Workshop on Soil Magnetism: Multi-disciplinary Perspectives, Emerging Applications and New Frontiers

Report

Jacqueline A. Hannam, Remke L. Van Dam and Russell S. Harmon
Workshop on Soil Magnetism: Multi-disciplinary Perspectives, Emerging Applications and New Frontiers: Report

Jacqueline A. Hannam¹, Remke L. Van Dam²
and Russell S. Harmon³

¹National Soil Resources Institute
School of Applied Sciences
Cranfield University
Cranfield MK43 0AL, U.K.
Email: j.a.hannam@cranfield.ac.uk

²Michigan State University
Dept of Geological Sciences
East Lansing, MI, U.S.A
Email: rvd@msu.edu

³U.S. Army Research Office
4300 S. Miami Blvd
Durham, NC, U.S.A
Email: Russell.harmon@us.army
Acknowledgement

The authors would like to thank the International Research Office (IRO) of the U.S. Army Engineer Research and Development Center (ERDC), in particular Julian Richmond, for the support to organize the workshop. RvD received additional support through Strategic Environmental Research and Development Program (SERDP) grant UX-1414. Finally, we wish to thank all the workshop participants for their contributions and enthusiasm that made the workshop a success.

Participants (l-r): Guenter Kletetschka, Len Pasion, Nicolas Lhomme, Thomas Mayr, Remke Van Dam, Adrian Muxworthy, Morten Bo Madsen, Mark Dekkers, Zdenek Hulka, John Crawford, Jack Hannam, John Dearing, Steve Billings, Yoga Das, Blair Kearney, Ryan North, Greg Harmer, Carl Chirgwin, Sven Altfelder, Hana Fialova, Pascal Druyts, Russ Harmon, Janet Simms, Michel Dabas, Mark Keene, Jan Igel, Yann Yvenic, Guenter Geiger, Holger Preetz, Neil Linford, Julien Thiesson (not pictured: Stephen Grant, Colin Jenkins, Ludovic Letourneur, Eric Foster).

This report should be referenced as:

Summary

Magnetic properties of soils have adverse effects on metal detectors, particularly hampering operations during clearance of landmines and unexploded ordnance.

Although there is well established research in soil magnetism and modeling electromagnetic induction systems, these have tended to exist in disparate disciplines. Hence, the workshop aimed to bring together researchers, academics, stakeholders, and manufacturers to discuss key priorities for research and technology in a unique multidisciplinary environment. The workshop was held 18-20 August 2008 at Cranfield University, U.K., with 35 participants.

Key knowledge gaps were identified in different disciplines and many of these were cross-cutting:

- Some mechanisms for the formation of magnetic minerals in soils are not well constrained.
- There is limited information on the spatial heterogeneity of soil magnetic properties in 2D and 3D, specifically in highly magnetic soil environments. This has fundamental implications for prediction of soil magnetic susceptibility and model parameterization.
- There is no good understanding of sensor performance based on a given set of soil properties and how this may additionally impact the efficacy of dual or multi sensor systems.
- Are there soils where the modelled \( 1/t \) response for frequency dependent soils is not appropriate?
- What are the implications for modeling where soils have heterogeneous magnetic properties within the depth and volume of investigation of the detector?
- Soil compensation methods in detectors need to be improved for highly variable soil environments.

Several funding priorities were identified to maximize future multi-disciplinary research and technology developments:

- Information on spatial variability in soil magnetic properties from small (target) to large (landscape) scale is required in 2D and 3D. Parameterization of the spatial variability would advance modeling to derive better constrained relationships between soil properties and detector response.
- Development of predictive models of soil magnetic properties, either through the use of pedotransfer functions or with process-based models would aid strategic planning. Additional soil and environmental properties pertinent to the efficacy of alternative detection systems and impacting on other Army activities should be investigated. Thus, a comprehensive decision support tool could be derived for clearance and Army activities.
Well constrained empirical data are required through measurements under controlled, repeatable conditions using artificial and natural soils and calibration standards. The measurements should cover the entire frequency range used by electromagnetic induction systems.

Improved communication between disciplines is key to effective targeting and realization of research priorities. Possible platforms include a multidisciplinary pilot study at an appropriate study site and the development of an online repository to assist dissemination of results and information.
# Table of contents

Acknowledgement ..........................................................................................i  
Summary ........................................................................................................ii  
1.0 Introduction..............................................................................................1  
2.0 Current knowledge in soil magnetism research ...................................2  
  2.1 Causes of soil magnetism ......................................................................2  
  2.2 Effects on detectors................................................................................3  
    2.2.1 Detector performance and soil responses during trials ....................3  
    2.2.2 Modeling ..........................................................................................4  
    2.2.3 Metal detector technology...............................................................6  
  2.2.4 Effects on other landmine and UXO detection systems ....................6  
3.0 Knowledge gaps ......................................................................................6  
  3.1 Soil, geology and weathering .................................................................6  
  3.2 Soil magnetic susceptibility ....................................................................7  
  3.3 Heterogeneity, scaling, and prediction ...................................................7  
  3.4 Modeling and measurement ...................................................................7  
  3.5 Instrumentation .......................................................................................7  
  3.6 Mine action and UXO detection ..............................................................7  
  3.7 Other ......................................................................................................8  
4.0 Directions for future research.................................................................8  
  4.1 Soil .........................................................................................................8  
  4.2 Theory and modeling..............................................................................9  
  4.3 Instrumentation .......................................................................................9  
  4.4 Communication ......................................................................................9  
References ...................................................................................................10  
Appendix 1 Presentation abstracts ...............................................................13  
  Keynote speakers (extended abstracts) .......................................................15  
  Additional speakers (abstracts) .................................................................57  
Appendix 2 Participant list ..........................................................................69
1.0 Introduction

In recent years it has become increasingly evident that magnetic susceptibility and particularly frequency dependent (FD) magnetic susceptibility of soils can have strong effects on the performance of electromagnetic induction and magnetic sensors (Billings and Youmans, 2007; Butler, 2003; Preetz et al., 2008; Zhang, et al., 2008). Superparamagnetic minerals in soils have FD properties and show similar decay signatures to metallic components of land mines and UXO, resulting in higher incidences of false alerts. In soils with high concentrations of FD minerals the ‘ground effect’ is so severe that detection by electromagnetic induction is sometimes not possible. Frequency-dependent properties are almost unique to iron oxides in soil environments that are formed naturally within the soil profile as it develops over time. Some soil environments are more conducive to the production of superparamagnetic minerals than others, resulting in heterogeneity of soil magnetic properties.

Available information in soil maps and surveys describe the spatial extent of different soil types but do not provide information on magnetic properties, as currently this is not part of any national or standard soil description procedure (Hannam and Dearing, 2008). Therefore, little information is available globally that is relevant to landmine and UXO metal detector technologies that are affected by electromagnetic properties. Magnetic properties of soils have traditionally been investigated in the environmental science and geophysics communities to indicate soil development (e.g. Singer et al., 1992) paleosols and climate (e.g. Maher and Thompson, 1995) and pollution (e.g. Hanesch et al., 2007). Also magnetic properties have been widely studied for archaeological prospection (Linford et al., 2005) and in the context of planetary studies (Kletetschka et al., 2000; Madsen et al., 1999). The application in mine and UXO detection and clearance is a relatively new consideration (Hannam and Dearing, 2008; Preetz et al., 2008; Van Dam et al., 2008) and communication between the academic community and mine clearance users is essential to further developments in soil magnetism and applications in demining technologies.

A workshop entitled “Workshop on Soil Magnetism: Multi-disciplinary Perspectives, Emerging Applications and New Frontiers” was organized from August 18-20, 2008, at Cranfield University, U.K. This workshop, sponsored by the International Research Office (IRO) of the U.S. Army Engineer Research and Development Center (ERDC), brought together a group of researchers and technologists from a broad spectrum of disciplines to discuss the theoretical base of soil magnetism and to identify emerging applications of soil magnetism in environmental, geological and soil sciences. The workshop included several keynote lectures and break-out sessions to define the current state of understanding, identify knowledge gaps, and determine priority areas for research investment and technology development. This report summarizes the outcomes of the workshop.
2.0 Current knowledge in soil magnetism research

2.1 Causes of soil magnetism

The basic causes for soil magnetism are well established and have been documented in textbooks and seminal papers (e.g. Dearing et al., 1996; Maher, 1998; Maher and Taylor, 1988; Mullins, 1977; Singer et al., 1996; Thompson and Oldfield, 1986). Soils with enhanced magnetic properties are a result of the presence of ferrimagnetic minerals (commonly iron oxides) in soils and are derived from a number of sources. These sources can be grouped around several key processes end members, including:

1. Magnetic minerals weather directly from basic and ultrabasic bedrock and result in the accumulation of primarily coarse grained (~ 10 μm) minerals (commonly with Ti and Ni substitutions) in overlying soils. These minerals are of primary lithogenic origin and are relatively unaltered by soil processes.

2. A ‘fermentation’ mechanism involves the weathering of iron from magnetic and non-magnetic soil parent material; the weathered product is transformed to magnetic phases via soil forming processes under oxidizing-reducing conditions. These processes tend to form fine-grained (<0.1 μm) secondary magnetite / maghemite with stable single domain (SSD) and superparamagnetic / viscous (SP) properties. In much of the early literature (e.g Le Borgne, 1955; Mullins, 1977) this is referred to as ‘magnetic enhancement’, indicating the topsoil has elevated values of magnetic susceptibility and frequency dependent magnetic susceptibility in comparison to the subsoil and soil parent material.

3. Fire transforms non-magnetic iron oxides to magnetic minerals of predominantly fine grained SSD and viscous SP grains.

4. Allochthonous sources include atmospheric pollution, and soil erosion and deposition. Atmospheric pollution from combustive sources such as coal-fired power and steel works tend to form large (~ 10 μm) minerals with varied compositions. Magnetic soil material eroded from other areas has the potential to be of mixed composition.

5. Other potential minor sources may include micrometeorites (allochthonous) and SP minerals from magnetic bedrock (in-situ).

Thus, the dominant drivers for the occurrence of magnetic soils are bedrock type (especially basic igneous rocks) and pedogenic conditions favoring the formation of secondary ultrafine magnetic minerals soils. However, there is a lack of specific understanding of the subtleties that control distribution of magnetic materials, particularly the conditions that favor the development of secondary minerals as a result of soil forming processes. Currently, no predictive model exists that links all these processes and sources.
2.2 Effects on detectors

Frequency dependent magnetic susceptibility is common to many soils that are problematic for metal detectors. This frequency effect is caused by viscous ferrimagnetic minerals that have a time-delayed response to an induced field similar to that of decaying eddy current produced by metallic components of mines. Evidence from clearance operations suggests that certain soils (1) can reduce the sensitivity of detectors so they cannot detect targets to desired depths; (2) can cause false targets; and (3) in extreme cases can render some detectors totally unusable. In addition, the effects of problem soils appear to be much worse now than in previous conflicts as users are trying to find very small metallic components (i.e. in ‘minimum metal landmines’) against strongly magnetic soil backgrounds found in many mine-affected tropical regions. However, direct or indirect relationships need to be established between soil magnetic properties and detector effects (for different systems) so that the performance of metal detectors can be predicted.

2.2.1 Detector performance and soil responses during trials

During metal detector trials using test lanes a ground reference height (GRH) method was developed to assess soil effects on metal detectors (Guelle et al., 2003; Guelle et al., 2006). The method uses a Schiebel AN 10 Mod9 detector where sensitivity is adjusted to a reference object (test piece or 10mm steel ball) in air. The detector is then placed on the ground surface and raised until the alarm ceases; the corresponding height is the GRH. GRH values have been positively correlated with FD magnetic susceptibility measurements of the soils used in test lanes during detector trials (Figure 1). Indicative ground reference height values, magnetic susceptibility values and corresponding potential effects on detectors have been identified in a CEN (European Committee for Standardization) Workshop agreement (CEN, 2008) and are summarized in Table 1. Although the GRH gives a rapid field assessment of potential detector performance, extrapolating the results to other detector models is difficult.
Figure 1 Relationship between GRH and magnetic susceptibility. $\chi_{LF}$ magnetic susceptibility at 465 Hz; $\chi_{FD}$ frequency dependent susceptibility is the difference of magnetic susceptibility between 465 Hz and 4650 Hz. GRH measured using a Scheibel AN19 Mod 7 detector. (Adapted from Hannam and Dearing, 2008).

