on the clay particles would provide the main conductivity paths. In the case of a soil texture of mixed clay and sand (Figure 6: middle), the clay-filled section is generally more conductive than that with only moisture filling the pore spaces, except for certain clays such as kaolinite (Table 2). As soil dries due to evaporation of the free water, it is expected that the soil resistivity increase will be more rapid in a clay-poor texture than a clay-rich texture, due to the grain surface conductivity.

![Figure 4](image1.png)

**Figure 4:** Curves showing soil $\rho$, increase with decreasing moisture content. The parameter WP is the wilting point.

![Figure 5](image2.png)

**Figure 5:** Comparison of magnetic susceptibility (MS), electrical resistivity ($\rho$) and grain-size characteristics (clay < 2 μm, silt = 2-63 μm, fine sand = 63-250 μm, medium-coarse sand = 0.25-2.0 mm) of soil samples from (a) Cambodia, (b) Croatia and (c) Mozambique.
Table 2: Magnetic susceptibility (MS) characteristics of some major rock types.\(^\text{12}\)

<table>
<thead>
<tr>
<th>Rock Types</th>
<th>MS (x10^-8 SI/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typical Soils</td>
<td>0.001 - 0.1</td>
</tr>
<tr>
<td>Typical Sedimentary Rocks</td>
<td>0.003 - 0.3</td>
</tr>
<tr>
<td>Acidic Rocks (average)</td>
<td>0.65</td>
</tr>
<tr>
<td>Basic Rocks (average)</td>
<td>2.6</td>
</tr>
</tbody>
</table>

3.4 The role of clay and electronic conductors in soil

An example of a rock containing layers rich (~10 %) in electronically conductive minerals (pyrite: FeS) is shown in Figure 7 (upper left). The bright spots are pyrite grains, which are electronic conductors. Whereas electronically conductive mineral grains (e.g., magnetite, hematite, maghemite) similarly distributed in soil can reduce the bulk resistivity of that soil due to their acting as short circuits, they can also be a source of increased resistivity.\(^3\) Electrochemical double layers form on surfaces of electronically conductive particles (e.g., metals and metallic minerals) that are in contact with moisture. These double layers act as capacitors and shut off the flow of electrical currents through these grains at lower frequencies.\(^7\) Therefore, the electrical current will flow through both the pore-fluid and layers rich in electronically conductive particles to result in lower bulk resistivity values at the higher frequencies. An increased resistivity will result at the lower frequencies due to the current flow being shut off from the layers containing the electronically conductive particles. That trend for electrical resistivity versus frequency is shown in the right-bottom part of Figure 7. This electrical conductive mechanism will apply to electronically conductive minerals in soil as well. It has been proposed to use the gradient of the resistivity change (\(\Delta \rho_t\)), that occurs as the electrical current shut off takes place, to distinguish between metallic particles in soil and in anti-personnel landmines.\(^7\)
3.5 Electrical conductivity structure of soil

As implied in the EC concept discussed above, electronically conductive minerals or metallic particles contribute to significant soil conductivity only if their grains are inter-connected. If dispersed homogeneously throughout the soil, they will have little effect on the soil EC. This applies to clay mineral particles as well. That is, clay particles may contribute to soil EC only if the particles are inter-connected and form continuous layers. Similar to the case of metallic particles, if clay particles are homogeneously dispersed, they will have little effect on soil EC. Failing any significant contribution from clay particles, the pore water will be the main contributor to soil EC. The pore water resistivity has a wide range of variation: $0.05-100 \, \Omega \cdot m$.

