Spatial variability of magnetic soil properties

Remke L. van Dam*[a], Jan M.H. Hendrickx[a], Bruce Harrison[a], Brian Borchers[a], David I. Norman[a],
Samuel Ndur[a], Chris Jasper[b], Patrick Niemeyer[b], Robert Nartey[c], David Vega[d], Lucas Calvo[d], and
Janet E. Simms[e]

[a]New Mexico Tech, 801 Leroy Place, Socorro, NM 87801, USA
[b]NRCS, Kealakekua Soil Survey Office, 81-948 Waena Oihana Lp, Kealakekua, HI 96750, USA
[c]Western University College, Tarkwa, Ghana
[d]Universidad Tecnológica de Panamá, Panama City, Panama
[e]US Army Engineer Research and Development Center, Vicksburg, MS 39180, USA

ABSTRACT

The presence of magnetic iron oxides in the soil can seriously hamper the performance of electromagnetic sensors for the detection of buried land mines and unexploded ordnance (UXO). Previous work has shown that spatial variability in soil water content and texture affects the performance of ground penetrating radar and thermal sensors for land mine detection. In this paper we aim to study the spatial variability of iron oxides in tropical soils and the possible effect on electromagnetic induction sensors for buried low-metal land mine and UXO detection. We selected field sites in Panama, Hawaii, and Ghana. Along several horizontal transects in Panama and Hawaii we took closely spaced magnetic susceptibility readings using Bartington MS2D and MS2F sensors. In addition to the field measurements, we took soil samples from the selected sites for laboratory measurements of dual frequency magnetic susceptibility and textural characteristics of the material. The magnetic susceptibility values show a significant spatial variation in susceptibility and are comparable to values reported to hamper the operation of metal detectors in parts of Africa and Asia. The absolute values of susceptibility do not correlate with both frequency dependence and total iron content, which is an indication of the presence of different types of iron oxides in the studied material.

Keywords: land mine detection, UXO detection, iron oxides, magnetic soils, spatial variability

1. INTRODUCTION

One of the main problems of using modern technology for the clearance of buried land mines and unexploded ordnance (UXO) is the large probability of false alarms and the associated time and labor that is required to excavate all suspect objects. Most soil physical properties exhibit significant variability at a wide range of scales [1,2], which poses a problem for many sensors that are used for the detection of buried objects. The natural variation in the soil properties gives rise to anomalies, similar to anomalies that are the result of buried objects. The discrimination between these geological or soil anomalies and buried object anomalies is extremely complicated and is one of the major problems that need to be addressed in order to improve the performance of sensors for buried land mine and UXO detection [3].

Geophysical instruments for buried object detection that use electromagnetic waves are various: time- and frequency domain EM, ground penetrating radar, and magnetic methods. However, the performance of these instruments can degrade significantly at sites with variable soil properties such as water content, texture, and magnetic characteristics. Several studies in the past have addressed the influence of variability in soil texture and soil water content on electromagnetic sensors for the detection of land mines [4,5]. The study of magnetic soil properties in relation to the problem of land mine and UXO detection is relatively new [6,7,8,9]. Also, little is known about the natural variability in magnetic characteristics of soils.

---

* rvd@nmt.edu; phone (+1) 505 835-6960; fax (+1) 505 835-6436; http://www.ees.nmt.edu/hydro/landmine

Detection and Remediation Technologies for Mines and Minelike Targets IX, edited by
Russell S. Harmon, J. Thomas Broach, John H. Holloway, Jr., Proceedings of SPIE Vol. 5415
(SPIE, Bellingham, WA, 2004) 0277-786X/04/$15 · doi: 10.1117/12.540693

In strongly magnetic soils, magnetic and electromagnetic sensors often detect anomalies that have a geologic or pedogenic origin [3]. To improve the discrimination performance of land mine and UXO detection sensors it is necessary to get a better understanding of the magnetic variability at survey sites, and to use the statistical information on the distribution of magnetic soil properties in data processing algorithms. To address this issue, we asked ourselves three basic questions: (1) what causes magnetic soil properties, (2) what is the spatial variability in magnetic soil properties at different locations, and (3) how can we explain the variability within a site and between different sites?

2. MAGNETICS

2.1 Theory

The physical background for the existence of magnetic behavior in minerals is the magnetic moment produced by electrons orbiting their nucleus and spinning around their axis. In many types of material the overall magnetic moment is zero because the orbital and spin components even out. When a mineral with zero magnetic moment is placed in a magnetic field the electron motions will rearrange so that the net magnetic moment is in the direction opposite to the applied field. These types of minerals are called *diamagnetic*. In contrast, when minerals with a small net magnetic moment get subjected to a magnetic field the electrons will attempt to line up in the direction of the magnetic field. These types of minerals are called *paramagnetic*. In some minerals, the interaction between electron spin and orbital movement in adjacent atoms causes these minerals to behave as active magnets. These types of minerals are called *ferromagnetic* when all magnetic moments line up in the same direction, or *ferrimagnetic*, when one-third of the magnetic moments line up in the opposite direction. A special group of minerals are those in which the electron interaction leads to magnetic moments being aligned in opposite directions. These minerals with a net magnetic moment of zero are called *antiferromagnetic*. Many books and review papers have addressed the physical background of magnetic minerals in general [10,11] and magnetic soils in particular [12,13,14].

2.2 Magnetic soil properties

Magnetic properties in soils are largely a consequence of the presence of different forms of iron. Although pure iron can occur naturally in rocks and soil, it is very rare. Specific types of iron oxides, iron-titanium oxides and iron sulfides are the predominant causes of magnetic soil characteristics. In abundance, iron (Fe) is the fourth element in the earth crust. Although the most abundant minerals in the earth's continental crust are essentially Fe-free (plagioclase, feldspar, quartz), many other minerals contain significant amounts of iron [11]. Iron-containing minerals can be found in igneous rock such as basalt, gabbro, and granite, but also in metamorphic and sedimentary rocks. Therefore, it is no surprise that iron occurs in one form or another in many soils. The concentration of (magnetic) iron oxides is affected by the parent material, soil age, soil forming processes, biological activity, and soil temperature [15,16].