<table>
<thead>
<tr>
<th>Soil effect</th>
<th>GRH (cm)</th>
<th>Magnetic susceptibility (978Hz) $\times 10^{-5}$ SI</th>
<th>Frequency dependent susceptibility (465 and 4650 Hz) $\Delta\times 10^{-5}$ SI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutral</td>
<td>&lt;1</td>
<td>&lt; 50</td>
<td>&lt;5</td>
</tr>
<tr>
<td>Moderate</td>
<td>1 to 10</td>
<td>50 to 500</td>
<td>5 to 15</td>
</tr>
<tr>
<td>Severe</td>
<td>10 to 20</td>
<td>500 to 2000</td>
<td>15 to 25</td>
</tr>
<tr>
<td>Very severe</td>
<td>&gt;20</td>
<td>&gt; 2000</td>
<td>&gt; 25</td>
</tr>
</tbody>
</table>

2.2.2 Modeling

The relationships between soil magnetic properties and detector effects have been investigated primarily by modeling as there are very few commercially available instruments that can measure magnetic susceptibility over the complete frequency range in which most detectors operate. Specifically, homogenous halfspace models with frequency-dependent complex magnetic susceptibility have been developed to determine the effect of magnetic soils on metal detectors (Das, 2006; Meglich, et al., 2008). A generalized magnetic susceptibility model is described below (Equation 1), where the susceptibility is modeled as a complex quantity, where $\chi'$ and $\chi''$ are the real and imaginary parts of susceptibility. $\chi_0$ is d.c. susceptibility, and $\tau_1$ and $\tau_2$ are the limits of the relaxation times of soil magnetic grains. This particular model assumes the time constant distribution to be log-uniform.
Based on the model, several observations were made (also see Appendix 1 Das)

- Continuous wave and pulse system metal detectors will behave differently to soil magnetic properties as far as a user is concerned. Previous modeling work (Das, 2006) shows the influence of soil magnetic properties far exceed (by orders of magnetite in some cases) that of soil conductivity. With the exception of very specific situations, typical soil conductivities are generally too low to exert a strong effect on detectors.

- If the soil is non-conducting and has a frequency-independent susceptibility (Equation 2); the soil-induced voltage will affect all frequencies in a continuous wave detector and the user will see a strong effect on the imaginary part of the signal (Equation 3). In pulse systems the effect is concentrated at a particular time (the transition of the transmitter pulse) and hence in principle it would not affect the general operation of the detector (Equation 4).

\[
\frac{\partial \chi'}{\partial \ln \omega} = \frac{2}{\pi} \chi'' = -\frac{\chi_0}{\ln(\tau_2/\tau_1)}
\]  

(1)

- If the soil is non-conducting, but has frequency-dependent susceptibility (Equation 5), which is the case for many soils reported to cause problems with detection, both continuous wave and pulse systems are affected. In the time domain, the response from soils with frequency dependence of susceptibility is typically 1/t (Equation 6).

\[
\sigma_1 = 0 \quad \chi(\omega) = \chi_0
\]  

(2)

\[
\text{CW : } v_{\text{soil}}^{\text{soil}}(\omega) \propto \left[ \frac{\chi_0}{2 + \chi_0} \right] i\omega
\]  

(3)

\[
\text{Pulse : } v_{\text{soil}}^{\text{soil}}(t) \propto \left[ \frac{\chi_0}{2 + \chi_0} \right] \delta(t)
\]  

(4)

\[
\sigma_1 = 0 \quad \chi(\omega) \neq \text{constant}
\]  

(5)

\[
\text{Pulse : } v_{\text{soil}}^{\text{soil}}(t) \propto \frac{\chi_0}{2\ln(\tau_2/\tau_1)} \cdot \frac{1}{t}
\]  

(6)

- Some soils can produce such a strong response that it exceeds the response from a buried metal target under certain conditions.

- Although in many cases soil signals are found to exceed target signals, no definitive statement about the detectability of a target in soil can be made solely from this
observation as considerations of soil horizontal uniformity and the particular design of a detector need to be taken into account.

### 2.2.3 Metal detector technology

Many metal detectors are equipped with soil rejection techniques, where signal processing algorithms separate the signals from the soil and metallic target. However, details on the exact nature of these techniques are limited because they have been primarily developed by metal detector manufacturers. Although these detectors present significant improvements in detectability compared to detectors without soil compensation, they can still be affected by soils with high magnetic susceptibility. In some cases the signals from the soil and metallic targets can only be partially separated, the depth sensitivity is reduced and signals are difficult to compensate when there is high spatial heterogeneity of magnetic susceptibility.

### 2.2.4 Effects on other landmine and UXO detection systems

Other geophysical techniques affected by strongly magnetic soils are magnetic sensors and ground-penetrating radar. Magnetic sensors are particularly affected by the induced magnetization, which is associated primarily with soils and parent materials rich in ferrimagnetic minerals. Relatively little is known about the limitations of magnetic soils for ground penetrating radar (GPR) (Cassidy and Millington, 2009). It has been widely recognized, however, that not all methods can work under all circumstances. Therefore, multi-sensor platforms and joint inversion may be needed to maximize identification and characterization of subsurface targets (Pasion et al., 2008).

### 3.0 Knowledge gaps

The workshop used breakout sessions (three cross-disciplinary groups of ~10 people) to identify current gaps in knowledge, where some may be the result of poor communication across disciplines. The outcomes are summarized in seven categories and examples for identified gaps are provided.

#### 3.1 Soil, geology and weathering

- How do weathering mechanisms favor formation of magnetic minerals and consequently impact the magnetic susceptibility values of soils?
- How common are primary lithogenic SP grains weathered from bedrock?
- Can we define the importance of and identify past climate, specifically for soils that have long weathering histories commonly found in mine affected regions?
3.2 Soil magnetic susceptibility

- There is insufficient understanding of soil magnetism in tropical soils and of the influence of bacteria in the formation of in-situ minerals.
- As not all the processes of formation are well understood it is difficult to use magnetic measurements as a proxy for other soil functions/properties.
- A data base of magnetic properties of soil types that are common in mine affected regions would be useful.
- Too much time is currently required to make high-quality measurements and to produce useful data and maps.

3.3 Heterogeneity, scaling, and prediction

- How does in-situ formation of minerals relate to the conditions in lab experiments where magnetite has been produced in-vitro?; how to up-scale the lab experiments?
- Gaps exist in the knowledge of heterogeneity of magnetic soils over a range of scales from target size, to field and landscape scales.
- How can changes in soil magnetic properties across landscapes be predicted?
- Small scale heterogeneity “hot rocks” - need better algorithms for calibration of instruments.
- How does small scale soil variability relate to the operating range (decimetres and few metres) of a deminer using a metal detector?

3.4 Modeling and measurement

- There is a lack of empirical experimental data to test and confirm theory and modeling results, and to provide input for model parameterization.
- The frequency-dependent magnetic susceptibility model with 1/t decay characteristics needs to be better understood. Are there soils where this model is not appropriate?
- What are the effects of laterally variable magnetic properties within the depth of investigation of the sensor?
- The volume of investigation needs to be better parameterized, particularly in heterogeneous soil.

3.5 Instrumentation

- Currently no rigorous mechanism is available to select standards for calibration of instrumentation.
- Multi-sensor platforms are needed to identify and characterize a target fully but it is essential that cross-calibration of these sensors is achieved.
- Methods and algorithms for metal detector compensation must be improved.

3.6 Mine action and UXO detection

- Small-scale heterogeneity (e.g. hot rocks) and surface roughness effects show the need for better algorithms for instrument ground compensation.
• Understanding of the meaning of ground reference height (GRH) measurements in the context of viscous remanent magnetization (VRM) needs to be improved.
• There is no good understanding of the prediction of sensor performance based on a given set of soil properties.
• Discrimination between hazardous vs non-hazardous material in UXO studies requires higher quality data, including soil influence and height variation.
• Characterization of soil magnetic susceptibility, conductivity and permittivity could be achieved through constructing artificial soils.
• Are current assumptions of the distribution of magnetic susceptibility as a function of frequency accurate? Measurements in the entire frequency range of metal detectors are required.

3.7 Other
• Planetary studies: Should a fluxgate magnetometer be included on the next Mars mission? How effective will it be?
• Geomagnetism: Geomagnetic field intensity as a function of time is not always known (in comparison to inclination and declination).
• Geomagnetism: Grain-size distribution to coercivity relationship is not always known.

4.0 Directions for future research
Directions for further research are grouped around three themes: soils, theory/modeling, and instrumentation. The following are highlighted as the priority areas for research, many of which cross-cut disciplines.

4.1 Soil
• Spatial variation of magnetic properties of soils needs to be addressed across a range of scales from landscape to plot and target scales to inform strategic planning and on-the-ground applications, respectively.
• There is a strong need for the development of predictive models of soil magnetic properties, either through the use of pedotransfer functions or with process-based models. Expert systems should be developed that can predict a) magnetic properties, b) other soil properties impacting geophysical sensors (e.g. for GPR, Doolittle et al., 2007), and c) additional environmental factors important for army related activities.
• 3D variation is clearly important but more research is needed to define the appropriate spatial scale required to improve modeling efforts. Additionally, more research in complementary geophysical techniques (e.g., GPR for soil horizon depth estimates) and multi-sensor platforms and joint inversion is needed.
4.2 Theory and modeling

- Spatial variability in soil magnetic properties needs to be incorporated into modeling. Improved data is required to parameterize (statistical) models to represent scale and magnitude of soil magnetic properties and effects on detector systems. This would represent more realistic soil scenarios improving on the current homogenous half space models.

- The links between soil properties and sensor effects need to be better constrained. Hence, measurements under controlled, repeatable conditions using artificial and natural soils and calibration standards should be performed.

4.3 Instrumentation

- Standard calibration materials are required and calibration between field and laboratory instruments is necessary.

- Efforts should be made to invert geophysical properties to estimate mineral distribution and characteristics.

- User-proof instrumentation design, for example including automatic calibration and check responses, should be developed. Development of field and lab instrumentation should include increased field strengths, frequency and temperature ranges to improve detection / characterization of SP grains and ‘hard’ minerals (minerals difficult to magnetize) such as goethite and hematite.

4.4 Communication

A cross-cutting theme at the workshop was to improve information dissemination between user groups. For example, anecdotal evidence of detector effects from end-users in the field should be better reported to aid modelers in providing answers and offering solutions to the problems. Also, volume-specific magnetic susceptibility measurements of soils undertaken by soil and environmental scientists can be used to develop and constrain models and instrumentation. In summary, better communication and partnerships between disciplines should be developed and encouraged. Possible platforms for such improved communication include a multidisciplinary pilot study at an appropriate study site and the development of an online repository to assist dissemination of results, and to include soil information (e.g., as a database) and additional data (e.g., from field to theory), reports, and pertinent references.
References

Additional references related to the keynote talks are supplied in Appendix 1


Appendix 1 Presentation abstracts

Presentations given at the workshop are provided in additional documents accompanying this report (SMW_Mondaytalks.pdf and SMW_Tuesdaytalks.pdf). The following section provides some additional text that accompanies the keynote presentations to give an overview of current knowledge in multidisciplinary aspects of soil magnetism. Abstracts by additional speakers are also provided. Poster authors and poster titles are also listed.

**Keynote speakers**

<table>
<thead>
<tr>
<th>Keynote speakers</th>
<th>Presentation title</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dr Yogadish Das</td>
<td>Soil magnetism and landmine (metal) detectors</td>
</tr>
<tr>
<td>Prof John Dearing</td>
<td>Soil magnetism: theory, hypothesis-testing and modelling</td>
</tr>
<tr>
<td>Dr Mark Dekkers</td>
<td>Coercivity spectrum analysis as a tool for assessing the size distribution of magnetic particles</td>
</tr>
<tr>
<td>Dr Mark Keene</td>
<td>Metal detector technologies for difficult soils</td>
</tr>
<tr>
<td>Dr Neil Linford</td>
<td>Archaeogeophysics: Applications and challenges for magnetic methods</td>
</tr>
<tr>
<td>Dr Morten Bo Madsen</td>
<td>Magnetic properties of dust and soil by the landed missions on Mars</td>
</tr>
<tr>
<td>Dr Thomas Mayr</td>
<td>Digital Soil Mapping – spatial variability and prediction of soil properties</td>
</tr>
<tr>
<td>Dr Janet Simms</td>
<td>The influence of magnetic soils on Army activities</td>
</tr>
</tbody>
</table>

**Additional Speakers**

<table>
<thead>
<tr>
<th>Additional Speakers</th>
<th>Presentation title</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mr Carl Chirgwin</td>
<td>The challenges of soil magnetism to efficient UXO remediation in a commercial environment</td>
</tr>
<tr>
<td>Mr Pascal Druyts</td>
<td>Volume of influence for the response of magnetic soils to electromagnetic induction sensors</td>
</tr>
<tr>
<td>Dr Jacqueline Hannam</td>
<td>Spatial prediction of soil magnetism using digital terrain analysis</td>
</tr>
<tr>
<td>Dr Guenther Kletetschka</td>
<td>Magnetic signatures of soil due to wild fires</td>
</tr>
<tr>
<td>Dr Nicolas Lhomme</td>
<td>Discrimination of buried metal objects in soils with viscous remanent magnetization</td>
</tr>
<tr>
<td>Mr Ryan North</td>
<td>Multifrequency soil electromagnetic property characterization</td>
</tr>
<tr>
<td>Dr Len Pasion</td>
<td>Soil compensation techniques for the detection of buried metallic objects using electromagnetic sensors</td>
</tr>
<tr>
<td>Dr Holger Preetz</td>
<td>Soil susceptibility and landmine detection</td>
</tr>
<tr>
<td>Dr Yann Yvenic</td>
<td>An international collaboration to write guidelines to characterise soil impact on metal detectors and GPRs</td>
</tr>
</tbody>
</table>

**Poster Presentations**

<table>
<thead>
<tr>
<th>Poster Presentations</th>
<th>Presentation title</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dr Sven Altfelder</td>
<td>Classifying tropical soils with regard to landmine detection</td>
</tr>
<tr>
<td>Dr Michel Dabas</td>
<td>Feasibility of a towed electromagnetic and magnetic platform</td>
</tr>
<tr>
<td>Dr Hana Fialova</td>
<td>Strongly magnetic soils developed on limestone: a case study</td>
</tr>
<tr>
<td>Dr Jacqueline Hannam</td>
<td>Soil magnetism mapping in Bosnia and Herzegovina</td>
</tr>
</tbody>
</table>
Dr Jan Igel  
Magnetic soil properties and their spatial variability on former minefields in Mozambique

Mr Ryan North  
Identification of naturally occurring false alarms at Jefferson Proving Ground

Dr Holger Preetz  
Soil susceptibility map of Angola - A basis for predicting metal detector performance

Dr Julien Thiesson  
Are magnetic properties a possible proxy of the carbon content in soil?

