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Magnetic viscosity of tropical soils: classification and prediction as an aid for landmine detection

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SUMMARY

Electromagnetic induction (EMI)-based metal detectors are the most widely used sensing techniques in landmine clearance operations; however, they are negatively influenced by frequency dependence of magnetic susceptibility. A total of 466 rock and soil samples collected from across the tropics are investigated in this study. The data show that frequency-dependent susceptibility depends on the parent material as well as on the degree of weathering. Ultramafic and mafic rocks and their derivatives have higher susceptibility and absolute frequency dependence than material originating from intermediate, felsic and sedimentary rocks. Within each parent material group, absolute frequency dependence increases steadily with increasing alteration from unweathered rock to topsoil. This effect is likely due to either the residual enrichment of weathering resistant ferrimagnetic minerals including superparamagnetic (SP) grains, the comminution of larger ferrimagnetic minerals or the neoformation of SP minerals during soil formation.

Relative frequency dependence is generally lower than 15 per cent for the investigated samples with a few exceptions. It increases with alteration for igneous rocks but remains at the initially high level for sediments. This finding indicates that the relative concentration of SP minerals changes with respect to the total magnetic fraction for igneous rocks but remains constant for sediments. Soils derived from ultramafic, mafic and intermediate rocks show low relative frequency dependence, and their magnetic susceptibility is mainly the result of multidomain lithogenic minerals. In contrast, soils derived from felsic rocks and sediments show the highest values, and their susceptibility is due to SP minerals that are either formed during pedogenesis or residually enriched.

The average and extreme values of the absolute frequency dependence within each subgroup, based on parent material and alteration grade, are used to design a prognosis system for assessing the impact of the subsurface on EMI sensors for landmine detection. In general, intermediate, felsic and sedimentary rocks have no influence on the detectors and only a weak influence in the most extreme cases. Soils derived from these rocks typically have no influence; however, they can have a very severe influence in a few cases. In contrast, ultramafic and mafic rocks typically have a moderate influence and a very severe influence in extreme cases, with the associated soils resulting in a severe influence in general. The deduced prognosis system can be used by demining organizations to help them predict metal detector performance in tropical regions on the basis of geologic and/or soil maps, which do not supply information on electromagnetic properties. In this way, such a system may eventually help with the planning of demining campaigns and selection of appropriate sensors.

Key words: Environmental magnetism; Magnetic and electrical properties; Magnetic mineralogy and petrology; Rock and mineral magnetism.

1 INTRODUCTION

Today, thousands of square kilometres of land worldwide are contaminated by landmines and/or explosive remnants of war and other violent conflicts. In 2009, a total of 66 countries were affected by this hazard, and the number of officially registered casualties was 3956 (ICBL 2010). Furthermore, the estimated number of unreported cases victims is high. Many of the countries that are suffering most from this landmine problem are in the tropical regions of Africa and Southeast Asia.

Electromagnetic induction (EMI)-based metal detectors are the most widely used devices for landmine clearance. A time-varying magnetic field is generated using a current that flows through a coil. A metallic object close to the detector induces a secondary field that can be sensed by the receiving coil of the detector. When this signal exceeds a certain threshold, it triggers an alarm in the detector. The response signal is influenced by the material, depth, shape and orientation of the object, the detector layout and by the ground material in which the object is buried.

Das *et al.* (2002) report that the signal of EMI detectors can be biased by the background signal of different soil types. This bias can influence the sensitivity of the detector, as targets cannot be detected at the desired depths, false alarms can be generated and some detectors can even be completely unusable in extreme cases. Hence, the user community knows that certain soils are problematic, but there is much confusion on the physical cause and how to characterize these soils. A variety of terms are used to describe these soils, including 'conducting soil', 'red soil', 'iron-bearing soil' or 'mineralized soil'. Some of these self-made terms can be misleading, and the confusion results from a lack of knowledge and information on electromagnetic properties of soils and from the poor communication between scientists and the demining community. One problem is that conventional soil classifications, such as the widely available FAO (Food and Agriculture Organization of the United Nations) soil maps, do not contain information that is directly relevant to landmine detection techniques. Thus, there is a clear need for an information database and maps of electromagnetic soil properties. Such information will be helpful for (i) demining organizations, as they select appropriate equipment and predict its performance across different environments; (ii) developers and researchers, as they assess the potential of their proposed technologies in different regions of the world and (iii) researchers, as they establish suitable test facilities with realistic and representative soil properties (Das *et al.* 2002).