Table 1 shows magnetic susceptibilities for several iron- and iron-titanium-oxides, iron-sulfides and other soil constituents. Water and quartz are diamagnetic and have a small negative magnetic susceptibility. Hydrated iron oxides like goethite, which is the most abundant iron oxide in soils around the world, ferrihydrite, and lepidocrocite, play a minor role in determining the magnetic character of soils. Also hematite, which is the most abundant iron oxide in tropical soils, pyrite, and ilmenite hardly affect the magnetic soil characteristics. The magnetic character of soils is dominated by the presence of ferrimagnetic minerals such as magnetite and maghemite, and to a lesser degree by pyrrhotite [17].

Although iron oxides occur in most environments throughout the world [18] some locations are more favorable for the formation and/or maintenance of significant amounts of (magnetic) iron oxides than others. Unfortunately, soil maps and available laboratory data usually only contain information on the amount and not the type of iron oxides [19]. Tropical soils often contain large amounts of iron oxides [20]. Many tropical soils have deeply weathered profiles whose red and yellow colors result from an accumulation of iron and aluminum oxides. Large areas of these soils can be found in Africa and South America with minor acreages in South-East Asia. Another type of soil where iron oxides are abundant are relatively young soils developed from parent material of volcanic origin. The volcanic origin ensures in many cases the abundance of (ferri)magnetic iron oxides. Volcanic derived soils have a much smaller acreage than Fe-rich soils in the tropics but can be found on all continents. They may be present everywhere where geologically young volcanic rock is found (e.g., near continental margins and subduction zones).

Table 1. Magnetic susceptibilities for several iron oxides and soil constituents. Data from [11] and [21].

Material	Chemical formula	Magnetic status	Magnetic susceptibility (10^{-8} m^3 kg^{-1})
Water	H_2O	Diamagnetic	-0.9
Quartz	SiO_2	Diamagnetic	-0.6
Pyrite	FeS_2	Paramagnetic	30
Ferrihydrite	$5Fe_2O_3 \cdot 9H_2O$	Paramagnetic	40
Lepidocrocite	γ-FeO·OH	Paramagnetic	70
Ilmenite	$FeTiO_3$	Superparamagnetic	200
Hematite	α-Fe_2O_3	Antiferromagnetic	60
Goethite	α-FeO·OH	Antiferromagnetic	70
Pyrrhotite	Fe_7S_8 / Fe_8S_9 / Fe_9S_{10}	Ferrimagnetic	~5,000
Maghemite	γ-Fe_2O_3	Ferrimagnetic	40,000
Magnetite	Fe_3O_4	Ferrimagnetic	50,000

2.3 Characterization of magnetic soil properties

There are three magnetic effects that impact the (electro)magnetic characteristics of the subsurface, and thus electromagnetic sensors: (1) remanent magnetization, (2) induced magnetization, and (3) viscous remanent magnetization.

Remanent magnetization – Remanent magnetization exists in the absence of an applied field. The remanent magnetization must be added to any magnetization effects resulting from an applied magnetic field. Remanent magnetization occurs within ferromagnetic and ferromagnetic minerals that have a natural alignment of the magnetic moments. This type of magnetization directly affects magnetic sensors. Also, remanent magnetization can be the result of alignment and subsequent 'locking' of magnetic moments in the weak magnetic field of the Earth. Locking can occur due to cooling from high temperatures through the mineral-specific Curie temperature, due to critical-size crystal growth, or due to compaction and consolidation [11]. These thermoremanent, chemical-remanent, and detrital-remanent magnetizations are small and affect only the most sensitive magnetic sensors.

Induced magnetization – Induced magnetization results from a magnetic field being applied to a magnetically susceptible object. In the low-intensity field region, the net magnetic moment (i.e., the magnetization, M) is proportional to the strength of the applied field (H). Therefore, the low-field magnetic susceptibility, defined as the ratio of the magnetization over the field strength, is a material-specific property. The magnetic susceptibility is either expressed per unit volume (volume-specific susceptibility, κ) or per unit mass (mass-specific susceptibility, χ). Induced magnetization can be measured by applying a magnetic field to a sample (in the laboratory or in the field). By measuring the difference between this primary magnetic field and the secondary magnetic field one can determine the material specific magnetic susceptibility. The magnetic induction of a sample, measured by a magnetic or electromagnetic sensor, is the sum of all the different entities of induced magnetization, weighed for volume, distance to the sensor, and magnitude of the susceptibility. Ferrimagnets are the most important minerals for affecting the magnetic susceptibility (Table 1).

Viscous remanent magnetization – Viscous remanent magnetization refers to the effect that the secondary magnetic field gets delayed relative to the primary magnetic field [11]. This effect differs from the standard induced magnetization, where the magnetization is instantaneous, and the secondary magnetic field is in-phase with the primary magnetic field. Viscous remanent magnetization occurs in ferrimagnetic materials with a range of different shapes (anisotropy) and especially grain sizes. Under these circumstances, the application or removal of a magnetic field to/from a sample causes a delayed change in the direction of magnetization. The time needed for the direction change to occur is known as the Neel relaxation time. One consequence of viscous remanent magnetization is that the susceptibility becomes frequency dependent. This effect has important implications for both time- and frequency-domain electromagnetic sensors [7,22]. Viscous remanent magnetization can be measured using dual-frequency magnetic susceptibility sensors.