Dr Remke Van Dam  
From rock to soil: changes in magnetic properties during weathering of basalt
Soil magnetism and landmine (metal) detectors

Although a large variety of technologies are being researched for landmine detection, the metal detector is the most widely used tool for detecting landmines at the present time. Metal detectors all work on the principle of electromagnetic (em) induction. In em induction a time varying (either pulsed or continuous wave) magnetic field is created by sending a current through a coil. Conducting and magnetic bodies in this field interact with this field and produce a secondary magnetic field which induces a signal in a receiver coil. This signal depends on many factors but the electromagnetic properties of some soils can influence this signal and can adversely affect the operation of a metal detector. The ability of a detector to deal with such a “problem soil” is of great importance in demining since many of the affected countries have soils problematic for detection.

Historically, this effect was recognized during World War II and some detector models were subsequently fitted with a means to reduce this effect. It was referred to as the “pave effect” because road stones containing magnetic iron oxides were known to cause it and consequently some research effort was conducted on the subject during 1945-47. However since then the problem seems to have been largely ignored by the mine detection community and interest in the issue has only recently been renewed. This arose from field observations during humanitarian demining that identified certain soils, particularly in tropical environments, were causing problems during metal detector use.

What is the nature of the problem that soil causes to metal detectors?

- Users have found that certain soils (1) can reduce the sensitivity of detectors so they cannot detect targets to desired depths; (2) can cause false targets; and (3) in extreme cases can render some detectors totally unusable.
- The “soil problem” appears to be much worse now than in previous conflicts. Users are trying to find very small pieces of metal (in so-called minimum metal landmines) in strongly magnetic soils found in many mine affected in tropical areas.
- This was the situation around the year 2000. Although there was a slow realization that certain soils are a problem, there was much confusion in the user community and even in the research community about what caused it or how to characterize it. You
often heard people talk about “conducting soil”, “lateritic soil”, “red soil”, “iron content” in soil and so on. For example researchers often carried out extensive texture and chemical analysis of soil, including determining the iron content to characterize the effect, but did not measure electromagnetic properties of soils.

- There was also the issue of how to set up test soil lanes and tests to reliably compare or predict the relative performance of detectors in coping with different soils expected in different parts of the world. There a number of ITEP publications relating to test and evaluation in mine affected regions and test lanes (http://www.itep.ws).

Faced with the above scenario, the research issues were identified and scientists at CCMAT (The Canadian Centre for Mine Action Technologies) and researchers in other countries started addressing the following issues.

- To identify electromagnetic properties that are relevant to the ‘soil problem’ and determining the appropriate instrumentation required or available to measure them effectively.
- Study the relevant parameters in well-known problem soils of the tropics where most landmines also happen to exist.
- Quantifying their effects on metal detector performance.
- Establish either directly or indirectly, the relationship between values of these properties and the performance of detectors of various designs such as pulse or continuous wave operation.
- Use this information to develop a database for soils of mine affected countries in various parts of the world.

**Simple analytical modeling conducted by CCMAT**

*Model methods*

Geophysical techniques applied specifically to the mine detection geometry where:

- the soil is represented as a homogeneous half-space (although it is recognized that horizontal variation of properties will likely be the limiting factor in practice ),
- constant conductivity,
- no displacement current, and
- based on some previous experience assumed a certain general frequency-dependent model for the soil magnetic susceptibility.

The susceptibility is modeled as a complex quantity where $\chi'$ and $\chi''$ are the real and imaginary parts of susceptibility, $\chi_0$ is d.c. susceptibility, $\tau_1$ and $\tau_2$ are the limits of relaxation.
times of soil magnetic grains. This particular model assumes the time constant distribution to be log-uniform.

In numerical computation, one can use this general model assuming one knows the parameters $\chi_0$, $\tau_1$ and $\tau_2$; but it is very difficult to use it in analytical solutions. Luckily for most natural soils and metal detector frequencies a useful approximation can be made. The model reduces to this simple one under certain conditions (as shown here) that are valid for most real-world soils. The slope of $\chi'$ wrt $\ln \omega$, where $\omega$ is the radial frequency. The metal detector is modeled with coplanar transmitter coil of radius $a$ and a $\text{rx}$ coil of radius $b$ at a distance $h$ over the ground.

$$\chi(\omega) = \chi'(\omega) + i\chi''(\omega) = \frac{\chi_0}{1 - \frac{1}{\ln(\frac{\tau_2}{\tau_1})}} \cdot \ln \left( \frac{i\omega\tau_2 + 1}{i\omega\tau_1 + 1} \right)$$

$$\frac{\partial \chi'}{\partial \ln \omega} = \frac{2}{\pi} \chi'' = -\frac{\chi_0}{\ln(\frac{\tau_2}{\tau_1})}$$

when $\omega\tau_1 << 1$ and $\omega\tau_2 >> 1$ (or equivalently $t/\tau_1 >> 1$ and $t/\tau_2 << 1$)

Key results and outcomes

- CW and pulse systems behave differently to soil properties as far as a user is concerned.
- Soil magnetic susceptibility has a much stronger effect than conductivity.
- If the soil is non-conducting and has a frequency independent susceptibility, then in a CW detector, the soil-induced voltage will affect all frequencies and the user will see a strong effect on the imaginary part of the signal, while for a pulse system the effect of such soil is concentrated at a particular time (the transition of the transmitter pulse); hence it would not affect the general operation of the detector in principle.
- If the soil is non-conducting, but has frequency-dependent susceptibility (this is the case with a lot of real-world problem soils) both CW and pulse systems are affected.
- For pulse systems, which constitute the bulk of the detectors in use, the soil signal has a 1/t variation which is stronger than the signal from a target that is only conducting t to the power -5/2.

Expanding on the simple modeling with additional measurements using a small conducting sphere as a target (representing the small metal parts in a mine) we further learned:

- that real-world soils can produce a strong response which can exceed that due to the buried metal target under certain situations;
- although soil signal was found to exceed target signal in many cases, no definitive statement about the detectability of a target in soil can be made just from that.
observation – one needs to consider horizontal uniformity of soil and the particular
design of a detector;

- that for many real-world magnetic soils the response to the target itself is not
  significantly changed by soil (i.e. no significant shielding effect). This is a positive
  aspect as it allows in-air target response (which is easier to calculate) to be used in
  calculations. In essence the in-air target response can be added to soil response to
  estimate response from a buried target.

Modeling work is continuing and is being conducted by various researchers looking in detail at
the interaction of soil and a metal detector.

**Soil electromagnetic property measurements**

**Soil conductivity**

- Several instruments were available for laboratory and field use and it was a matter of
  choosing an appropriate one.

**Soil magnetic susceptibility**

- There was hardly any suitable commercial instrument available to measure relevant
  magnetic properties during the early research period, except for the Bartington dual
  frequency MS2 system.
- A number of instruments have since been developed that are capable of measuring
  susceptibility spectrum of soils over a wide range of frequencies. One such example
  is the University of Toronto spectrometer that we helped develop (West and Bailey,
  Proc SPIE vol 6217 6217021, [2006]). This is the only instrument currently that
  provides both the real and imaginary parts of susceptibility spectrum.

**Soil property database**

Why do we need to develop such a database?

- Landmines are buried in the top 30 to 50 cm of soil and the properties of this near-
surface layer affect a wide range of mine detection technologies including metal
  detectors and ground penetrating radar (GPR).
- The large amount of information that exists for soil properties were developed for and
  mostly meant for agricultural, environmental and other such applications. Little or no
  information seems to exist in a form that is directly useful to humanitarian demining
  and the related R&D community.
- Thus there is a need for information on soil properties specifically related to mine
detection and related technologies.

Who could use such information?
• Organizations that plan demining operations such as the United Nations Agencies and in-country demining organizations could use this information in their planning and proper equipment selection.
• Manufacturers of detectors could use this information to improve their detectors.
• Organizations engaged in landmine detection research and test and evaluation would benefit from such data in developing detectors as well as in setting up test soil lanes and test plans for performance evaluation of detectors.

Towards achieving the research goals

• The World Congress of Soil Science and other soil-related scientific organizations were approached in 2002 for help; although there was a lot of interest there were no concrete actions.
• CCMAT carried out analysis and spot measurements of electromagnetic properties of soils from many mine-affected regions – enough to confirm the wide variation of magnetic properties of soil in various regions.
• We also studied the possibility of predicting soil conductivity from RadarSat data.
• There are some ongoing feasibility studies, which were inspired by this requirement, to see if one can predict electromagnetic properties of soil from a knowledge of conventional soil classification data, geological data, climatic data and so on. This is a tall order, but if a successful model could be developed from these efforts it will reduce the effort required for direct measurement.
• A project (CCMAT, ITEP and Institute of Agropedology, Sarajevo) measured and mapped magnetic properties of soils in Bosnia and Herzegovina. The magnetic susceptibility at two frequencies using the Bartington MS2 was measured on a subset of archive soil samples and used to produce susceptibility maps for the entire country (Hannam and Dearing, 2008).
• The Leibniz Institute for Geosciences and CCMAT have just started a project of spectrum measurement of some 1000 soil samples from all over the world (Preetz, et al, 2007).

Further studies and directions

• We need to study the effect of small scale spatial variation of soil magnetic susceptibility on metal detectors. Pascal Druyts of Royal Military School of Belgium has started some work on this.
• Further studies on the effect of voids in soil are required, although studies have been done in the past, suitable experiments are lacking. I have recently done some work in this area to see if the void created by the plastic casing of a mine has an effect on the signal produced by it.
A need to develop calibration standards and agree on some soil standards to use in test and evaluation. Ryan North of the Engineer Research and Development Center has done some work on this.

Study the effect of conductivity in conjunction with susceptibility and possibly the frequency dependence of conductivity if appropriate. Dr. Guy Cross of Terrascan Geophysics has started some work on this.

There is need for improved and less expensive in-situ methods of measuring soil properties related to detection performance.

Extend the soil property database development work - through modeling and in-country measurements.

Improve the techniques of mitigating the problems caused by soil. Real time techniques and experiments are needed.

There is an immediate need to do a similar investigation on the effect of soil on the performance of GPR since some GPR systems are in the early stages of field deployment in humanitarian demining.

Extend the studies to properties of soil that affect the host of other detection techniques under research.

As a final comment, because of the shift in international focus away from demining since 911, I am concerned that some of the aforementioned issues may not be completed due to lack of allocated resources.
Professor John Dearing

School of Geography,
University of Southampton,
Southampton UK
email: j.dearing@soton.ac.uk

Soil magnetism: theory, hypothesis-testing and modeling

John Dearing (Southampton), Anthony Blundell (University of Liverpool), John Boyle (University of Liverpool), Jacqueline Hannam (Cranfield University).

The magnetic properties of soils is a subject first addressed more than 50 years ago by Le Borgne. Since then, there have been several theories put forward to explain the concentration and distributions of the ferrimagnetic minerals: biotic transformation of hydrous ferric oxides (redox cycling); abiotic transformation of hydrous ferric oxides; dehydration of lepidocrocite (FeOOH); residual primary minerals; magnetic inclusions in silica sand grains; micro-anaerobic magnetotactic bacteria; anaerobic dissimilatory bacteria (GS-15); greigite (Fe$_3$S$_4$); burning; and atmospheric contamination. The generally accepted view is that most soils produce secondary nanoscale iron oxides magnetite/maghemite in surface horizons. These minerals contribute to measurements of low field magnetic susceptibility and frequency-dependent susceptibility because the grain sizes straddle the boundary between superparamagnetic (SP) and single domain (SD) ferrimagnetic magnetic properties.

The role of environmental factors in the formation of secondary ferrimagnetic minerals (SFMs) in temperate soils has been recently studied in an analysis of over 5000 surface soils from England and Wales. It was found that parent material and drainage are the dominant explanatory factors (together account for ~30% magnetic variability), while mean annual rainfall, slope and altitude, land use, organic carbon and pH are significant secondary factors. Mean annual temperature and time were found not to contribute to an explanatory model at this scale. These results are consistent with SFM production driven by Fe-supply from weathering, followed by the production of hydrous ferric oxides with conversion to ferrimagnetic minerals within the SP and SD grain size ranges. The secondary importance of organic carbon and pH suggests that biomineralization through bacteria-mediated Fe reduction plays a role in the production of SFMs.