4. SOIL STRUCTURE AND IMPLICATIONS

4.1 Initial process

Soil is an accumulation of loose material of various grain sizes. The initial process for soil formation is the disintegration of the bedrock by several weathering processes, such as mechanical and chemical processes. Loosening of tight rocks by temperature changes in warm climates or by volume expansion of freezing pore water in cold climates, and erosion of the rock surfaces by wind, glaciers and water flow are mechanical processes that produce soil. Chemical processes due to acids from plants can also loosen tight rocks and produce soil. Once a layer of soil is formed on the bedrock surface, additional chemical processes due to acids from the plants or meteoric water movements in the soil can cause alteration of the mineral grains by changing the grain-size or type of minerals. Clays are an example of fine-grain material formed by such processes. There can also be mechanical migration of material, such as clays moving downwards from the surface due to water movement process. Following these processes, an initial soil can be removed by wind or water, or additional soil material can be deposited on top of the initial soil due to the same processes transporting material from other sources. This implies that significant vertical changes in the soil column has to be expected due to different degrees of chemical weathering with depths, or soil material being deposited from origins in different rock types.
4.2 Implication of processes due to vertical movement of water

Vertical movement of water can occur in soil due to temperature variation, evaporation of soil pore water and precipitation. This movement can take place to considerable depth, particularly in tropical climates that reach several tens of metres. This implies that chemicals dissolved by water as deep as the underlying bedrock can be transported to the surface by this vertical water movement. The chemicals that reach the surface can reproduce certain minerals of the bedrock or form new minerals. Certain minerals can even be formed at higher concentration than those in the bedrock. For example, maghemite pebbles at the surface may have a higher iron-oxide content than its bedrock origin7.

4.3 Distribution of magnetic minerals

The source of the ferro-magnetic minerals in soil is the bedrock or transported material. When bedrock containing ferro-magnetic minerals (e.g., magnetite) disintegrate due to the weathering processes previously described, these ferro-magnetic minerals will remain in the resulting soil. In the case of vertical movement of water in the soil column, new ferro-magnetic minerals (e.g., hematite and maghemite) can be produced and deposited at the surface. These minerals can be relatively large in grain sizes, such as 0.25-2 mm (medium to coarse sand sizes) or >2.0 mm (pebble sizes) and may have very high MS values, as previously indicated7. Transformed material, from other areas and deposited on the soil formed from the local bedrock, can also contain significant amounts of ferro-magnetic minerals, such as magnetite, sulphides (e.g., pyrrhotite). These materials can be a result of eroded bedrock containing ferro-magnetic minerals, iron-rich ore deposits or less commonly sulphide rich veins (e.g., pyrite, pyrrhotite).

4.4 Distribution of electrically conductive material

As previously implied, the main source of low soil resistivity or high conductivity is saline water or clays, excluding kaolinite. Clay particles are usually interconnected. Metallic minerals or particles are not necessarily considered to be a significant source, as previously indicated, as they usually lack inter-connectivity. Normal soil water resistivities are expected to be in the range of 0.05-100 Ω. A sample of loose sea floor material with a porosity (φe) of 46 % displayed a formation factor value10 of 5-10. If we use these values in Equation (2), soil can be expected to have resistivities in the range of 0.25-1000 Ωm, a range similar to that in Table 3. If the grain or pore surface conductivity is considered, the low end of this resistivity range could be still slightly lower (e.g., 0.2 Ωm 11). The soil water resistivity values are related to the bedrock type9 and the climate. For example, areas with considerable evaporation can result in high salinity water at the surface and reduce the soil resistivity values.

Interconnected clay layers are another source of low soil resistivity or high conductivity (Table 3). The clay resistivity values are related to their cation exchange capacity (CEC) and surface area (A), with montmorillonite showing some of the lowest resistivity values (Table 3) and highest CEC and A values (Table 4). Similarly, kaolinite shows one of the highest resistivity and lowest CEC and A values. Clay is a result of chemical alteration of rock or soil-forming minerals, and is due to various weathering and mechanical transport processes, as previously indicated. It is distributed throughout a soil column, often forming layers of different concentrations.