3. APPROACH

To study the variability of magnetic soil characteristics we have selected a number of sites in the tropics, for they are expected to have significant amounts of iron oxides: Hawaii, Panama, and Ghana. Furthermore we have gathered information from two locations in the continental United Sates, in New Mexico and Wyoming (Appendix A). In our magnetic measurements we have focused on induced magnetization (magnetic susceptibility) and viscous remanent magnetization (frequency dependent magnetic susceptibility). For these measurements we used Bartington magnetic equipment (Table 2). We have not separately measured the remanent magnetization of the material.

Table 2. Overview of Bartington sensors for measurement of magnetic susceptibility

Bartington sensor	MS2D	MS2F	MS2B
Application	Field	Field	Lab
Frequency	0.96 kHz	0.58 kHz	0.46/4.6 kHz
Area/volume	268.7 cm^2	1.8 cm^2	10 cm^3

At most of the sites we have selected one or more transects in agricultural fields for in-situ measurement of magnetic susceptibility at the surface. Also, we have collected sample material for further analysis in the laboratory. The sampling locations were partly based on the extremes in magnetic susceptibility readings, and partly using a stratified random sampling scheme [23] where we took one random sample from every 5 meter interval. In many of the locations we were able to use soil pits in order to study soil development and to measure the variation in magnetic properties with depth. From these soil pits we have taken samples for analysis in the laboratory. In the laboratory we performed a wide range of tests, such as frequency dependent magnetic susceptibility measurements (using the Bartington MS2B sensor). Also, we have measured textural characteristics (bulk density and grain size analysis), and we have performed a number of tests (X-ray fluorescence spectroscopy, magnetic iron extraction) to better understand the type and quantity of iron oxides. Appendix A summarizes the work that was done at the different field sites.

At all the studied locations on the Big Island of Hawaii the soils were formed in similar parent material (volcanic ashes) with comparable ages of 20k to 30k years. This allowed us to study the role of climate on soil forming processes in general, and magnetic soil properties in particular. Our assumption is that the degree of soil formation is a result of, amongst others, soil age and climatic factors. Due to the position in the trade wind belt and the general shape of the island (high mountains with steep slopes) the Island of Hawaii experiences extreme gradients in rainfall [24,25]. The windward eastern slopes of the island receive larger amounts of rainfall than the leeward western slopes, while on both sides the rainfall increases with elevation. The mean annual rainfall is greatest at around 1500 meters elevation and then decreases with further elevation, which is a result of the air flowing around rather than over the highest mountains. We have selected 7 locations for our measurements; 3 on Kohala Volcano, and 4 on Mauna Kea Volcano. Lines 1, 2, and 3 gradually decrease in elevation and mean annual rainfall and lie on an imaginary line on the leeward side of Kohala Volcano. The same holds for Lines 5, 7 and 6 on the windward side of Mauna Kea. Line 4 lies on the other side of Mauna Kea and experiences a much lower mean annual rainfall (Appendix A).

4. RESULTS

4.1 Spatial variability

The spatial variability in magnetic susceptibility was measured along several transects on the Big Island of Hawaii and the Island of O’ahu, as well as in Panama, and New Mexico (Appendix A). There exists considerable variability at small scales and between the sites. It can be seen in the scatter plots that for most sites the minimum and maximum readings differ by a factor between 2 to 5 (Figs. 1 – 5).

O’ahu, Hawaii – Figure 1 shows the variability in magnetic susceptibility for Shofield Barracks on O’ahu, Hawaii, measured with two types of sensors. The difference between the readings of the MS2D and MS2F sensor readings are a result of differences in sensitivity [26]. Also, the sensors relate to different volumes of material, and because soils are rarely homogeneous, different sensors may result in different readings. Furthermore, the field measurements depend highly on the ground coupling of the probe. Air gaps will significantly decrease the measured susceptibilities; the MS2F probe is most vulnerable to this problem.

The data in Figs. 1b and 1c, which show densely spaced measurements along the same line as in Fig. 1a show that the small MS2F sensor is not able to pick up a lot more variation than is observed with the larger-diameter MS2D sensor. Also, the MS2F sensor gives significantly lower susceptibility readings. These considerations have made us decide to do all further measurements with the MS2D rather than the MS2F sensor.

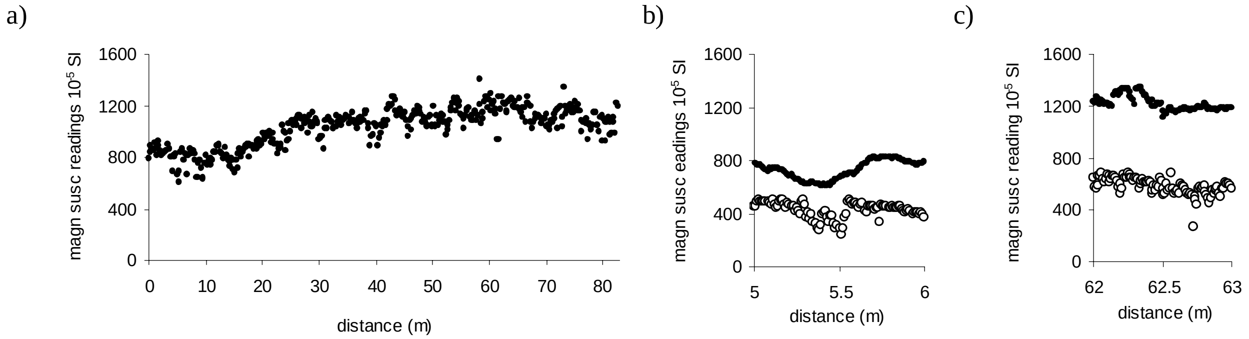

Figure 1. Spatial variability in magnetic susceptibility for Schofield Barracks, O'ahu, Hawaii. a) Transect measured with the Bartington MS2D sensor. The detailed measurements in b) and c) are collected at a smaller step size and with both the Bartington MS2D and MS2F sensors, where the open circles represent the measurements taken with the MS2F sensor. Note the different horizontal scales in these diagrams. See appendix A for additional information.