With ~45–110 million landmines remaining to be cleared worldwide there is the pressing need for efficient land mine detection. Landmine detection using electromagnetic methods is often hampered by interference in so-called ‘problem soils’. Previously, the interference was believed to be due to the electromagnetic properties of soils, primarily magnetic permeability
and electrical conductivity. New research suggests that a more important property is the magnetic effect of magnetic iron oxides that form in the soil, especially magnetically viscous grains at the boundary of superparamagnetic and stable single domain states. A first attempt at classifying and mapping ‘problem soils’ on this basis worldwide suggests that they exist in 74 out of the 87 listed landmine-affected nations. For Bosnia-Herzegovina, national soil magnetic maps produced by analogue and measurement methods show that the dominant soils in northern Bosnia tend to be unproblematic for detectors, while in central Bosnia there is likely to be moderate detector interference. However, there is a high likelihood of dominant soils affecting detectors in southern and western Bosnia and Herzegovina, equivalent to ~30% of the total land area.

First attempts to produce a process based model of SFM formation are encouraging. The model is based on a theoretical scheme for the competitive production of magnetite and goethite/hematite from hydrous ferric oxides (HFO eg. ferrihydrite) through oxidation and reducing conditions in presence of dissimilatory iron reducing bacteria (DIRB). A mineral weathering model (ALLOGEN) is used to provide outputs of Fell as inputs to new model simulating secondary magnetite. Simulated production of magnetite and goethite/hematite production through oxic-anoxic cycles shows the build up of Fe oxides during the initial oxygenated stage, followed by the rapid build up of magnetite during the anoxic phase. The impact of P-E (runoff) on magnetite production shows similar relationships to empirical rainfall-susceptibility curves for loess regions. A preliminary comparison of simulated and observed magnetic properties for the England and Wales dataset supports the view that Fe supply rate is a pivotal factor, which in turn implies that the time factor (longevity of pedogenesis) may be important.

Overall, the conclusions of this review are:

- Regional-global databases point to the majority of soil magnetic properties as dominated by secondary SP/SSD ferrimagnetic minerals;

- Modeling strongly supports the theoretical view that Fe supply rate is the dominant driving process, at least in temperate zones;

- Strong relationships between mapped soil units and soil magnetism suggests that analogue approaches to modeling soil magnetism are appropriate;

- Early stages of process modeling are promising and may provide alternative means for reconstructing climate from palaeosol magnetism.

Key references:


Dearing, J.A. and Hannam, J.A. Landmine detection and soil magnetism: a global assessment, Environmental Science and Technology (in review)


Coercivity spectrum analysis as a tool for assessing the size distribution of magnetic particles

Individual data points of, for example, the acquisition of isothermal remanent magnetization (IRM) as function of applied field (at room temperature) represent the contribution of more than one mineral in cases of mixed magnetic mineralogy, the rule in natural samples. Therefore, interpretation in terms of grain size required for paleomagnetic and environmental analysis is less straightforward. Coercivity spectrum fitting enables such analysis in detail, it relies on an appropriate base function that describes the behavior of individual coercivity components. In the absence of significant magnetic interaction a cumulative log-Gaussian (CLG) function is reasonable (Robertson and France, 1994, Phys. Earth Planet. Inter., 82, 223-234). Individual components making up a measured IRM acquisition curve add linearly (e.g. Carter-Sltglitz et al., 2001, J. Geophys. Res., 106, 26397-26411). A more generalized base function is the Skewed Generalized Gaussian (SGG) base function proposed by Egli (2003, J. Geophys. Res., 108, Art. 2081). In CLG fitting a particle assemblage from a single coercivity component (magnetic mineral) is characterized by three free parameters: (1) the saturation IRM (SIRM), (2) the field at which half of the SIRM is reached: $B_{1/2}$ (or $B_{cr}$) and (3) the width of the distribution: the dispersion parameter DP, given by one standard deviation of the logarithmic distribution. Processing IRM acquisition curves by fitting log-normal components is straightforward (Kruiver et al., 2001, Earth Planet. Sci. Lett., 189, 269-276; Heslop et al., 2002, Geophys. J. Int., 157, 58-64) but limited by the symmetry dictated by the distribution. Skewed distributions must be fitted mathematically by two components while the physical meaning of the skewness is magnetic interaction and/or thermal activation (Heslop et al., 2004, Gephys. J. Int., 157, 55-63; Egli, 2004a, Phys. Che. Earth, 29, 851-867). The physical interpretation of the parameters in SGG fitting or its simpler CLG version is still being refined. Also typical ranges for DP and skewness are being explored (kurtosis appears to be irrelevant). The current understanding of the physical meaning of the fitted parameters is as follows.

S(IRM): The concentration parameter, the abundance of the given coercivity component.

$B_{1/2}$: The median acquisition field. The midpoint of the coercivity component.

DP: The width of a component, the distribution of microcoercivities. Ideal crystals with a minimum amount of lattice defects have a narrow microcoercivity distribution. Very wide components are physically less realistic. In IRM acquisition curves, biogenic magnetite has DP values of ~0.15 (log field units) (Kruiver and Passier, 2001, Geochem. Geophys. Geosyst,
2, Art 2001GC000181; Egli, 2004b, Stud. Geophys. Geod., 48, 391-446), detrital magnetite a DP range of 0.25-0.35, and oxidized magnetite a range of 0.4-0.5. High-coercivity components (hematite or goethite) seem to have slightly higher DP values than magnetite. Skewness: Skewed-to-the-left: thermal activation and/or magnetic interaction. Skewness-to-the-right may be due to a second coercivity fraction that is convolved in the fit.
Dr. Mark Keene
Qinetiq,
Malvern, UK.
Email: mnkeene@qinetiq.com

Metal detector technologies for difficult soils

Abstract

We present a brief overview of magnetic soil rejection technology in metal detectors. Although effective in weakly magnetic soils, the strategies that are employed in modern detectors are insufficient for more heavily mineralised areas. There is a clear need for improved soil rejection techniques. We propose that current methods, by themselves, will be difficult to directly improve upon in simple detectors. However, we speculate that together with more sophisticated sensors, advantages may be gained in soil rejection. Specifically we consider position sensors and arrayed receivers.

Introduction

There are several detection applications where the magnetic properties of soils have a significant impact upon the detector. One important application is metal detection. Metal detectors (MDs) are used for landmine and unexploded ordnance (UXO) detection. Here magnetic soils can trigger the detector's alarm, raising the false alarm rate. Usually, each alarm requires resolving by excavating the soil to determine whether a munition is present. This is a slow process: because each detection is treated as if an explosive device is in the ground until the source of the detection is found to be otherwise. When the detection is caused by a small metallic fragment, finding it can take a long time. When it is caused by the soil it may take longer.

Another problem occurs when the signals from the soil in the demining lanes are larger than those from the metal components in a minimum metal landmine. In many detectors the sensitivity can be reduced by the operator until the soil ceases to generate false alarms. This reduces the sensitivity to the mines as well. For anything other than very weakly magnetic soils the reduction in sensitivity is often unacceptable and the de-miners abandon their detectors and manually excavate their lanes with prodders to the prescribed depth (usually 20 cm).

This also occurs with detectors equipped with state of the art soil rejection. The threshold in soil susceptibility above which such detectors cannot be used is certainly raised, but there are still vast mined areas where the soil susceptibility is too high to use them.
There is only a limited amount of open scientific literature on the subject of soil rejection for several reasons. Mainly the techniques have largely been developed by the MD manufacturers with commercial interests to protect. There appears to be more patents than papers in science journals. It is also reasonable to say that little serious academic work has been directed at the problem.

In this note we present an overview of soil the main rejection strategies in MDs, aimed at the non-expert. Although these strategies are a big improvement on not having soil rejection, they are not effective enough in medium to highly susceptible soils. We speculate on some of the most promising future routes for more effective soil rejection.

**Soil rejection in CW detectors**

A metal object in a sinusoidal magnetic field can exhibit a combination of three behaviours depending upon the conductivity and magnetic permeability of the object. These are shown in figure 1. The weak shielding limit is where the applied field fully penetrates the volume of the object because the skin depth is long compared to the objects size. The detected secondary field from the object is out of phase with the primary field and appears in the imaginary direction. When the applied field is excluded from the interior because the skin depth is small compared to the object’s size, the secondary field is in anti-phase with respect to the applied field. This is the diamagnetic response where eddy currents flow to directly cancel the applied field. If the object has permeability then it magnetises in sympathy, i.e. in phase with the applied field.

*Figure 1 The three response types in a CW metal detector*
In general, a metal object will have a response between the weak and strong shielding limits, depending on its conductivity and the frequency of the applied field, plus a ferromagnetic response if applicable. Some examples of the effect of frequency to detected signals are shown in Figure 2. Starting at the origin, (low frequency,) the relative contributions from the three behaviours changes until at high frequency, everything ends up in a strongly shielded condition.

![Figure 2](image)

*Figure 2 Top: The effect of increasing frequency on the detected signal from a conductive and a magnetic object. Bottom: The relative response due to different materials with increasing frequency.*

Examination of Figure 2 suggests that soil has a nearly linear dependence on frequency whereas metal objects are more non-linear. This difference is exploited for soil rejection as illustrated in Figure 3. There are several possible strategies for soil rejection that are based on this. One is to detect the phase difference between the responses at the two frequencies which is very small for soil. Alternatively, the response at $\omega_1$ may be multiplied by a linear factor to map it to the response at $\omega_2$. A mismatch indicates a non-linear response hence a metal.
Soil magnetism workshop. Hannam et al, 2009

Soil Rejection in PI detectors

PI or time-domain detectors transmit discrete magnetic pulses and measure any magnetic effects that the pulse has caused. Figure 4 illustrates the response caused by a good conductor is a relatively long decay compared to that of a poor conductor.

normally the shape of the Tx pulse is arranged to ensure that before it is switched off every conductive and magnetic object in the vicinity is in a steady state i.e. that all eddy currents have died away and magnetic equilibrium has been reached. Once switched off, eddy currents are induced in conductive objects that decay with time. Any magnetic material relaxes from its magnetised state and directly applies a changing field to the Rx coil. This is also manifest as a decaying signal. Magnetic soils intrinsically have relatively fast relaxation times compared to many metal objects.

There are several strategies for soil rejection in PI detectors that have been used by manufacturers. A simple one is shown in Figure 5a where the whole decay is recorded and analysed to determine whether there is any residual signal after the soil effect is expected to have decayed away. The decay characteristics of the soil can be predetermined in use by the
operator by recording reference signals over a soil patch with no metal objects. The temporal (not magnitude) characteristics of the Rx signal may be used to determine the optimum time after the Tx pulse to observe. Residual signal indicates the presence of a metal object.

The disadvantages of this strategy are the detections are confined to later decay times when the signal, hence signal-to-noise ratio, is poor. Furthermore, some minimum metal landmine components have intrinsically fast decays that would be missed; also any differences in the soil magnetism between the calibration spot and the demining area presents difficulty.

Another strategy uses a regular Tx pulses alternating with ones of shorter duration as illustrated in Figure 5b. During the narrow Tx pulse the objects with fast time responses, such as soil, fully charges with field, whilst any with long time constants, such as metal objects, only partially charge before the pulse ends. The resulting decay that is measured in the coil is therefore dominated by the faster soil signal. The subsequent regular pulse contains all contributions, i.e. soil plus metal object. By recording and subtracting the pulses from consecutive Rx pulses any residual is due to metal objects. Another way to look at this is that the procedure chops the signal from the metal object but not that of the soil so the signal from the metal object can be extracted. This has the powerful advantage that it adapts to changing soil magnetisation without needing to calibrate. Although this technique is very effective it still has the drawback that the detection is conducted in a low signal-to-noise region due to subtracting two large signals.
Possible Future developments

It is difficult to envisage substantial improvements on the soil rejection capabilities described above. This is because the signals from soil and from metal objects can only be partially separated as they have some common features as seen by simple Tx-Rx detectors. With any signal separation problem, additional independent measurements are needed that accentuate the differences in the signals you wish to resolve.

If we assume that we are moving a detector over a heavily mineralized soil the signals from the soil will change with height above the soil, attitude of the sensor head and lateral position if the soil is not flat or homogeneous in its magnetic properties (as is nearly always the case). This motion related soil signal is the problem to be solved. We speculate on two alternative approaches that may provide a future solution although there are many ideas and concepts that may be attempted.

Figure 5. Soil rejection strategies in PI detectors (a) Detection at later times after the soil signal is expected to have decayed. (b) Alternating the Tx pulse widths and subtracting sequential decays.
One approach would be to cancel the soil signal from the output of a detector by recording a decay over a metal-free patch and subtracting that signal from all subsequent measurements. Simple subtraction will not work because of the motion effects described above. However, if the height and attitude are measured with independent sensors, see Figure 6, then an intelligent cancellation can occur. This requires having a model for how a halfspace of susceptible material will influence the detector. The model has time dependent variables that are the angles and height.

\[ S(t) = f(\text{Angle1}(t), \text{Angle2}(t), \text{height}(t), \text{more}?) \]

The function \( f \) that relates the variables to the output signals is highly non-linear and specific to the design of the MD. The calculated soil contribution, \( S(t) \), would be subtracted from the measurements. A digital processor would be required to perform the calculations. Although this would further increase the soil rejection performance over the standard methods, it would not be able to compensate for inhomogeneity in the soil (for some applications, e.g. archaeological survey, this would actually be an advantage), or surface roughness. Furthermore accurate height detection could be difficult if vegetation is present.