<table>
<thead>
<tr>
<th>Material</th>
<th>Soils and Clays</th>
<th>Electrical Resistivity (Ωm)</th>
<th>Electrical Conductivity (mS/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil Types</td>
<td>Clay (general term)</td>
<td>1 - 100</td>
<td>10 - 1000</td>
</tr>
<tr>
<td></td>
<td>Loam</td>
<td>4 - 40</td>
<td>25 - 250</td>
</tr>
<tr>
<td></td>
<td>Top Soil</td>
<td>40 - 200</td>
<td>5 - 25</td>
</tr>
<tr>
<td></td>
<td>Clay-rich Soil</td>
<td>100 - 400</td>
<td>2.5 - 10</td>
</tr>
<tr>
<td></td>
<td>Sandy Soil</td>
<td>400 - 4000</td>
<td>0.25 - 2.5</td>
</tr>
<tr>
<td></td>
<td>Loose Sands</td>
<td>1000 - 10^5</td>
<td>0.01 - 1</td>
</tr>
<tr>
<td>Clay Type</td>
<td>Kaolinite</td>
<td>50 - 5000</td>
<td>0.2 - 20</td>
</tr>
<tr>
<td></td>
<td>Montmorillonite</td>
<td>4 - 15</td>
<td>67 - 250</td>
</tr>
</tbody>
</table>
Table 4: Cation exchange capacity (CEC) and surface areas (A) of some common clay minerals.

<table>
<thead>
<tr>
<th>Clay Minerals</th>
<th>CEC (me/100 g)</th>
<th>Surface Area (m²/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vermiculite</td>
<td>100 - 150</td>
<td>600 - 800</td>
</tr>
<tr>
<td>Montmorillonite</td>
<td>80 - 120</td>
<td>600 - 800</td>
</tr>
<tr>
<td>Illite</td>
<td>10 - 40</td>
<td>65 - 100</td>
</tr>
<tr>
<td>Chlorite</td>
<td>10 - 40</td>
<td>25 - 40</td>
</tr>
<tr>
<td>Kaolinite</td>
<td>3 - 15</td>
<td>7 - 30</td>
</tr>
</tbody>
</table>

4.5 Layered structure of soil

Soil is an accumulation of loose material with a layered structure consisting of various grain-size combinations. The layered structure and varied grain-size composition are a result of the various soil-forming and secondary alteration processes, previously described. A schematic diagram of a landscape section, consisting of fresh bedrock overlain with layers of various degrees of weathered rock and soil is shown in Figure 8. Soil resulting from weathered bedrock of ultramafic and felsic type are shown in the left-hand side of Figure 9. In this case, the former is a basic rock rich in ferro-magnetic minerals and latter is an acidic rock that is poor in these minerals. As shown in the diagram, soil above the basic and acidic bedrocks are rich and poor in ferro-magnetic minerals, respectively. The upper section of the right-hand side of Figure 9 illustrates a case where a ferro-magnetic rich soil has been transported and deposited above a ferro-magnetic poor soil. The lower section illustrates a case where ferro-magnetic minerals (e.g., magnetite) in a bedrock poor in such minerals has dissolved by the vertical movement of ground water and been transported to the surface to produce a new ferro-magnetic mineral (e.g., maghemite). In this case, the new ferro-magnetic mineral can be of higher iron concentration than that in the bedrock. This section also illustrates the case where relatively large pebble-size (>2 mm) concretions of ferro-magnetic minerals have formed at the surface. The layers immediately below that layer contains smaller grains of the same new mineral that have not yet grown to the pebble-sized grains at the surface.

Figure 8: Landscape model illustrating fresh bedrock overlain with layered structure of soil, consisting of various degrees of weathered rock and soil transported by different processes.
Figure 8 illustrates the case where the uneroded uppermost layer is rich in the new ferro-magnetic pebble-sized mineral grains. This figure also illustrates that erosion of the uppermost layer has removed the ferro-magnetic material and deposited it in the ravines below on the right hand section. Figure 10 illustrates how electrical conductivity (EC) and magnetic susceptibility (MS) can vary in a soil column, due to its layered structure. This is a Canadian example, but represents typical EC and MS variations in the subsurface.

**Figure 9:** Layered structure of soil. [Left-hand side] Soil resulting from weathered bedrock of ultramafic (upper) and felsic (lower) types. [Upper-Right] An illustration of a case where a ferro-magnetic rich soil has been transported and deposited above a ferro-magnetic poor soil. [Lower-right] Illustration of a case where ferro-magnetic minerals (e.g., magnetite) in a bedrock poor in such minerals has dissolved by the vertical movement of ground water and has been transported to the surface to produce a new ferro-magnetic mineral (e.g., maghemite).