Panama – Transects 1 and 3 (Figs. 2a and 2b) for Panama show magnetic susceptibility readings with a somewhat larger spatial variability than in O'ahu, Hawaii. The one notable exception relative to all other sites with respect to absolute susceptibility readings and variability within a site is Line 4 in Panama. This site was the only one not in agricultural land, but on a beach, rich in pure magnetite. Here, the continuous hydraulic sorting in the surf zone has caused the heavy minerals (magnetite) and the quartz sand to be deposited in different areas. Due to the large extremes and the higher than average variability many sensors for the detection of land mines and UXO will experience significant problems.

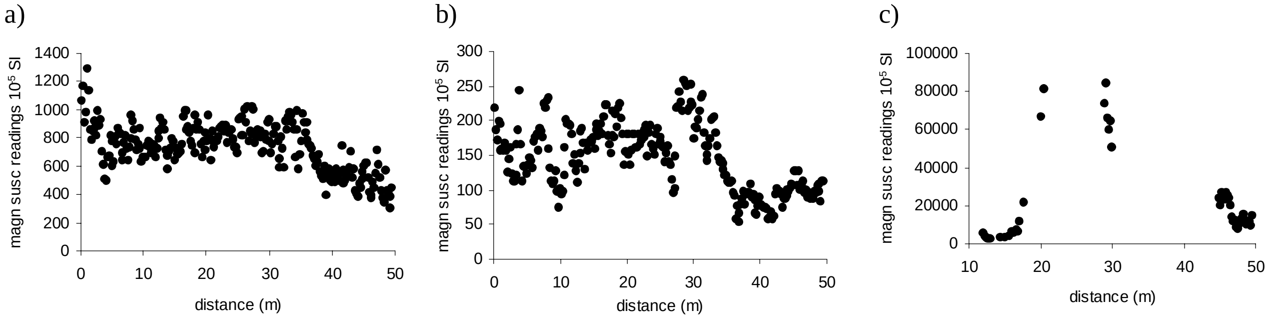

Figure 2. Spatial variability in magnetic susceptibility (Bartington MS2D sensor) in Panama. a) Line 1 at Universidad Tecnológica de Panamá, b) Line 3 at Achiote, and c) Line 4 at Playa Gorgana. Note the different vertical scales of the diagrams. See appendix A for additional information.

Socorro – For reference we collected a transect in Socorro, New Mexico. The soil material is wind blown sand, or loess. The climate can be described as semi arid, which results in totally different soils than for the rest of the transects presented in this paper. Many soils in New Mexico are characterized by the presence of so-called calcic horizons within the first meter of the soil profile. These calcic horizons are accumulations of salts that form either through precipitation or biochemical alterations. The susceptibility readings along a 35m long transect (Fig. 3) show a variability that is comparable to the other locations, and absolute numbers that are comparable with low magnetic susceptibility sites in the tropics such as in Panama (Fig. 2b).

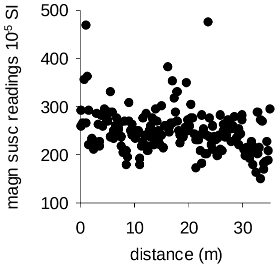

Figure 3. Spatial variability in magnetic susceptibility (Bartington MS2D sensor) at the New Mexico Tech land mine detection test lanes, Socorro, New Mexico.

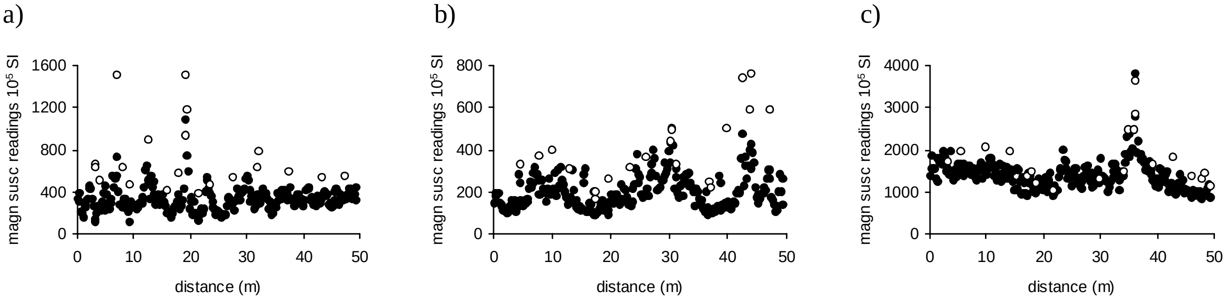

Figure 4. Spatial variability in magnetic susceptibility (Bartington MS2D sensor) on Kohala Volcano, the Big Island of Hawaii. a) Line 1, b) Line 2, and c) Line 3. Note the different vertical scales of the diagrams. The open circles represent measurements at sampling locations after removal of the vegetation. See appendix A for additional information.