The impeding influence of the magnetic susceptibility of various soils on electromagnetic sensors, which are used for the detection of landmines and unexploded ordnance, has recently been investigated by several authors. Indeed, they ranked magnetic susceptibility as most important soil property influencing EMI detectors and, to a lesser degree, electric conductivity (van Dam *et al.* 2005; Das 2006). Different types of EMI detectors can be categorized by their signal shape. Continuous-wave (CW) detectors use a sinusoidal field with frequencies of a few kHz. Simple instruments use one, only a single frequency. More sophisticated CW detectors use two or more frequencies and can measure the amplitude and phase difference between the received and emitted signals. Pulse induction detectors use a current pulse through the transmitting coil and measure the decay curve of the collapsing magnetic field when turning off this current. Some modern detectors have a ground compensation capability, meaning that they are able to 'learn' the default soil response signal and can therefore compensate to a certain degree. Single frequency CW detectors are highly influenced by the absolute value of soil magnetic susceptibility. Thresholds describing the influence of soil magnetic susceptibility on these detector types are given in CEN (2003). Based on these values, tropical soils were classified by Preetz *et al.* (2008), and maps for Angola were subsequently created using their data depicting the potential soil influence across different regions (Preetz & Hennings 2010). Similarly, Hannam & Dearing (2008) provided maps of Bosnia and Herzegovina that allow the prediction of impeding effects on both metal detector techniques.

Table 1. Indicative values classifying the influence of frequency dependent susceptibility on multifrequency continuous wave and pulse induction detectors (CEN 2008 and Bloodworth & Logreco 2004); neutral, no effect on the performance of the detector even without ground compensation; moderate, effect on the detector performance is notable but the metal detector can be used without ground compensation; severe, the use of ground compensation is necessary; very severe, the metal detector cannot be used even with ground compensation.

Soil influence	Frequency dependence $\Delta\kappa$ [10^{-5} SI]
Neutral	<5
Moderate	5—15
Severe	15—25
Very severe	>25

The bulk magnetic susceptibility of the soil has only a small influence on pulse induction detectors or CW detectors that operate at several frequencies. However, these detector types are influenced by magnetic viscosity, causing susceptibility variations with the frequency of the applied field. Table 1 provides indicative values for the influence of the frequency-dependent susceptibility of a soil according to CEN (2008) and Billings (2004). It should be noted that the given values are only indicative values, as metal detector performance always depends on the specific detector model used (Guelle *et al.* 2006). Influencing factors include both the physical detector layout and the individual interpretation algorithm used to transform the measured voltage signal into an alarm signal.

Our studies were motivated by the need for information on magnetic soil properties and the enormous potential benefit that such information could offer the field of landmine clearance. A large number of lateritic soils and their corresponding parent rocks were analysed for their magnetic susceptibility with respect to its influence on landmine detectors. The investigated lateritic soil type is widespread in the tropics. A previous study concentrated on the absolute magnetic susceptibility of such lateritic soils (Preetz *et al.* 2008). In this study, we instead focus on the frequency dependence of susceptibility to

(1) determine frequency-dependent magnetic susceptibility for a large number of tropical soils and their parent rocks,

(2) investigate the correlation between frequency-dependent susceptibility and the parent material as well as the degree of alteration of the samples, and

(3) assess the influence that soil magnetic susceptibility has on EMI detectors and generate a classification system that can be used to predict metal detector performance on the basis of geological and pedological information.

2 MAGNETIC SUSCEPTIBILITY OF SOILS

2.1 Bulk magnetic susceptibility

Magnetic susceptibility describes the degree to which a material is magnetized when it encounters an external magnetic field. It can be expressed as a volume-specific value κ or a mass-specific value $\chi = \kappa/\rho$, where ρ denotes the bulk density of the material. In low magnetic fields, there is a linear relationship between the applied field and the acquired magnetization. The magnetic susceptibility of a soil is determined by the mineral composition of its matrix, including the minerals with diamagnetic, paramagnetic and ferromagnetic (ferrimagnetic and antiferromagnetic) behaviour. The ferrimagnetic minerals (magnetite, titanomagnetite and maghemite) have very high susceptibilities and can therefore dominate the bulk magnetic susceptibility of soils even at low abundances of <1 per cent. Susceptibility depends on the content of other iron-bearing minerals only if these dominant ferrimagnetic minerals are absent. Most iron in soils is stored in the form of other iron oxides and hydroxides, such as goethite and hematite. Both are antiferromagnetic minerals and have low susceptibilities. Therefore, these iron oxides have practically no influence on EMI detectors, even though they represent the biggest contingent of iron bound in soil.