![Figure 6. Attitude and position measurement for soil cancellation.](image)

The second approach we wish to discuss is the use of arrayed MD systems. These are MDs with either 1D, 2D or 3D Rx receiver arrays. The powerful advantage of these is that they can measure the returning signals at many different points simultaneously. The pattern of
detected fields over the array provides powerful information on the sources producing the fields. Some examples are shown in figure 7a including the Marmot experimental detector. This detector can determine the exact locations of point-like (dipolar) metal objects in three dimensions and classify them according to their signatures (*magnetic polarizability tensors in the case of dipoles*) for the purposes of discrimination. It does this by assuming a generic model for the sources of signal and fitting the measurements to determine the values of the model’s variable parameters. So far, only simple target models such as dipoles, quadrupoles, and needles have been considered. In principle, a distributed susceptibility model, i.e. the soil, could also be solved for. The height and angles in Figure 6 would be some of the parameters for the soil’s forwards model and would be determined during the measurement process without the need for separate sensors. MD arrays can solve for multiple targets simultaneously so they can, in principle, be configured to solve for soil effects (for compensation) and metal objects at the same time. In effect the soil becomes another target to solve for.

There is a limitation to this method. The substitution of a large area receive coil for many smaller coils means that unless the receivers are being used collectively there will be a penalty in the range at which small metal objects will be detected.

Figure 7. Examples of arrayed metal detectors (a) The coil set for DSTL’s MARMOT mine detector with an array of 40 Rx coils. (b) A flat array metal detector designed for a waste sorting application. (QinetiQ Ltd.) (c) The inside of a small array MD for medical use in locating small metal objects that are embedded in flesh. (Metrasens Ltd.) (d) A miniature MD array with 250micron resolution for microscopy applications. (QinetiQ Ltd.)
Conclusion

Soil rejection is a blind signal separation problem and in simple Tx-Rx metal detector systems it is somewhat ill conditioned. The current methods for soil rejection in these systems are probably as good as they’re going to get. Improvements could be made if additional information about the soil is gathered and used by the detector to improve the conditioning of the signal separation problem. We have suggested that likely candidates include position/attitude sensing and using detectors with arrayed receiver coils.

References


Archaeogeophysics: Applications and challenges for magnetic methods

The ubiquitous presence of iron minerals within the soils and sediments forming archaeological sites can often provide a valuable record of past human activity. These records are formed through the alteration and concentration of weakly magnetic minerals to fine grained iron oxides, such as magnetite or maghaemite, that leave an almost indelible magnetic “finger print” in the soil. Archaeologists have exploited these magnetic records at a variety of levels from landscape scale geophysical survey to reveal the location of entire “lost” cities, to determining how old a particular excavated feature may be through archaeomagnetic dating.

Following the advances of environmental magnetism made in many other disciplines, recent studies have used similar methodology and instrumentation to investigate the archaeological processes influencing magnetic alteration, occurring through the often complex interaction of pedogenic, microbial and anthropogenic mechanisms. This research has revealed many unique magnetic signatures within archaeological sediments that may help to identify a range of significant environmental conditions, such as the effects of climate change or the deliberate use of fire.

Many of the processes leading to the alteration and concentration of magnetic minerals associated with archaeological activity, appear to represent the small scale perturbation of pedogenic mechanisms recognized over much larger regional landscapes. These processes may be driven by easily recognizable factors, for example the repeated use of fire, or more subtle means such as a highly localized increase in organic material associated with a former timber post setting, rubbish pit or even a buried human body. However, it seems even more remarkable that these accumulations of magnetic material survive over significant archaeological periods of time, despite often being subjected to unfavorable conditions for the survival of fine grained magnetic minerals (e.g. flood plains).

An increased knowledge of the magnetic properties of soils, near-surface sediments and the archaeological targets buried within them allows a greater understanding of the most appropriate geophysical methods for locating such remains. The application of ever more sensitive instrumentation, either enhanced fluxgate, alkali-vapor or even field deployable, low-temperature SQUID devices should be considered against specific site characteristics and
other practical constraints. In some circumstances these conditions may well dictate that there is little to be gained from the application of higher sensitivity magnetometers, for example where the archaeological features demonstrate a strong magnetic contrast to the surrounding soil. However, there are many environments, such as remains buried deeply under alluvial or colluvial deposits, which may now be investigated with a greater degree of success using more highly sensitive instrumentation. In addition, the increasing use of multiple, sometimes vehicle towed, arrays of magnetic sensors has greatly increased both the sample density and rates of data acquisition over traditional hand-held systems.

The use of more sensitive instrumentation at higher sample densities has also begun to reveal classes of magnetic anomalies that may not otherwise be recognized in more conventional data sets. When visualised as a greyscale image these anomalies appear as a distinct contrast in the apparent texture of the plot and are related to quite small scale, physical variations in the near-surface properties of the soil. The ability to resolve this variation tends to be lost with both increasing depth from the surface or interpolation over a more sparsely recorded data set. A recent survey over a Roman farmstead villa complex suggests that the origin of the response at this site was due to an increased volume of thermoremanent building material, such as fired roof and floor tiles, within the plough soil. As the site is located on arable land the presence of this building material is almost certainly due to erosion through mechanical ploughing, a constant and ever encroaching threat to archaeological remains.

Figure 1 Caesium magnetometer survey of an Iron Age circular enclosure revealing a wealth of archaeological activity, including the possible remains of timber buildings.
Magnetic properties of dust and soil by the landed missions on Mars

Magnetic soils and dust on Mars

Background: Inspired by a magnetic properties experiment on the NASA Surveyor Moon lander, Robert B. Hargraves, Princeton University became the principal investigator for a magnetic properties investigation for the NASA Viking landers launched in 1975. From the Viking experiments we learned that both airborne dust and soils (strictly regolith; no organic component found to date) on Mars is rather strongly magnetic, the cause of this was interpreted as being due to the presence of the magnetic mineral maghemite providing the soil with an average saturation magnetization in the interval 1 to 7 Am$^2$kg$^{-1}$.

Later experiments on Mars Pathfinder in 1997 showed that airborne dust seems to be made primarily of composite particles with an average total diameter of about 3 micrometers. Average saturation magnetization of airborne dust was from images estimated to be between 1 to 4 Am$^2$kg$^{-1}$.

The German Mössbauer-spectrometer and German/American elemental particle analyzer (APXS-instrument) onboard the two Mars Exploration rovers, Spirit and Opportunity, along with the Danish built magnets and an American Microscopic Imager was used to show that the mineral responsible for the magnetic properties of the Martian soil and dust is a slightly non-stoichiometric, probably slightly titanium-substituted magnetite, i.e., a titanomagnetite, inherited directly from Martian bedrock. Based on analysis of all data from these instruments the saturation magnetization of the Martian soil is estimated to be between 1 and 6 Am$^2$kg$^{-1}$. The average value of saturation magnetization for airborne dust is below 2 Am$^2$kg$^{-1}$, while the value for the most magnetic fraction of the dust (i.e., that sticking to the capture magnet of the rovers) is higher than 7 Am$^2$kg$^{-1}$.

Recent analysis of airborne dust using the Phoenix lander in Vastitas Borealis, the northern polar region of Mars indicate that airborne dust there is essentially similar to dust caught in the equatorial region of Mars.
References:


Digital Soil Mapping – spatial variability and prediction of soil properties

Abstract

Soil is an important factor in de-mining and we need to understand it in order to make most of the available technology for mine detection. In order to get a better appreciation for soil, the presentation initially introduces soil as a living environment and illustrates the function soil performs and the benefits we it provides to our environment. As most soil information is still obtained from traditional soil maps, traditionally soil mapping is introduced and the pros and cons discussed. Increasingly, however, traditional soil mapping is replaced by Digital Soil Mapping techniques in which spatial inference engines are used to predict soil classes and/or soil properties. The major benefit of this approach is the potential for customizing the models to particular user requirements. In the last section of the presentation, the benefits of Digital Soil Mapping are illustrated with an emphasis on de-mining.

Introduction

- Why is soil important – we need to understand the substance in which are the majority of mines are placed as soil properties are an important factor in determining detection rates
- What can soil science contribute to humanitarian de-mining?

What is soil?

- Top 1 - 2 meters, is a living environment and is physically, chemically and biologically complex.
- It has ecological and economic functions. It provides food and fiber, supports above and below ground biodiversity. Environmental services include functions related to air, water and waste. It provides a platform for construction and forms part of our landscape and cultural heritage.
- It has 3D variation in space, depth and time.

Soil mapping

Traditional mapping

Need to look at traditional soil mapping to provide the background for digital soil mapping.

Classification
- Soil is very complex in space
- Classification required to generate simple (human) concept
- Classification scheme tend to be based on hierarchical approaches
- But soils are not black and white – not like biology – they are fluid and change as a continuum in the landscape rather than as distinct boundaries between soil types.

**Mapping**

- Map units – predominantly class maps (figure 1)
- Mapping is an art rather than a science
- Landscape understanding (line work)
- Auger bores and representative profiles
- Map units (soil series versus soil associations)
- Scale dependent
- Limitations – purity, accuracy and properties
- Limited validation

![Conceptual Soil-Landscape Model](image)

Figure 1 Traditional soil mapping process. A polygon map is produced by a conceptual model developed by the soil surveyor that is augmented by manual delineation of units, aerial photography interpretation (API) and soil sampling to depth with auger bores.

**Digital Soil Mapping (DSM)**

- Predicting the spatial distribution of soils in the landscape using models (figure 2)
- Still requires training data, though pure expert knowledge can be used
- Environmental covariates – digital data are the key – new information such as Digital Terrain Modals (DTM) are required from inference, airborne geophysical, high-resolution spectral imagery but depends on area of interest
- NIR/MIR spectroscopy can be used as a tool for rapid soil property assessment
- Based on data mining techniques using a wide variety of inference engines
- Initially soil were mapped as class maps (ie. soil types) but increasingly property maps can be developed (e.g. organic carbon content, soil depth, soil habitat functions) (figure 3).
- Still issues to be considered – do not make new soils
- Continuous surfaces
- Resolution rather than scale
- Custom-made products
- Pedotransfer functions

Figure 2 Digital soil mapping process. A soil similarity vector is produced by an inference engine that uses automatic delineation through environmental co-variates (scorpan: soil is a function of climate, organisms, relief, parent material, age and landscape position).
Figure 3 Digital soil mapping process including extension of concepts to mapping soil properties and functions.

Applications

- Biomass mapping has been achieved.
- Mapping wet soils has been determined in the landscape (Hannam, unpubl.)
- Soil property data such as soil depth and electrical resistivity mapping can be achieved (figure 4)
- Expert systems such as for sea mines could be developed using similar approaches (figure 5)
- There are still issues with data availability and suitability and understanding of environmental covariate interactions
Conclusions

- Soil mapping and DSM in particular can contribute significantly to de-mining by providing custom-made predictions.
- Requires funding
The influence of magnetic soils on Army activities

Abstract

It has only been within the past 10 to 15 years that the Army has been concerned with the influence of soil properties on sensors used for surface and subsurface target detection. The concern with magnetic soils arose during the early phases of the Jefferson Proving Ground (JPG), Indiana unexploded ordnance (UXO) technology demonstrations. Although UXO investigations are a primary effort in which magnetic soils are a concern, other army activities, both military and civil, are also influenced by magnetic soils. These activities include the detection of landmines and other near-surface targets of interest, underground structures and weapons caches, installation of perimeter security systems, aircraft compass calibration sites, archaeological sites, wetland delineation, and potentially all geophysical investigations. Three case histories are presented where magnetic soils and/or surface materials adversely affected a military test or were exploited to benefit one.

Introduction

For much of the Army’s history and still relevant today, “Own the Ground” is a phrase that describes a basic premise of its tactical strategy. Optimal troop and vehicular positioning provides an advantage for observing, attacking, and defending against an opponent. As the tools of conflict become more technologically advanced, factors other than topography and weather justify greater consideration in strategic planning. Rather than relying on an individual’s senses, electronic sensors are providing more reconnaissance information. These electronic sensors are influenced by the surrounding environment, both above and below ground, therefore it is no longer sufficient to “Own the Ground,” the Army must “Own the Soil.” It is important to recognize the importance the engineering and geophysical properties of soil have on Army activities, because they influence issues such as vehicle tire tread design and performance, construction of roads and runways, and sensors used for the detection of subsurface targets. In recent years, the presence of magnetic soils has become a particular concern. Some Army activities that may be affected by magnetic soils include the detection of unexploded ordnance (UXO), landmines, underground structures and caches; the installation of perimeter security systems; aircraft compass calibration; investigations at archaeological sites; the delineation of wetlands; and potentially any geophysical investigation. Of these
Examples cited, magnetic soils are usually a hindrance, however, the presence of magnetic soils can be exploited when performing archaeological investigations or wetland delineation. Electronic sensors used for interrogating the Earth face environmental challenges posed by the atmosphere, surface and subsurface conditions. The geo-environment is a complex, dynamic environment where property values measured can vary throughout the day depending on, among others, the amount of cloud cover, sun position, temperature, and moisture conditions. In addition to these challenges is the presence of magnetic soils. The Army’s concern with magnetic soils arose during the early phases of the Jefferson Proving Ground (JPG), Indiana unexploded ordnance (UXO) technology demonstrations (1994 to 1999). During that time, a spatially-large anomaly was noted in the magnetometer, electromagnetic (EM), and ground penetrating radar (GPR) datasets, but most prominent in the magnetic data. Initially, there were differing opinions as to whether the magnetic anomaly was caused by a geologic source, however further investigations proved that it was of geologic origin. The acknowledgement that local soils can significantly influence detection sensors led to phenomenological studies at JPG, and soil background characterization studies prior to the installation of UXO test sites at Fort Carson, Colorado, Fort A.P. Hill, Virginia, Aberdeen Proving Ground, Maryland, and Yuma Proving Ground, Arizona. Of prime concern for the Army is the detection of UXO in both nominal and magnetic soil environments, a concern driven by the mandate to cleanup UXO-contaminated lands under the Base Realignment and Closure (BRAC) program. This requirement has led to studies comparing magnetometry, EM induction, and GPR sensors in magnetic environments, such as Kaho’olawe, the development of multi-sensor and co-located sensor systems, and the advancement of inversion techniques for the discrimination between UXO and non-UXO.