**Figure 10:** An example of electrical conductivity (EC) and magnetic...
susceptibility (MS) variation in a soil column. This data was obtained by a downhole geophysical survey.

5. PRINCIPLES OF SOIL EM CHARACTERISTIC PREDICTION

The purpose of predicting soil electromagnetic (EM) characteristics is to select detection equipment and set up efficient detection strategies for areas targeted for demining, as previously indicated. Based on the foregoing discussions, the first item to be considered for soil EM characteristic (MS and EC) prediction is the distribution of bedrock type around the target area. The origin of the ferro-magnetic minerals is the bedrock either underlying or surrounding the target area. This is also the case for the clay or saline ground water that are the source of soil EC. The second item to be considered for soil EM characteristic prediction is the climate history that would be responsible for chemical alteration and transportation of various chemical species within and from the underlying bedrock. The third is the transportation history of geological material into the area from soil and bedrock in surrounding areas.

Prediction from regional agricultural soil maps, air photographs and airborne geophysical maps are also options to be considered. Soil bulk density and cation ion exchange capacity (CEC) from soil maps may provide indications of the possible existence of heavy minerals (e.g., ferro-magnetic minerals) and conductive clays in the soil. Air photographs can provide information on areas and their extent affected by transportation of geological material from surrounding areas. Airborne magnetic and radiometric survey maps may provide information on areas with high concentrations of ferro-magnetic minerals. Figure 11 displays an example of an airborne magnetic map showing ravines containing high concentrations of ferro-magnetic minerals (dark-black areas). Figure 12 displays an example of an airborne radiometric image showing areas with high concentrations of thorium, which may represent iron-rich minerals (red areas) which could be ferro-magnetic minerals. The high frequency component of airborne electromagnetic survey maps can be expected to display areas of high soil conductivity.

The soil consists of a layered structure with varied concentrations and grain-sizes of minerals (including ferro-magnetic and clay minerals), which could confuse predictions from other surveys just discussed above. The final stage of a soil characteristic survey should be a surficial geological survey of areas adjacent or similar to the target area. This would consist of examination of landform units, surficial geological units, variability within units, soil structure exposed in作为一名AI助手，我专注于提供准确的信息，而不涉及个人情感或主观评价。
pits and erosional slopes.

6. METHOD FOR VALIDATION OF SOIL EM CHARACTERISTICS

It is reasonable to consider the final stage of the soil EM characteristic prediction validation to be laboratory analysis of the soil. However, the question is whether the samples are representative of the soil units of significance and how can representative samples be selected, although appropriate analytical methods can provide much of the required information. For example, magnetic and electrical properties of soil samples randomly collected from three parts of the world, Cambodia, Croatia and Mozambique, are compared in Figure 5a, b and c. These figures suggest that the high magnetic susceptibility (MS) values are related to the fine-sand (0.063-0.25 mm) content. The Cambodian soil (Figure 5a) shows the highest MS value (330-660 \([x10^5 \text{ SI/kg}]\)) with a high fine-sand content and the Croatian one (Figure 5b) shows the lowest MS value (2-15 \([x10^5 \text{ SI/kg}]\)) with lowest fine-sand content of the three. Similarly, these figures suggest that the electrical resistivity (\(\rho\)) values are related to the clay content. The Cambodian soil (Figure 5a) shows the highest \(\rho\) value (150 \([\Omega \text{m}]\)) with little clay and the Mozambique sample (Figure 5c) shows the lowest \(\rho\) (6.7 \([\Omega \text{m}]\)) value with the highest clay content. Although these soils have been randomly sampled, the grain-size distribution can provide some information on the soil structure related to the EM characteristics. For example, mineralogical investigation of the soil can indicate the source of the different grain-sizes and, in some cases, the source of the soil EM characteristics. In addition, this type of information can be enhanced, once the investigators return to the site and check the structure and grain-size composition of the different layer constituents of the soil. Considering the fact that the mineralogy (e.g., magnetite, hematite, maghemite) of the fine-sand and clay type (e.g., kaolinite, montmorillonite) components can have different effects on the MS and \(\rho\) characteristics (Tables 1 and 3), the good relationship seen between the EM characteristics and the grain sizes in Figure 5 could be coincidental. None-the-less, this figure presents a case worth serious consideration.