There are different sources of ferrimagnetic minerals in soils. Titanomagnetite is always lithogenic, and magnetite is often of lithogenic origin. This finding indicates that these minerals crystallized during the cooling and solidification of magma and are therefore part of many igneous rocks or of the clastic sediments derived from such rocks. The concentration of lithogenic ferrimagnetic minerals may be higher in soils than in the parent rock material due to residual enrichment during soil forming processes (Singer & Fine 1989). This enrichment occurs because these minerals have a higher resistance to weathering compared to many other minerals (Friedrich *et al.* 1992). Maghemite is of pedogenic origin and is formed during weathering and soil genesis. It can be formed through the oxidation of magnetite (Schwertmann 1988) or as a new mineral by the crystallization of dissolved iron (Mullins 1977). Magnetite and maghemite can also be formed as a result of bacterial activity (e.g. Fassbinder *et al.* 1990), by thermal transformation of Fe-oxides during fires (Kletetschka & Banerjee 1995) and by further chemical and microbial processes, or they may arise from anthropogenic atmospheric inputs (Dearing *et al.* 1996b).

Thus, soil magnetic susceptibility depends on both the parent material and the mineral forming processes that take place during soil development. In general, magnetic susceptibility increases with increasing weathering and soil development (van Dam *et al.* 2008).

2.2 Magnetic viscosity and the frequency dependence of susceptibility

The magnetic susceptibility of ferrimagnetic minerals strongly depends on their grain size. Larger mineral grains are composed of several magnetic domains and are called multidomain (MD) grains. Smaller grains are referred to instead as single-domain grains and can be further classified as either stable single domain (SSD) and ultra-fine grained superparamagnetic (SP) minerals, whose magnetic energy is of the same order of magnitude as their thermal energy (Thompson & Oldfield 1986). Although magnetic energy tends to orient the magnetization in the direction of the applied magnetic field, thermal energy tends to disorient the magnetization, making the magnetization of SP minerals a time-dependent process. When the externally applied magnetic field is turned off, the magnetized grain loses its magnetization rapidly. This phenomenon is called magnetic viscosity, and it can be described by a relaxation process (Néel 1949). Susceptibilities are much higher for SP minerals than for an equal quantity of SSD or MD minerals (Thompson & Oldfield 1986). The susceptibility for 0.03 μm cubes of magnetite at room temperature, for example, is two orders of magnitude higher than for typical SSD and MD susceptibilities (Dunlop & Özdemir 1997). Thus, even a small fraction of SP minerals in a sample can govern magnetic susceptibility. Indeed, various authors have suggested that the grain size at which a SSD grain turns into a SP grain (e.g. the SSD/SP threshold) falls in the range of 1 nm to some tens of nanometres (Thompson & Oldfield 1986; Dearing *et al.* 1996a and references therein). This threshold depends on mineral type, grain shape, temperature and measuring frequency. At higher frequencies, the threshold is shifted to smaller grain sizes, and consequently, fewer magnetic grains within a given grain size distribution show SP characteristics. Susceptibility, thus, decreases with increasing frequency.

This effect can be expressed either by an absolute value as absolute frequency dependence $\Delta\kappa = \kappa_{LF} - \kappa_{HF}$ or as relative frequency dependence $\kappa_{FD} = \Delta\kappa/\kappa_{LF}$, where κ_{LF} and κ_{HF} refer to the susceptibility measured at low and high frequencies, respectively. The absolute frequency dependence $\Delta\kappa$ is linked to the total amount of superfine-grained ferrimagnetic minerals present, whereas relative frequency dependence κ_{FD} denotes a semi-quantitative measure of the concentration of pedogenic fine-grained magnetic minerals with respect to the total magnetic fraction (Torrent *et al.* 2006). It is generally measured at low field strength (<1 mT due to Thompson & Oldfield (1986), i.e. <800 A m^{-1}) and usually specified for a frequency difference of one order of magnitude.

For most geological materials, the relative frequency dependence of magnetic susceptibility is not higher than 15 per cent (Forster *et al.* 1994; Dearing *et al.* 1996a). This limit holds true for most soils and rocks and can be explained using either a relatively broad log-normal grain size distribution or a bimodal distribution of ferrimagnetic minerals (Worm 1998). However, this is not an absolute limit caused by physical principles. Indeed, Worm & Jackson (1999) report tuff samples from Tiva Canyon at Yucca Mountain (Nevada) that possess a higher frequency dependence of more than 30 per cent. These materials are characterized by a narrow grain size distribution of magnetic minerals near the SP/SSD boundary that, according to Néel's (1949) theory, can feasibly result in such a high frequency dependence.