Table 1 shows values of soil magnetic susceptibility (MS) from sites ranging across the United States. Generally, soils within the continental U.S. exhibit values of low ($\leq 50 \times 10^{-5}$ SI) to moderate ($50 < MS \leq 100 \times 10^{-5}$ SI) volume magnetic susceptibility. However, there are areas where higher magnetic susceptibility soils are found, especially in volcanic environments such as the Hawaiian Islands. Soils exhibiting moderate MS values will have some effect on magnetic and electromagnetic sensors, whereas those having high volume MS ($> 100 \times 10^{-5}$ SI) will definitely influence geophysical sensors and the sensors may be ineffective.
Table 1. Magnetic susceptibility values for soils in select areas of the United States.

<table>
<thead>
<tr>
<th>Location</th>
<th>Volume Magnetic Susceptibility x 10^5 SI</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SOILS</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
| Aberdeen Proving Ground, MDUXO Standardized Test Site | 0.4 to 45 | Geology: fluvial over bank deposit  
Soil: silt or clay with small amount of sand |
| Former Fort Ord, CA ODDS | 24 to 68 | Geology: dune  
Soil: sand |
| Jefferson Proving Ground, IN 40-Acre Site | 7 to 74 | Geology: weathered glacialdeposits  
Soil: sandy silt |
| Yuma Proving Ground, AZ UXO Standardized Test Site | 74 to 50 | Geology: alluvial fan complexes and alluvial plains  
Soil: gravelly silty sand |
| Kaho‘olawe Island, HI Seagull Site Lua Kakika Site | 805 to 3300  
1330 to 2430 | Geology: volcanic  
Soil: tholeiitic basalt parent rock with up to 20% magnetite |
| **ROCKS** | | |
| Kaho‘olawe, HI | 250 to 905, Avg 552 | Orange-brown, not vesicular, rough surface |
| | 200 to 249, Avg 225 | Orange-brown, flattened, vesicular on one side |
| | 167 to 243, Avg 196 | Orange-brown, flattened, vesicular |
| | 213 to 265, Avg 238 | Orange-brown, not vesicular, spherical |
| | 248 to 420, Avg 319 | Orange-brown, not vesicular, spherical |

Figure 1 is a histogram of 1,000 mass magnetic susceptibility measurements measured throughout Bosnia and Herzegovina (Das, 2006). The inset map shows that the sample locations (solid circles) are fairly well distributed across the country. A significant aspect of these data is that 42% of the mass MS values are greater than 100×10^-8 m^3 kg^-1, a high MS value that will affect magnetic and EM sensors. The yellow circles on the inset plot represent the location of these samples, which are distributed throughout the country. It can be seen that the presence of magnetic soils should be a major concern when performing geophysical investigations in Bosnia and Herzegovina. It is likely that other countries also have a wide distribution of high MS soils, and therefore it is necessary to understand their formation, global distribution, and influence on sensors to better predict when they will be encountered and how to compensate for their effect.
Geologic Sources of Magnetic Soils

Throughout numerous UXO cleanup efforts, explosive ordnance disposal (EOD) personnel have encountered anomalies that are not caused by metallic material, but instead have a geologic source. Geologic anomalies include those caused by the deposition of heavy minerals through natural sorting processes, basaltic environments, “hot rocks,” lightening strikes, and animal burrows (Simms et al., 2005). A well documented geologic anomaly representative of natural sorting is that discovered on the 40-acre site at Jefferson Proving Ground (Butler et al., 1999; Butler, 2002). An intermittent drainage channel runs through the length of the anomaly. It was shown that peaks in the magnetic susceptibility occur at the same elevation along the banks of the channel, and is attributed to the settling and concentration of heavy magnetic minerals during an over-bank depositional event.

The presence of shallow, basaltic bedrock or soils formed from mafic igneous rocks often has measured susceptibilities in the 100s to 1000s (see Table 1, Hawaii samples). Reported MS values of volcanic soils at several locations in Hawaii (Van Dam et al., 2004) indicate mass MS values ranging from 500 to $1,300 \times 10^{-8} \text{ m}^3\text{kg}^{-1}$, and a correlation between mean annual rainfall and a decrease in magnetic susceptibility. Geophysical measurements using time domain EM (TDEM) systems generally will not be influenced by magnetic soils that do not
exhibit frequency dependence. However, TDEM systems are affected by viscous magnetic soils, where the geologic response in later time channels has been observed (Li et al., 2005, 2006; Pasion, 2007).

Various instances have been reported where “hot rocks” and gravel have been the culprits of what was thought to be an UXO anomaly. Many dollars were spent chasing hot rocks, isolated rocks that have a high magnetic response relative to the local background, during the UXO cleanup effort at Former Fort Ord, California.

An interesting magnetic anomaly pattern is observed in areas where lightning has struck the ground. Figure 2 shows the magnetic gradient response of data collected from an airborne gradiometer system (personal communication, Les Beard, Battelle). The star-shaped anomaly is on the order of tens of nanotesla, with most of the energy dissipated as heat into the ground. The heat generated by the lightning is great enough to heat the magnetic minerals in the soil past their Curie temperature, and upon cooling acquire a new remanent magnetization.

![Figure 2. Airborne gradiometer data showing star-shaped pattern from lightning strike (courtesy Les Beard, Batelle).](image)

**Case Histories**

Three examples are presented that illustrate the impact of magnetic soils on Army activities.

**Magnetic Surface Clearance System**

The first example involves the demonstration of a magnetic surface clearance system designed for removal of surface UXO. A photograph of the system in use and a close-up view is given if Figure 3. The two electromagnets are energized and iron-bearing material collects on the bottom surface. To remove the material, the magnets are lifted into the cart and positioned over a collection bin, where the magnets are de-energized and the material falls into the bin.
The magnetic clearance system was demonstrated at the Air Force Research Laboratory Test Site #3 on Tyndall Air Force Base, Florida. The system was being tested for effectiveness for removing surface UXO. Both pre- and post-magnetic and EM induction surveys were performed. Results of the total magnetic field (TMF) survey are shown in Figure 4. The pre- and post-survey 1 plots use the same color bar scale. The pre-survey plot shows numerous anomalies present. The post-survey 1 plot has two main characteristics. First, the majority of anomalies present in the pre-survey data are also present in the post-survey 1 data, with the addition of many smaller anomalies. This suggests that either the surface clearance system did not perform well, or that the majority of the anomalies are in the subsurface; it is assumed that the latter is true. The second prominent feature is that the strength of the anomalies in the post-survey 1 dataset is greater than that in the pre-survey. This indicates that an induced remanent magnetization has been imparted upon the iron-bearing material in the subsurface.

There was concern that the soil, a coarse-grained white sand, may also have been affected by the magnetic clearance system. Laboratory analysis of a soil sample using the Bartington MS2B revealed no anomalous behavior, with mass MS values representative of a
diamagnetic material. Black particles present in the sand were observed under a microscope and determined to be organics. A second post-magnetic survey was conducted nine months later, along with in situ magnetic susceptibility measurements. The post-survey 2 (Figure 4) is quite similar to the first post-survey. Note that the color scale bar for the second post-survey is slightly different than the first, but that does not change the interpretation. The MS data were collected over five grids (locations are shown on the pre-survey plot) at 50-cm intervals, along with TMF data sampled at 10-Hz along lines spaced 50-cm apart. A soil sample was collected in each grid for future laboratory analysis. Figure 5 shows a color contour plot of the TMF data obtained over grid 3. The numbers on the plot are the measured volume MS values (using the Bartington MS2D). These values range from $-0.9 \times 10^5$ SI to $6.0 \times 10^5$ SI, which are representative of a diamagnetic sand. These data are typical of that obtained in the other grids. It was concluded that the soil did not contain a measurable quantity of magnetic minerals, and therefore was not responsible for any magnetic enhancement observed in the post-magnetic surveys. The demonstration of this magnetic clearance system emphasizes the need to perform a soil investigation and pre-geophysical surveys prior to using such a system, to ensure that the magnetization imparted by the electromagnet will not adversely affect the soil and subsequent geophysical investigations at a site.

![Figure 5. TMF (color contour) and volume magnetic susceptibility (posted values) data measured over a 2-m by 2-m grid (grid 3, location shown in Figure 4).](image)

**Compass Rose**

This next example describes an investigation of a compass calibration hardstand at Little Rock Air Force Base, Arkansas (Butler and Kean, 1990, 1993). The calibration hardstand (compass rose) was constructed in 1957 for the purpose of calibrating the compass on aircraft. Since its initial construction, personnel had reported “magnetic disturbances” and
failure of the hardstand to pass certification. The compass rose is constructed of concrete. In 1990 the U.S. Army Waterways Experiment Station was requested to investigate the “magnetic disturbances” around the hardstand. This request was initiated because of impending construction in the area around the hardstand and the possibility of constructing a new calibration hardstand in an adjacent area. Figure 6 shows the layout of the hardstand and locations of three survey lines at the possible site of a new compass rose. Total magnetic field data were acquired over the calibration hardstand and three survey lines (Figure 7). The contours of the hardstand data are at 100 nanotesla (nT) intervals (Figure 7a). The TMF data show that there is a strong magnetic field response over the hardstand. Magnetic measurements over the ground surrounding the hardstand, and while the base radar systems were in operation, did show any unusual response. It was then decided to investigate the concrete that the calibration hardstand was constructed. This led to the discovery that the concrete was composed of a dark aggregate that contained magnetic minerals (Figure 7b), which was the cause of the “magnetic disturbances.” Magnetic surveys in the area of the proposed compass rose site showed little variation in the magnetic field (approximately 5 nT, Figure 7c). The large spike in the top plot was caused by an aircraft taxiing near by.

![Diagram of the compass rose site and locations of the survey lines at site of proposed calibration hardstand.](image-url)
Figure 7. (a) TMF contour plot over calibration hardstand. (b) Photograph of concrete containing dark aggregate used to construct the calibration hardstand. (c) TMF data along survey lines at proposed hardstand site.

Wetlands Delineation

The preservation of natural resources on military installations is of primary concern to the Army. The closing of installations and addition of more troops to existing ones results in an increase in use and stress on the limited natural resources of a base. Most installations are unable to expand because of surrounding development, so they are tasked with using the resources they possess more effectively and wisely. Wetlands are one natural resource that are protected under federal regulations, therefore, the delineation of wetlands is necessary to
ensure their protection. A study was undertaken to identify the transition zone between non-hydric (uplands) and hydric (wetlands) soils. Hydric soils form in anaerobic environments and are characterized by the reduction of iron oxides (ferric Fe$^{+3}$ to ferrous Fe$^{+2}$). Previous researchers (Grimley and Vepraskas, 2000; Arruda, 2002; Grimley et al., 2004) have exploited this iron transformation and correlated hydric soil indicators with magnetic susceptibility with some success. These earlier efforts sampled random areas within a wetland and adjacent upland, and were primarily concerned with identifying a given MS value that could be used to differentiate the wetland in that area. This study takes a different approach, in that it aims to consistently locate the transition zone (TZ) between upland and wetland throughout different seasons of the year, and thus at different levels of soil moisture content. Figure 8 shows the location of the survey site and a photograph of the survey area.

The survey line incorporated a wetland-TZ-upland sequence at both the southwest (SW) and northeast (NE) ends. The transition zone within the SW sequence was considered well defined, whereas that within the NE sequence was viewed as complex. Its sequence consisted of wetland-TZ-intermediate ridge-TZ-upland. It was anticipated that the SW sequence could be defined using MS, however, it was questionable if differentiating the transition zone boundaries within the NE sequence would be successful.