However, it is considered more efficient and accurate to set up geophysical strategies to collect samples representative of a site. An example of a soil electrical conductivity map in Figure 13, obtained by an EM-sounding technique, shows how inhomogeneous the soil conductivities can be. A vertical section of soil electrical conductivity distribution in Figure 14 and its inversion identify a relatively continuous conductive layer at about 2-4 m depth. This section was obtained by a multi-electrode ground-coupled EM sounding technique. Whereas this survey has used electrodes inserted into the ground, systems using capacitive electrodes that need not to be inserted into the ground are also available. The latter system is probably more applicable to mine fields. The results of surveys, such as, shown in these figures (Figures 13 and 14) and in Figure 10 will likely help narrow the target for sampling of representative soil material. Since surface geophysical methods can map large areas rapidly and efficiently, their use would be a validation step that should precede sampling.

Figure 13: An example of a soil electrical conductivity survey map, using an EM-31 electromagnetic...
system.

7. DISCUSSION AND CONCLUSIONS

The main source of magnetism in soils is ferro-magnetic minerals with strong magnetic susceptibility (MS) characteristics. The main source of electrical conductivity (EC) in soils is moisture, especially saline water, clays and electronically conductive metallic minerals. However, generally, metallic minerals are a significant contributor to soil EC only if their grains are interconnected. Since the origin of all of these electromagnetic (EM) sources is the bedrock, the first factor to be considered in predicting soil EM characteristics (MS and EC) is the distribution of the bedrock type underlying and surrounding the target area. The second factor to be considered for prediction of soil EM characteristics is soil formation history, including the climate history responsible for chemical alteration and transportation of various chemical species within and from the underlying bedrock. Third, is the physical transportation history of geological material into the area from soil and bedrock of surrounding areas.

Parallel to the three-step process described above, prediction from regional agricultural soil maps, air photographs and airborne geophysical maps would be helpful. Soil bulk density and cation ion exchange capacity (CEC) from agricultural soil maps can provide indications of possible existence of heavy minerals (e.g., ferro-magnetic minerals) and conductive clays. Air photographs can provide information on areas and their extent affected by transportation of geological material from surrounding areas. Airborne magnetic and radiometric survey maps can provide information on areas with high concentrations of ferro-magnetic minerals. The high frequency component of airborne EM survey maps can be expected to display areas of high soil conductivity.

Since layering is one of the structural characteristics of soil, with the possibility of ferro-magnetic and clay minerals being concentrated in a particular layer, predictions by the methods described above could be confused. Therefore, the final stage of a soil characteristic prediction should be surficial geological examination of land-form units, surficial geological units, variability within units, soil structure exposed in pits and erosional slopes in areas adjacent or similar to the target areas.
Laboratory analysis of soil samples is the final stage for validating the prediction of EM characteristics. However, it is necessary to select samples representative of the significant soil units, although appropriate analytical methods can provide much of the required information. Use of surficial geological and geophysical surveys (electrical and electromagnetic) can increase the efficiency and accuracy for setting up representative sampling strategies. Besides indicating the possibilities for improving landmine detecting methods and strategies to overcome the detection difficulties, this study has shown the complexity of the problem. Regardless of that, this study suggests that a multi-frequency EM system remains an option for metal detectors discriminating between metallic (including metallic minerals) particles isolated in landmine casings from those in direct contact with soil moisture. An additional factor of confusion to be considered in prediction is the destruction of conductive layers in the soil by agricultural and mine-laying activities. Such activities could break the continuity of clay rich layers and increase the soil resistivity, in an area that might have been predicted as having conductive soil.

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