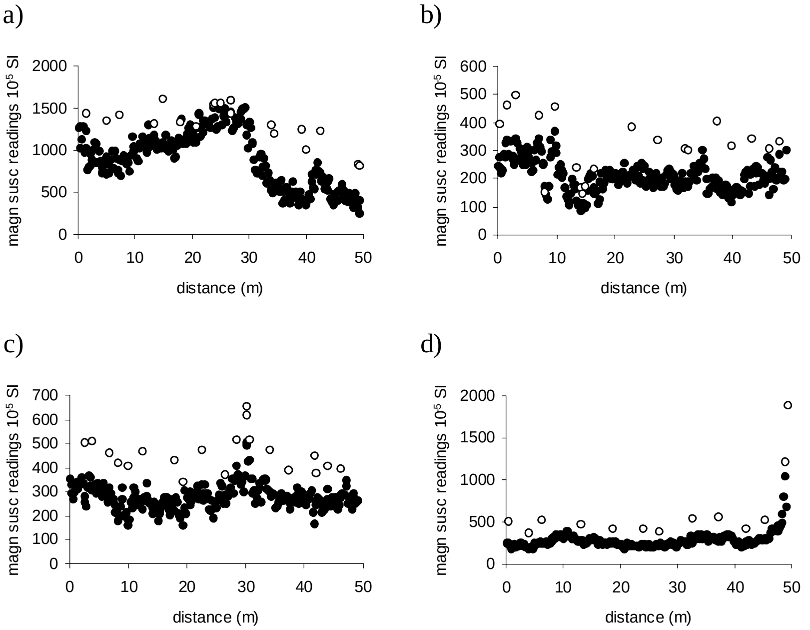

Figure 5. Spatial variability in magnetic susceptibility (Bartington MS2D sensor) on Mauna Kea Volcano, the Big Island of Hawaii. a) Line 4, b) Line 5, c) Line 6, and d) Line 7. Note the different vertical scales of the diagrams. The open circles represent measurements at sampling locations after removal of the vegetation. See appendix A for additional information.

Big Island, Hawaii – For all transects, except for Line 3 and Line 4, the magnetic susceptibility readings are below 1000 10^{-5} SI. The spikes in the readings (e.g., at 20m in Fig. 4a and at 50m in Fig. 5d) are the result of volcanic rocks or sinter blocks at or near the surface. Probably, in these rocks a larger amount of magnetite is present than in the surrounding soil. The sudden change in susceptibility readings at a distance of 30m on Line 4 (Fig. 5a) follows the transition from a lava flow onto a soil formed in depositional material. Much higher magnetic susceptibilities were measured at Line 4 and especially Line 3 (Figs. 4c and 5a) than for the rest of the transects. In the soil of Line 3, many black grains behaving as small magnets were found, indicating that significant amounts of magnetite are present in this soil. Considering the fact that all these soils have the same parent material, it seems that dry conditions (see Appendix A) favor the occurrence of ferrimagnetic minerals.

Nevertheless, it seems impossible to make a direct correlation between susceptibility readings and mean annual rainfall. For the transects 1 to 3 on Kohala Volcano, the average mean annual rainfall decreases from 1300 mm/y, via 750 mm/y to 180 mm/y while the average susceptibility readings are $325\cdot10^{-5}$ SI, $198\cdot10^{-5}$ SI, and $1375\cdot10^{-5}$ SI, respectively. Part of this bad correlation can be attributed to the presence of vegetation, which has a strong effect on the susceptibility readings. The open circles in the diagrams in Figs. 4 and 5 represent measurements at the locations that were selected for sampling. Here, the vegetation was removed and before the sample material was collected we repeated the susceptibility measurements. The data Figs. 4 and 5 show that in many instances the vegetation has a strong effect on the measurements.

4.2 Vertical variability in magnetic susceptibility

Magnetic measurements in soil pits have three advantages over measurements at the surface. Firstly, soil pits allow for the study of soil development. This may provide clues to magnetic behavior. Secondly, soil pits eliminate the effect that vegetation has on the measurements. Even when vegetation is removed, the presence of a litter layer can lower the surface readings. Thirdly, most EM sensors for the detection of buried land mines and UXO have a larger penetration depth than the highly sensitive Bartington sensors. Due to the shallow penetration of the Bartington sensors, surface measurements can not fully characterize all the variability in magnetic soil properties.

Figure 6 shows the results of the magnetic measurements in the soil pits, which were done using a vertical sensor orientation. For half of the soil pits the magnetic susceptibility increases with depth, while for the other half a decrease with depth is observed. In all but one soil pit we observe a gradual change in magnetic susceptibility with depth. Only in soil pit 3 on the Big Island of Hawaii (Fig. 6c) the readings experience a sudden large change. Future chemical analysis will have to explain this trend.

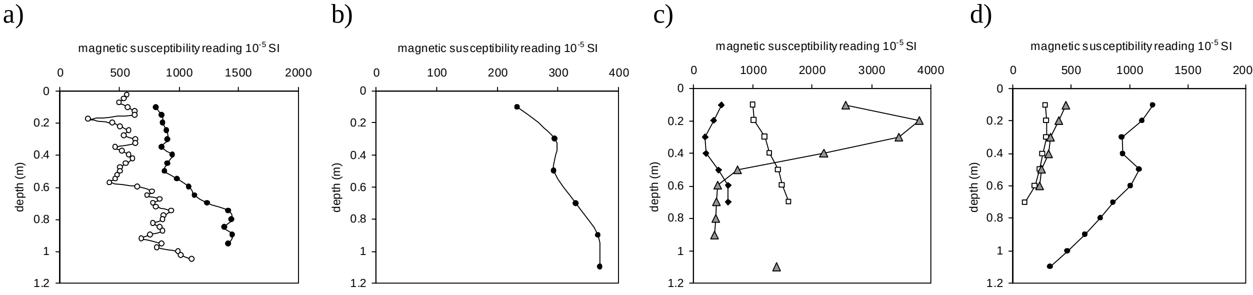

Figure 6. Vertical variation in magnetic susceptibility in soil pits. a) O'ahu, Hawaii. The open circles represent measurements with the Bartington MS2F sensor while the black circles are results of the MS2D sensor measurements. b) Panama, Line 3. c) Kohala Volcano, Big Island, Hawaii. The black diamonds and open squares represent soil pits measurements for Lines 1 and 2, respectively, while the triangles represent the measurements in the soil pit at Line 3. The measurement at 1.1 m depth is for unweathered basalt. c) Mauna Kea Volcano, Big Island, Hawaii. The black circles, open squares, and the triangles represent measurements in soil pits at Lines 4, 5 and 6, respectively. See appendix A for more information.