**Figure 8. Location of survey line within Pearl River floodplain (a) and photograph of survey line within wetland (b).**

The survey line was 50-m in length and located in the floodplain of the Pearl River, Hinds County, Mississippi. Magnetic susceptibility data were collected using a Bartington MS2D and ZInstruments SM-30 at 5-m intervals along the survey line, except within the suspected transition zone where a 0.5-m sample spacing was used. The susceptibility data are plotted in Figure 9 for both sensors during four different time periods when the soil was either considered wet, moist or dry. The wet period was after a recent flood; the moist period was several weeks after the flood event with light rain in between sampling periods; and the dry period had minimal or no rain between the sampling periods. The MS curves for the two sensors are similar in character, and they display similar behavior for data collected during
different times of the year under varying soil moisture conditions (Figure 9a). To simplify the plot, the data have been re-plotted in Figure 9b for just the MS2D sensor. At the SW end there appears to be a steep decrease in MS values that would represent the transition zone. Not as prominent on the NE end is a gradual increase in MS values that represents theTZ-ridge-TZ zone. To determine if the smaller sampling interval has any effect on the ability to interpret the transition zones, the data are plotted in Figure 9c with a 2-m sampling interval within the transition zones; the transition zones can still be identified at the coarser scale. The use of magnetic susceptibility to delineate the wetland boundaries was successful at this site which has a clayey soil. Additional investigations are necessary at sites possessing different soil types to determine where magnetic susceptibility can be used to compliment the traditional use of wetland indicators.

Summary

Magnetic soils are found world-wide and therefore can impact Army activities, both in the civil and military realms. Their influence on geophysical sensors varies, ranging from minimal to rendering the sensor virtually useless. It is important to consider the soil properties prior to sensor selection. It is equally important to consider the potential impact a newly developed sensor may have on the near-surface environment. Magnetic soils often are considered a hindrance to geophysical investigations, however, in some applications, such as archaeology and wetlands delineation, their properties can be exploited.
Additional speakers (abstracts)

Mr Carl Chirgwin
CSG Demining Consultants assisting Lane Xang Minerals Limited. Australia.
Email: chirgwinsg@bigpond.com

The challenges of soil magnetism to efficient UXO remediation in a commercial environment

Lane Xang Minerals Limited (LXML) operates the Sepon Gold & Copper Operation in Savannakhet Province of Lao PDR. Commencing in 1993, the operation undertakes extensive exploration; survey and mineral extraction activities across a 2,400 hectare site – an area which will increase as exploration and mineral extraction activities continue to expand.

The LXML Sepon site sits astride the former Ho Chi Minh Trail and was subjected to intense aerial bombing during the Vietnam War. Some 60,000 items of UXO, ranging from hand grenades and incendiaries through cluster munitions and rockets to large 2000lb general purpose bombs, have been located since the commencement of operations at the Sepon site. The depth at which these UXO have been located varies from the surface to approximately 12 metres below the surface.

To meet its current needs, LXML has a UXO workforce of more than 250 local and international UXO technicians supported by up to 800 local vegetation cutters. Its annual output is in the order of 10,000,000m$^2$ of shallow and deep search per annum.

LXML conducts UXO remediation in three distinct ‘depth bands’. These are:
- Surface to 0.30 metres for foot tracks and non-ground intrusive works.
- 0.30 – 2.50 metres for vehicle tracks.
- 2.50 - 12.00 metres for mineral extraction and other excavation areas.

Currently, to achieve the necessary 12.00 metre detection depth when drilling exploration and mineral extraction boreholes, LXML must conduct a downhole borehole UXO check with a magnetometer every 2.50 metres. For each check, the drill rig must be withdrawn from the hole, the check conducted and the drill rig repositioned prior to recommencing drilling.

Despite the heavy UXO contamination in the area, LXML has not had a single UXO-related accident – and fully intends to keep it that way. Hence its pursuit of effective UXO
remediation. However, commercial realities dictate that it also achieves maximum efficiency in its UXO remediation.

Efficient UXO remediation in a commercial environment has its own peculiar requirements. With operational military UXO remediation, cost and the confidence level of complete clearance are factors to be considered but the chief imperative is time. With humanitarian UXO remediation, which includes non-operational military UXO remediation, cost and time are factors to be considered but the confidence level of complete clearance is the chief imperative. For commercial UXO remediation however, while the confidence level in complete clearance will always be the primary objective, cost and time are also crucial imperatives.

High and differing levels of background soil magnetism, as experienced in a number of portions of the Sepon site, greatly compound the difficulties in achieving efficient and effective UXO remediation. Primarily, the effect of soil magnetism on the detectability of UXO in different portions of the Sepon site creates inefficiencies of operation in that portion if the level of background soil magnetism is not correctly identified and managed.

The key challenges relating to this identification and management of soil magnetism at the Sepon site are:

1. Accurately identifying the detection depth capability of specific UXO detection equipments against specific UXO targets in the differing degrees of soil magnetism typical of the various portions of the Sepon site.
2. Accurately identifying the degree of soil magnetism in a particular portion of the Sepon site.
3. Designing and implementing a system that allows the efficient and effective ‘field’ identification of the background soil magnetism of a given area in which UXO remediation operations are to be conducted.
4. Designing and implementing a system that allows the efficient and effective ‘field’ confirmation of the detection depth capability of equipment in a particular portion of the Sepon site in which UXO remediation operations are to be conducted.
5. Identifying and empirically proving alternative detection technologies and methodologies, both current and near-future, to improve the efficiency and effectiveness of UXO remediation at the Sepon site.
Mr Pascal Druyts
Royal Military Academy,
Avenue de la renaissance 30, B-1000 Brussels,
Belgium.
Email : pascal.druyts@elec.rma.ac.be

Volume of influence for the response of magnetic soils to electromagnetic induction sensors

Druyts P., Das Y., Craeye C. and Acheroy M.

In the scope of humanitarian demining, the soil can significantly affect metal detector performances. The major effect is due to its magnetic susceptibility. In order to predict the difficulties of a metal detector on a given soil, it is necessary to measure its magnetic susceptibility. Then, the question naturally arises about the soil volume to take into consideration.

Most soils of interest have a very small magnetic susceptibility and a negligible conductivity, but nevertheless can be the cause of severe problems in mine detection as many mines only contain a very limited amount of metal and their response can be much smaller than the soil response, even in case of low magnetic susceptibilities.

The authors have developed a general and efficient model for such soils. This model only requires a modest computation power and can be applied to magnetic soil with arbitrary inhomogeneities and relief, as well as to arbitrary coil shapes, orientations and positions.

Here, we show that this model can be used to identify objectively the soil volume portion which has a significant influence on the soil response. The results are presented for a number of commonly used detector head designs.
Spatial prediction of soil magnetism using digital terrain analysis

As soil magnetism is a product of, and hence reflects, soil forming processes, soil magnetic properties can follow the differentiation of soil types. However, in some situations soil magnetic properties transcend soil type classifications and analogous relationships break down. This has implications for the spatial prediction and mapping of soil magnetism using previously determined soil type boundaries. At a regional scale soil types are determined by the changes in soil parent material and the position in the landscape. This relationship with terrain is investigated using a digital terrain model with a fuzzy inference system to determine elements in the landscape that have characteristic features. The landscape groups identified have characteristic soil types and soil associations. Field sampling validated the modeling results providing an interpretation of soil types within the modeled landscapes and measurements of the magnetic properties. Maps are produced for a pilot area in Bosnia and Herzegovina, which indicates areas that could be problematic for mine detection due to high magnetic susceptibility and frequency dependent susceptibility.
Dr. Guenter Kletetschka  
Catholic University, Physics, Washington DC, USA. 
GSFC/NASA, Astrochemistry, Greenbelt, MD, USA. 
GU ASCR, Prague, Czech Republic.  
Email:kletetschka@gmail.com

**Magnetic signatures of soil due to wild fires**

Occurrence of wild fires can trigger a neo formation of magnetic particles within the topsoil. Grass fires have lower burning temperature then forest fires. However grass fires occur every five years and forest fires occur every 80 years and therefore the higher frequency of fires can make up for the lower amount of neoformation of magnetic particles in the soil. An indicator of forest fires is an occurrence of Verwey magnetic transition near 120 K. If particular soil develops on weathered metamorphic or igneous rocks, the Verwey transition of the soil is not affected by fire, and if present, it is generally at lower temperature (~90K) due to nonstoichiometry. Another factor determining the fire effect is correlation between the Be10 isotope and magnetic susceptibility. If the soil magnetic susceptibility maximum occurs below the maximum of Be10 of the soil, magnetic signature is not fire related. However correlation between the Be10 and susceptibility record suggests the fire influence.
Discrimination of buried metal objects in soils with viscous remanent magnetization

Lhomme N., Pasion L.R., Billings S.D. and Oldenburg D.W.

Efficient and cost effective clearance of UXO contaminated sites consists of a two-step process: detection and discrimination. The presence of magnetic soils can compromise the ability to detect UXO using electromagnetic induction (EMI), as sensor movement and surface topography can produce anomalies with similar size and shape as compact metallic objects and obscure the presence of a metallic target. Generally discrimination of UXO can be achieved by inverting EMI data for the components of the dipole polarization tensor when the background geology response is negligible. In the contrary case, the presence of a strong geologic background introduces spatially correlated noise that greatly reduces the accuracy of dipole polarization estimates and thus degrades the ensuing discrimination.

We demonstrate in this presentation how explicitly modeling the EM response of magnetic soils can help solve a UXO discrimination problem. We assume a viscous remanent magnetization model where ferrite relaxation has a log-uniform distribution of time constants and the background magnetic susceptibility is spatially smooth. The predicted background response is subtracted from the sensor data and the remaining response is then inverted to obtain estimates of the dipole polarization tensor. This technique is first demonstrated using frequency domain data collected at the Former Lowry Bombing and Gunnery Range. These data were collected in a cued interrogation mode, where sensor positioning was achieved by placing the sensor on a series of locations marked on a plank. Secondly, we apply the soil modeling technique to pulse induction, time domain EM data collected in a dynamic mode where the constantly changing sensor position and orientation is recorded using GPS and IMU sensors. Soil compensation is achieved by incorporating the GPS and IMU data into the background response calculation. We conclude the presentation by introducing processing techniques for a newly developed man-portable vector (MPV) array detector that measures multi-static and multi-component EMI data. The additional receivers and components of the MPV array allows superior characterization of soil characteristics, and thus improved estimation of the dipolar polarization of the buried targets of interest.
Mr Ryan North
US Army Engineer Research & Development Center, Vicksburg, Vicksburg, USA.
Email: ryan.e.north@usace.army.mil

Multifrequency EM and Magnetic Measurements to Improve IED Detection

North R.E., McKenna J.R., Kelley J.R., Berry T.E. and Horton R.

Global military operations require that near-surface soils databases possess information relevant to improving target detection/discrimination at standoff.

This includes properties that provide information on the size, depth, and distribution of material properties of naturally occurring geologic formations and their intrinsic magnetic properties.

The methods which are used most often to facilitate this geo-environmental analysis are typically confounded by unexpected soil electromagnetic properties.

Experience in locations such as Kaho‘olawe have shown how important multifrequency electromagnetic properties are to aiding discrimination studies, and have lead to protocols requiring the quantification and addition of these suites of properties to military databases.

We will present some results of these ongoing analyses as well as articulate a path forward for the continued inclusion of these data in global datasets.
Soil compensation techniques for the detection of buried metallic objects using electromagnetic sensors

Pasion L.R., Billings S.D., Oldenburg D.W., Li Y. and Lhomme N.

Magnetic soils are a major source of false positives when searching for landmines or unexploded ordnance (UXO) with electromagnetic induction sensors. In adverse areas many electromagnetic (EM) anomalies are attributed to geology. The main source of the electromagnetic response from geology is the magnetic viscosity of the ferrimagnetic minerals magnetite and maghaemite. The EM phenomena that give rise to the response of magnetically viscous soil and metal are fundamentally different. The viscosity effects of magnetic soil can be accurately modeled by assuming a ferrite relaxation with a log-uniform distribution of time constants. The EM response of a metallic target is due to eddy currents induced in the target and is a function of the target's size, shape, conductivity and magnetic susceptibility.

In this presentation, we first demonstrate that the log-uniform distribution of time constants adequately describes the soil magnetic susceptibility at sites of interest. Next, we consider a number of different soil compensation techniques for time domain and frequency domain EM data. These techniques exploit the spectral (or temporal) and spatial characteristics of the EM response of viscous remnantly magnetized soil. These techniques will be demonstrated with time domain and frequency domain data collected at UXO clearance sites in Hawaii, U.S.A.
Soil susceptibility and landmine detection

Preetz H., Igel J. & Altfelder S.

For the past 5 years a team of soil scientists and geophysicists at the Leibniz Institute for Applied Geosciences in Hannover has been working on the issue of soil influence on metal detectors. Based on the physics behind the metal detectors design and the operating experience with such detectors two soil magnetic parameters are known to dominate the deterioration of detector performance:

- soil magnetic susceptibility
- frequency effect of soil magnetic susceptibility

The detection of land mines is further complicated by the fact that magnetic properties vary in space. Each of these three aspects responsible for the difficulties in landmine detection was investigated in an individual study.

One study investigated the susceptibility of tropical soils from 15 countries. More than a third of the samples showed susceptibilities that are likely to cause severe limitations for metal detectors. The study also revealed that parent rock and degree of weathering have significant influence on the soil magnetic susceptibility. Based on the results of this study a scheme classifying tropical soils according to their susceptibility from information on parent rock and degree of weathering was developed. The classification system may be used for the prediction of metal detector performance in tropical countries in advance of a demining campaign. The classification scheme was applied by compiling a map of Angola showing the likelihood of high susceptibilities in the various soil types found in Angola. The susceptibility map was deduced from the Angolan FAO soil map.

Past model calculations have clearly shown that the frequency effect of soil susceptibility can have a strong influence on metal detector performance. Using the same set of samples as for the first investigation, an analysis of the absolute values of the frequency effect of soil susceptibility in tropical soils shows that the highest values correspond to the most basic igneous soil parent material. This shows similar behavior to the absolute susceptibility. The relative frequency effect, on the other hand, shows a different correlation namely that the highest values are observed for the more acid igneous soil parent materials and sediments. This result can be interpreted as evidence for the neoformation of superparamagnetic...
minerals in tropical soils. The findings however, have to be put into perspective by the investigation on the frequency effect of basic igneous hard rocks. It is not uncommon that these rocks feature a remarkable frequency effect due to the presence of superparamagnetic minerals. These minerals were most likely formed during the rapid cooling of magma. These results show that the frequency effect of soil susceptibility is the result of pedogenesis combined with a contribution of certain parent rocks.

The third aspect influencing metal detectors - namely the spatial variability of magnetic soil properties - was investigated on former minefields in Mozambique where the work of the detectors was impeded. The results show that the correlation length of the susceptibility is generally in the range of 0.5 m. Since the work lanes during mine clearance operations have a width of 1 m the performance of the detector can be influenced due to the rapid change of soil susceptibility.

Further investigations on soil material used in test lanes for metal detector tests demonstrate that synthetic material is improper for that purpose since it mostly features only a high susceptibility but not the other two aspects that impede detector performance. Based on our research, an appropriate test lane for metal detectors can be achieved by using a tropical paleosol derived from basalt that combines all aspects. This soil - found in the Vogelsberg area in Germany - features a high susceptibility linked with a remarkable frequency effect and a small scale spatial variability. With such a test soil the problems of current tropical soils can be well reproduced.
An international collaboration to write guidelines to characterise soil impact on metal detectors and GPRs

The paper describes an international agreement on the soil properties to measure in order to characterize the effects that soils have on the performance of ground penetrating radars (GPRs) and metal detectors when used in humanitarian demining and how to measure these properties.

Soils can affect the performance of GPRs and metal detectors. Since metal detectors are widely used in humanitarian demining characterizing the effects of soils on their performance has become a major concern to the mine action community.

GPRs are now being combined with metal detectors into dual-sensor. Therefore the soil effects on GPR performance have received great attention too.

This is why it has been decided to find an agreement on how to characterize the soil effects on these two sensors through tests that could be carried out not only in laboratory but also in the field by users.

The document is written by a Workshop working under the guidelines set by the European Standard Committee (CEN). It will be a CEN Workshop Agreement (CWA), that is, a document based on a consensus among the Workshop participants. A draft is ready and is currently open for comments.

The current agreement includes the following topics:

- tests to be performed by demining companies using metal detectors (testing if mines are detected at given depths, smallest height above the ground at which the metal detector does not give an alarm indication, etc.)

- tests to be performed by demining companies using dual sensors (testing if mines are detected at given depths)

- how to recognise 'difficult' soils for metal detectors (highly magnetic soils, saline soils)
- list of properties to be determined (and how to determine them) when testing performance of metal detectors or dual sensors: magnetic susceptibility, electric permittivity, electrical conductivity, attenuation coefficient, impedance of soil, surface roughness, soil water content, soil texture, vegetation, presence of roots/rocks, etc.). The report can be found on the ITEP website: http://www.itep.ws/pdf/CWA_soil_characterization.pdf
## Appendix 2 Participant list

<table>
<thead>
<tr>
<th>Title</th>
<th>Surname</th>
<th>Forename</th>
<th>Institute/company</th>
<th>email</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dr</td>
<td>Altfelder</td>
<td>Sven</td>
<td>Federal Institute for Geosciences and Natural Resources, Germany.</td>
<td><a href="mailto:sven.altfelder@bgr.de">sven.altfelder@bgr.de</a></td>
</tr>
<tr>
<td>Dr</td>
<td>Billings</td>
<td>Stephen</td>
<td>Sky Research/ University of British Columbia, Canada.</td>
<td><a href="mailto:stephenbillings@skyresearch.com">stephenbillings@skyresearch.com</a></td>
</tr>
<tr>
<td>Mr</td>
<td>Chirgwin</td>
<td>Carl</td>
<td>CSG Demining Consultants, Australia.</td>
<td><a href="mailto:chirgwinsg@bigpond.com">chirgwinsg@bigpond.com</a></td>
</tr>
<tr>
<td>Mr</td>
<td>Crawford</td>
<td>John</td>
<td>RST Radar Systemtechnik AG, Switzerland.</td>
<td><a href="mailto:john.crawford@psi.ch">john.crawford@psi.ch</a></td>
</tr>
<tr>
<td>Dr</td>
<td>Dabas</td>
<td>Michel</td>
<td>Geocarta, France.</td>
<td><a href="mailto:dabas@geocarta.fr">dabas@geocarta.fr</a></td>
</tr>
<tr>
<td>Dr</td>
<td>Das</td>
<td>Yogadish</td>
<td>Defence R&amp;D, Canada.</td>
<td><a href="mailto:Yoga.Das@drdc-rddc.gc.ca">Yoga.Das@drdc-rddc.gc.ca</a></td>
</tr>
<tr>
<td>Prof</td>
<td>Dearing</td>
<td>John</td>
<td>School of Geography, University of Southampton, U.K.</td>
<td><a href="mailto:j.dearing@soton.ac.uk">j.dearing@soton.ac.uk</a></td>
</tr>
<tr>
<td>Dr</td>
<td>Dekkers</td>
<td>Mark</td>
<td>Department of Geophysics, Utrecht University, Netherlands.</td>
<td><a href="mailto:dekkers@geo.uu.nl">dekkers@geo.uu.nl</a></td>
</tr>
<tr>
<td>Mr</td>
<td>Druyts</td>
<td>Pascal</td>
<td>Ecole Royale Militaire, Belgium</td>
<td><a href="mailto:pascal.druyts@elec.rma.ac.be">pascal.druyts@elec.rma.ac.be</a></td>
</tr>
<tr>
<td>Dr</td>
<td>Fialova</td>
<td>Hana</td>
<td>Institute of Geophysics ASCR, Czech Republic.</td>
<td><a href="mailto:hfialova@ig.cas.cz">hfialova@ig.cas.cz</a></td>
</tr>
<tr>
<td>Mr</td>
<td>Foster</td>
<td>Eric</td>
<td>Pulsepower Developments, U.K.</td>
<td><a href="mailto:beachscan@aol.com">beachscan@aol.com</a></td>
</tr>
<tr>
<td>Mr</td>
<td>Geiger</td>
<td>Guenter</td>
<td>Institut Dr. Foerster GmbH &amp; Co. KG, Germany.</td>
<td><a href="mailto:guenter.geiger@foerstergroup.de">guenter.geiger@foerstergroup.de</a></td>
</tr>
<tr>
<td>Dr</td>
<td>Grant</td>
<td>Stephen</td>
<td>ERDC-IRO, U.K.</td>
<td><a href="mailto:Steven.A.Grant@usace.army.mil">Steven.A.Grant@usace.army.mil</a></td>
</tr>
<tr>
<td>Dr</td>
<td>Hannam</td>
<td>Jack</td>
<td>National Soil Resources Institute, Cranfield University, U.K.</td>
<td><a href="mailto:j.a.hannam@cranfield.ac.uk">j.a.hannam@cranfield.ac.uk</a></td>
</tr>
<tr>
<td>Dr</td>
<td>Harmer</td>
<td>Greg</td>
<td>Minelab Electronics, Australia.</td>
<td><a href="mailto:gregh@minelab.com.au">gregh@minelab.com.au</a></td>
</tr>
<tr>
<td>Dr</td>
<td>Harmon</td>
<td>Russell</td>
<td>US Army Research Office, USA.</td>
<td><a href="mailto:russell.harmon@us.army.mil">russell.harmon@us.army.mil</a></td>
</tr>
<tr>
<td>Dr</td>
<td>Hulka</td>
<td>Zdenek</td>
<td>ZH Instruments, Czech Republic.</td>
<td><a href="mailto:zhinstruments@email.cz">zhinstruments@email.cz</a></td>
</tr>
<tr>
<td>Dr</td>
<td>Igel</td>
<td>Jan</td>
<td>Leibniz Institute for Applied Geosciences, Germany.</td>
<td><a href="mailto:Jan.Igel@gga-hannover.de">Jan.Igel@gga-hannover.de</a></td>
</tr>
<tr>
<td>Mr</td>
<td>Jenkins</td>
<td>Colin</td>
<td>Bartington Instruments, U.K.</td>
<td><a href="mailto:colin.jenkins@bartington.com">colin.jenkins@bartington.com</a></td>
</tr>
<tr>
<td>Mr</td>
<td>Kearney</td>
<td>Blair</td>
<td>BACTEC South East Asia, Cambodia.</td>
<td><a href="mailto:bkearney@bactec.com.au">bkearney@bactec.com.au</a></td>
</tr>
<tr>
<td>Dr</td>
<td>Keene</td>
<td>Mark</td>
<td>QinetiQ, U.K.</td>
<td><a href="mailto:mnkeene@QinetiQ.com">mnkeene@QinetiQ.com</a></td>
</tr>
<tr>
<td>Dr</td>
<td>Kletetschka</td>
<td>Guenter</td>
<td>CU / GSFC-NASA, USA.</td>
<td><a href="mailto:kletetschka@gmail.com">kletetschka@gmail.com</a></td>
</tr>
<tr>
<td>Mr</td>
<td>Letourneur</td>
<td>Ludovic</td>
<td>Bartington Instruments, U.K.</td>
<td><a href="mailto:keeeley.lally@bartington.com">keeeley.lally@bartington.com</a></td>
</tr>
<tr>
<td>Dr</td>
<td>Lhomme</td>
<td>Nicolas</td>
<td>Sky Research/ University of British Columbia, Canada.</td>
<td><a href="mailto:nicolas.lhomme@gmail.com">nicolas.lhomme@gmail.com</a></td>
</tr>
<tr>
<td>Dr</td>
<td>Linford</td>
<td>Neil</td>
<td>English Heritage, U.K.</td>
<td><a href="mailto:Neil.Linford@english-heritage.org.uk">Neil.Linford@english-heritage.org.uk</a></td>
</tr>
<tr>
<td>-------</td>
<td>----------</td>
<td>-----------------------</td>
<td>------------------------</td>
<td>-------------------------------------</td>
</tr>
<tr>
<td>Dr</td>
<td>Madsen</td>
<td>Morten</td>
<td>Niels Bohr Institute, University of Copenhagen, Denmark.</td>
<td><a href="mailto:mbmadsen@fys.ku.dk">mbmadsen@fys.ku.dk</a></td>
</tr>
<tr>
<td>Dr</td>
<td>Mayr</td>
<td>Thomas</td>
<td>National Soil Resources Institute, Cranfield University, U.K.</td>
<td><a href="mailto:t.mayr@cranfield.ac.uk">t.mayr@cranfield.ac.uk</a></td>
</tr>
<tr>
<td>Dr</td>
<td>Muxworthy</td>
<td>Adrian</td>
<td>Imperial College London, U.K.</td>
<td><a href="mailto:adrian.muxworthy@imperial.ac.uk">adrian.muxworthy@imperial.ac.uk</a></td>
</tr>
<tr>
<td>Mr</td>
<td>North</td>
<td>Ryan</td>
<td>US Army Engineer Research &amp; Development Center, USA.</td>
<td><a href="mailto:ryan.e.north@usace.army.mil">ryan.e.north@usace.army.mil</a></td>
</tr>
<tr>
<td>Dr</td>
<td>Pasion</td>
<td>Len</td>
<td>Sky Research/ University of British Columbia, Canada.</td>
<td><a href="mailto:Len.Pasion@skyresearch.com">Len.Pasion@skyresearch.com</a></td>
</tr>
<tr>
<td>Dr</td>
<td>Preetz</td>
<td>Holger</td>
<td>Leibniz Institute for Applied Geosciences, Germany.</td>
<td><a href="mailto:Holger.Preetz@gga-hannover.de">Holger.Preetz@gga-hannover.de</a></td>
</tr>
<tr>
<td>Dr</td>
<td>Simms</td>
<td>Janet</td>
<td>US Army Engineer Research &amp; Development Center, USA.</td>
<td><a href="mailto:Janet.E.Simms@erdc.usace.army.mil">Janet.E.Simms@erdc.usace.army.mil</a></td>
</tr>
<tr>
<td>Dr</td>
<td>Thiesson</td>
<td>Julien</td>
<td>University of Paris 6, France.</td>
<td><a href="mailto:julien.thiesson@upmc.fr">julien.thiesson@upmc.fr</a></td>
</tr>
<tr>
<td>Dr</td>
<td>Van Dam</td>
<td>Remke</td>
<td>Michigan State University, USA.</td>
<td><a href="mailto:rvd@msu.edu">rvd@msu.edu</a></td>
</tr>
<tr>
<td>Dr</td>
<td>Yvenic</td>
<td>Yann</td>
<td>Ecole Royale Militaire, Belgium</td>
<td><a href="mailto:yvinec@elec.rma.ac.be">yvinec@elec.rma.ac.be</a></td>
</tr>
</tbody>
</table>