4.3 Correlation of mean annual rainfall and magnetic susceptibility

Comparison of the magnetic susceptibility readings and values of the mean annual rainfall at the Big Island of Hawaii suggests there may be correlation between the two. Figure 7 shows average magnetic susceptibility readings for surface measurements and soil pits plotted versus the mean annual rainfall. The averages for the surface were calculated based on the measurements at the 20 sampling locations where vegetation was removed (open circles in Figs. 4 and 5). The averages for the soil pits were calculated over the interval from 0.1 to 0.6 m. This range is chosen somewhat arbitrarily but is the maximum range for which we were able to take measurements in all 6 soil pits. The results in Fig. 7 show a clear trend of decreasing magnetic susceptibility readings with an increasing mean annual rainfall. When combining the two datasets (i.e., averaging between the values from the soil pits and the surface measurements) a power function of the form $y=22834x^{-0.5087}$ fits the data with an R^2 of 0.963 (dashed line in Fig. 7). Although a few assumptions and simplifications were made this strong fit demonstrates the clear correlation between mean annual rainfall and magnetic susceptibility.

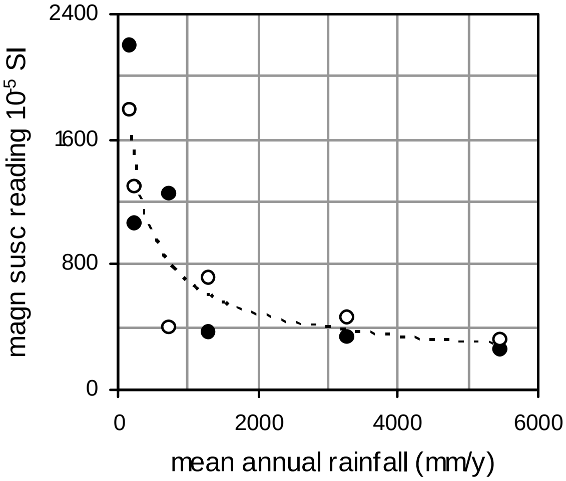

Figure 7. Cross plot of average magnetic susceptibility readings versus mean annual rainfall for 6 locations on the Big Island of Hawaii. The open circles represent the magnetic susceptibility values averaged over measurements at 20 vegetation-cleared sampling locations. The black circles represent the average magnetic susceptibility between 0 and 0.6 meter depth measured in soil pits at these locations. The dashed line is a regression for both datasets combined.

4.4 Laboratory measurements

Laboratory analysis provides the opportunity to determine the magnetic minerals responsible for the measured magnetic susceptibility in soils. The most important question to be answered is the frequency dependence of the material. When comparing the average low- and high frequency magnetic susceptibility readings with the frequency dependence one important observation can be made (Table 3): there is no correlation between the absolute magnetic susceptibility and the frequency dependence of a sample. O'ahu and Panama both have a similar magnetic susceptibility, but while the material from Panama exhibits virtually no frequency dependence, the samples from O'ahu have a very large frequency dependence (a frequency dependence of >5 can be significant for time- and frequency-domain electromagnetics; S. Billings, personal communication). Also some samples from Ghana show significant frequency dependence, while for these samples the high- and low-frequency magnetic susceptibility appears to be very low.

The total iron content (using XRF) was determined only for samples from O'ahu and Ghana. These data show that the samples from both these locations contain a significant percentage of iron. However, there is a large difference between he high- and low-frequency magnetic susceptibility at these sites. Samples from O'ahu have a high susceptibility, while in Ghana the susceptibility is low. This indicates that different iron oxides are present at these locations. While in Ghana most of the iron oxide is probably hematite, in O'ahu ferrimagnetic minerals must be present.

Table 3. Summary of laboratory data.

	O'ahu surface	O'ahu soil pit	Panama[1]	Ghana[2]	New Mexico	Wyoming
Number of samples	20	40	5	20	12	5
Low frequency magnetic susceptibility readings (Bartington MS2B sensor)						
Maximum	1153	1312	1304	118	328	13
Minimum	519	567	678	35	204	9
Average	893	956	1051	69	249	10
Standard deviation	221	198	273	27	38	1.4
High frequency magnetic susceptibility readings (Bartington MS2B sensor)						
Maximum	1121	1279	1303	111	326	–
Minimum	506	548	679	35	203	–
Average	743	929	1052	65	247	–
Standard deviation	205	194	272	25	38	–
Frequency dependence (LF – HF)						
Maximum	33	35	1.3	9	4	–
Minimum	13	19	-3	-0.2	0.1	–
Average	22	27	-0.4	3.6	2	–
Standard deviation	6	4	1.9	2.6	1.3	–
Other measurements						
XRF - total iron content (%)	–	21 – 27	–	20 – 40	–	–
Bulk density[3] (kg·m^{-3})	827	803	843	1176	1090	1366

[1] Only individual samples (see Appendix A).

[2] Only samples from Line 4.

[3] Bulk densities for laboratory samples.

5. DISCUSSION

This paper is a first attempt at characterizing the variability in magnetic soil properties for different locations in the tropics. In the discussion we try to relate our findings with existing literature.

The variation in absolute or mean magnetic susceptibility between sites varies significantly. Comparing the values for Ghana (only laboratory measurements), Hawaii, and Panama (excluding Line 4 on the magnetite beach) we see the mean of the susceptibility readings vary by about a factor 15 maximum. Also between transects within the same geographical region the variation can be significant. On the Big Island of Hawaii we found the mean susceptibility for 7 soils formed in parent material of similar age and origin to vary by as much as a factor 10. With respect to the spatial variability in magnetic susceptibility readings within a site two observations can be made.

(1) The magnetic susceptibility for most transects, whether they are on Hawaii, in Panama, Ghana or New Mexico, varies in most cases by a factor 2 to 5, which are numbers similar as those presented in earlier studies [3]. The one exception to this is the line that we collected on the beach in Panama, where the variability is much higher. In this case we dealt with natural variability in a depositional environment, rather than in a soil.

(2) In most areas, a frequency distribution of the magnetic susceptibility gives a unimodal histogram with one narrow peak [3,26]. This holds for most of our measurement areas, except for Line 4 on the Big Island of Hawaii which has a bimodal distribution. This can be explained by the measurements being collected on two different parent materials.

Comparison of the mean annual rainfall and the magnitude of the magnetic susceptibility readings show a strong correlation between the two. For low-rainfall sites high susceptibilities were measured while magnetic susceptibility readings at locations with high amounts of annual rainfall were low. A study by [24] for four soils on the Big Island of Hawaii (with rainfall amounts ranging between 1000 and 3800 mm/year) shows that ferrimagnetic minerals accounted for less that one percent of the soil material. These low amounts of ferrimagnetic minerals and, thus, low magnetic susceptibility readings may be the result of reduction and subsequent leaching of iron down the soil profile [15]. This may also explain the observation in many soil profiles of an increase in magnetic susceptibility with depth (Fig. 6). However, in most soils on the Big Island of Hawaii we observe a decrease in magnetic susceptibility with depth. This may be a interpreted as an local enrichment rather than a depletion due to leaching [15,21,27]. Further study is needed if the vertical distribution of magnetic susceptibilities is to be understood fully.

The laboratory analyses led to the observation that high- and low-frequency magnetic susceptibility do not correlate with the frequency dependence in magnetic susceptibility. A similar effect was observed for a series of samples from Mozambique [8]. Also, the high- and low-frequency magnetic susceptibility and the frequency dependent susceptibility do not correlate with the total iron content (Table 3). We are not aware of any existing studies studying these relationships for different regions in the world. Therefore, we believe that further study is desirable, especially because of the important effect of frequency dependent behavior in magnetic soils on time- and frequency-domain electromagnetic sensors.

ACKNOWLEDGEMENTS

We would like to thank Stephen Billings and Leonard Pasion (University of British Columbia) for useful discussions on the subject. Roger Young and Julie Staggs (Oklahoma University) provided us with the sample material from the Lewis Shale deposits in Wyoming. Lee Dalton performed part of the laboratory analyses.

REFERENCES

[1] Hendrickx, J.M.H., Wierenga, P.J., and Nash, M.S., "*Variability of soil water tension and soil water content*," Agricultural Water Management, Vol. 18, pp. 135-148, 1990.
[2] Wilson, D.J., Western, A.W., Grayson, R.B., Berg, A.A., Lear, M.S., Rodell, M., Famiglietti, J.S., Woods, R.A., and McMahon, T.A., "*Spatial distribution of soil moisture over 6 and 30 cm depth, Mahurangi river catchment, New Zealand*," Journal of Hydrology, Vol. 276, pp. 254-274, 2003.
[3] Butler, D.K., "*Implications of magnetic backgrounds for unexploded ordnance detection*," Journal of Applied Geophysics, Vol. 54, pp. 111-125, 2003.
[4] Jenwatanavet, J. and Johnson, J.T., "*An analytical model for studies of soil modification effects on ground penetrating radar*," IEEE transactions on antennas and propagation, Vol. 49, pp. 923-933, 2001.
[5] Hendrickx, J.M.H., Borchers, B., Woolslayer, J., Dekker, L.W., Ritsema, C., and Paton, S., "Spatial variability of dielectric properties in field soils," in *Detection and Remediation Technologies for Mines and Minelike Targets VI*, A.C. Dubey, J.F. Harvey, J.T. Broach, and V. George, eds., Proceedings of the SPIE, Volume 4394, pp. 398-408, 2001.
[6] Das, Y., McFee, J.E., Russell, K., Cross, G., and Katsube, T.J., "Soil information requirements for humanitarian demining: the case for a soil properties database," in *Detection and Remediation Technologies for Mines and Minelike Targets VIII*, R.S. Harmon, J.H. Holloway, and J.T. Broach, eds., 5089, pp. 1146-1157, 2003.
[7] Pasion, L.R., Billings, S.D., and Oldenburg, D.W., "Evaluating the effects of magnetic susceptibility in UXO discrimination problems," in *SAGEEP*2002.
[8] Borry, F., Gulle, D., and Lewis, A., "Soil characterization for evaluation of metal detector performance," in *EUDEM-SCOT2, International Conference on Requirements and Technologies for the Detection, Removal and Neutralization of Landmines and UXO*2003.
[9] Keene, M.N., Horton, T.J., Styles, M.T., Steadman, E.J., Kemp, S.J., and Hodgkinson, E., "Synthetic magnetic soils for landmine detector testing," in *Detection and Remediation Technologies for Mines and Minelike Targets VIII*, R.S. Harmon, J.H. Holloway, and J.T. Broach, eds., 1169-1180, 2003.
[10] Lindsley, D.H., Oxide minerals: petrologic and magnetic significance, Mineralogical Society of America, 1991.
[11] Thompson, R. and Oldfield, F., Environmental magnetism, Allen & Unwin, 1986.
[12] Cornell, R.M. and Schwertmann, U., The iron oxides - structure, properties, reactions, occurrence and uses, VCH publishers, 1996.
[13] Stucki, J.W., Goodman, B.A., and Schwertmann , U., Iron in soils and clay minerals, Reidel, 1988.
[14] Mullins, C.E., "*Magnetic susceptibility of the soil and its significance in soil science - a review*," Journal of Soil Science, Vol. 28, pp. 223-246, 1977.
[15] Singer, M.J., Verosub, K.L., Fine, P., and TenPas, J., "*A conceptual model for the enhancement of magnetic susceptibility in soils*," Quaternary international, Vol. 34-36, pp. 243-248, 1996.

[16] Kitayama, K., Schuur, E.A.G., Drake, D.R., and Mueller-Dombois, D., "*Fate of a wet montane forest during soil aging in Hawaii*," Journal of Ecology, Vol. 85, pp. 669-679, 1997.

[17] Ward, S.H., Geotechnical and environmental geophysics, Society of Exploration Geophysicists, 1990.

[18] Driessen, P.M. and Dudal, M., The major soils of the world, Koninklijke Wöhrmann B.V., 1991.

[19] Hendrickx, J.M.H., Van Dam, R.L., Borchers, B., Curtis, J.O., Lensen, H.A., and Harmon, R.S., "Worldwide distribution of soil dielectric and thermal properties," in *Detection and Remediation Technologies for Mines and Minelike Targets VIII*, R.S. Harmon, J.H. Holloway, and J.T. Broach, eds., 2003.

[20] Goulart, A.T., Fabris, J.D., De Jesus Filho, M.F., Coey, J.M.D., Da Costa, G.M., and De Grave, E., "*Iron oxides in a soil developed from basalt*," Clays and clay minerals, Vol. 46, pp. 369-378, 1998.

[21] Maher, B.A., "*Magnetic properties of modern soils and Quaternary loessic paleosols: paleoclimatic implications*," Palaeogeography Palaeoclimatology Palaeoecology, Vol. 137, pp. 25-54, 1998.

[22] Billings, S.D., Pasion, L.R., Oldenburg, D.W., and Foley, J., "The influence of magnetic viscosity on electromagnetic sensors," in *EUDEM-SCOT2, International Conference on Requirements and Technologies for the Detection, Removal and Neutralization of Landmines and UXO*2003.

[23] Webster, R. and Oliver, M.A., Statistical methods in soil and land resource survey, Oxford University Press, 1990.

[24] Parfitt, R.L., Childs, C.W., and Eden, D.N., "*Ferrihydrite and Allophane in four Andepts from Hawaii and implications for their classification*," Geoderma, Vol. 41, pp. 223-241, 1988.

[25] Department of Land and Natural Resources, An inventory of basic water resources data: Island of Hawaii, State of Hawaii, Report R34, 1970.

[26] Dearing, J.A., Environmental magnetic susceptibility: using the Bartington MS2 system, Chi Publishing, 1994.

[27] Singer, M.J. and Fine, P., "*Pedogenic factors affecting magnetic susceptibility of Northern California soils*," Soil Science Society of America Journal, Vol. 53, pp. 1119-1127, 1989.

APPENDIX A

This table summarizes the field sites for measurement of magnetic susceptibility, the number of samples collected, and provides information on performed laboratory analyses.

	Location description	GPS position	Elevation (m)	Mean annual rainfall (mm)	Soil information	Vegetation	Line length (m)	Sensor	Stepsize (m)	Number of samples	Soil pit	Sensor	Number of samples	XRF	Dual frequency magn susc.	Bulk density
Hawaii – Big Island																
Line 1	Kohala volcano	N20º04'05" W155º43'46"	1375	1300	Maile series	Grassland	50	MS2D	0.2	20	Y	MS2D	7	–	–	Y
Line 2	Kohala volcano	N20º03'07" W155º44'20"	1010	750	Waimea series	Grassland	50	MS2D	0.2	20	Y	MS2D	7	–	–	Y
Line 3	Kohala volcano	N20º08'21" W155º53'18"	50	180	Kawaihae series	Bare soil	50	MS2D	0.2	20	Y	MS2D	9	–	–	Y
Line 4	Mauna Kea	N19º57'23" W155º49'44"	75	230	Waikui series	Bare/grass	50	MS2D	0.2	20	Y	MS2D	11	–	–	Y
Line 5	Mauna Kea	N19º51'11" W155º09'12"	377	5485[1]	Akaka series	Grassland	50	MS2D	0.2	20	Y	MS2D	7	–	–	Y
Line 6	Mauna Kea	N19º52'12" W155º06'11"	51	3275[2]	Hilo series	Grassland	50	MS2D	0.2	20	Y	MS2D	7	–	–	Y
Line 7	Mauna Kea	N19º52'14" W155º07'11"	136	3563[3]	Hilo series	Grassland	50	MS2D	0.2	13	–	–	–	–	–	Y
Hawaii – O’ahu																
Line 1	Schofield Barracks	–	–	–	–	Bare soil	85	MS2D	0.2	20	Y	MS2D MS2F	40	Y	Y	Y
Line 1a/b	Schofield Barracks	–	–	–	–	Bare soil	2×1	MS2D MS2F	0.01	–	–	–	–	Y	Y	Y
Panama																
Individ samples		–	–	–	–	–	–	–	–	–	–	–	5	Y	Y	Y
Line 1	UTP	–	–	–	–	Grassland	50	MS2D	0.2	20	–	–	–	–	–	–
Line 3	Achiote	–	105	–	–	Grassland	50	MS2D	0.2	20	Y	MS2D	6	–	–	–
Line 4	Playa gorgana	–	–	–	–	Bare	–	MS2D	0.2	10	–	–	–	–	–	–
Ghana																
Line 1	Prestea-Bondaye	N5º23'77" W2º09'62"	165	2100[4]	–	Corn	10	–	–	20	–	–	–	–	–	Y
Line 2	Tarkwa	N5º17'44" W2º00'27"	85	2100[4]	–	Cassava	10	–	–	20	–	–	–	–	–	Y
Line 3	Tarkwa	N5º17'85" W2º00'33"	85	2100[4]	–	Cassava	10	–	–	20	–	–	–	–	–	Y
Line 4	Tarkwa	N5º17'77" W2º00'23"	85	2100[4]	–	Cassava	10	–	–	20	–	–	–	–	Y	Y
New Mexico																
Line 1	Socorro	–	–	–	–	Bare	35	MS2D	0.2	12	–	–	–	–	–	Y
Wyoming																
Lewis Shale		–	–	–	–	Sedimentary rock	–	–	–	5	–	–	–	–	Y	Y

[1] From weather station Honomu Mauka [25].

[2] From weather station Pepeekeo Makai (lower elevation) [25].

[3] From weather station Honomu Makai (lower elevation) [25].

[4] From weather station at N5º35' W1º56' during 1961-1968.