2.3 Origin of SP minerals

A consensus exists in the literature that several pathways of inorganic neoformation are the main sources of SP minerals in soils. The major theories of neoformation are as follows: Dearing *et al.* (1996b) hypothesize a partial dehydration and oxidation of ferrihydrite to SP magnetite, followed by a slow oxidation to the end product, SP maghemite. Fe minerals can be dissolved and form secondary SP magnetite and maghemite minerals (Singer *et al.* 1996; van Dam *et al.* 2005). Torrent *et al.* (2006) deduce from laboratory experiments a reaction chain from ferrihydrite to SP maghemite to SD maghemite to hematite. The role of the iron supply in neoformation is discussed controversially. Dearing *et al.* (1996b) suggest that the strong iron content originating from the parent rock material is actually a precondition for the effective neoformation of SP minerals in soils (*cf*. Evans & Heller 2003), whereas Maher (1998) assumes that the Fe content is rarely a limiting factor. However, there is a consensus that changing the redox conditions is crucial for the process described above. Furthermore, iron-reducing bacteria in the soil may also play a role in pedogenic formation of ultrafine-grained magnetite (Maher 1998).

However, SP minerals can also arise from the solidification of rapidly cooling magma, forming fine-grained crystals (Butler 1992). Thus, SP minerals can be found in mid-ocean ridge basalts, volcanic rocks and in volcanic glasses and ashes in particular (Worm & Jackson 1999; Zhou *et al.* 2000; Knudsen *et al.* 2005). Such magnetic behaviour is not the rule for igneous rocks but it is not

Table 2. Overview of the samples of the study: country of origin and parent rock material.

Origin	Ultramafic	Mafic	Intermediate	Felsic	Sediments	Σ
Australia	1	7	–	29	41	78
Brazil	22	30	–	9	20	81
El Salvador	–	6	3	–	–	9
Ghana	–	–	–	17	16	33
Guatemala	8	–	–	–	–	8
Hawaii	13	6	–	–	–	19
India	–	6	13	22	10	51
Madagascar	11	15	–	16	–	42
Mexico	–	–	–	4	–	4
New Caledonia	20	–	–	–	–	20
Philippines	5	–	–	–	–	5
Puerto Rico	21	–	3	–	–	24
Sri Lanka	–	4	15	5	–	24
Uganda	–	8	–	16	16	40
Venezuela	13	8	–	7	–	28
Σ	114	90	34	125	103	466

an anomaly either, and our own measurements on unweathered volcanic rocks have suggested frequency dependencies of up to 11 per cent. Ashes can also be transported in the atmosphere over longer distances and thereby form a detrital input (Béget *et al.* 1990). Further, comminution of initially MD lithogenic magnetic minerals during the weathering of the parent rock material can contribute to an enrichment of the fine fraction (Maher 1998).

3 MATERIALS AND METHODS

3.1 Sample characteristics

For this study, a collection of lateritic soils and their parent rocks at the Federal Institute for Geosciences and Natural Resources (Hanover, Germany) is used. This sample set includes laterites with silicatic parent rocks from tropical regions all over the world (Schellmann 1974). Following the revised soil classification system provided by the FAO (2006), these are referred to as ferralsols and plinthosols or oxisols, according to US Soil Taxonomy (NRCS 2006).

Lateritic soils generally occur on ancient land surfaces, some dating back to the Tertiary period. Many of these have been subjected to strong erosional processes. Hence, topsoil, subsoil and weathered parent rock appear side-by-side in those landscapes (Mulcahy 1960), such that the investigation of soil profiles, including that of the parent rock, can be seen as an analogue for the variety of the material in which mines commonly are buried. Indeed, mines are usually not buried in bedrock directly; however, unweathered and weathered stones and gravel originating from the parent rock are often part of soils and are thus within the sensing range of the detector. Furthermore, it is important to keep in mind that landmines are not only buried in fine earth material, but are also placed under and on loose rock covers that can interfere with their detection.

The entire collection is made of 1475 samples that include topsoils and subsoils from various depths, as well as samples of weathered and unweathered parent rock. Only samples from profiles that include soil horizons as well as their parent rocks and for which a chemical analysis was available were selected for use in the study. This approach left a resulting set of 466 samples for our analysis. Geochemical analysis of the samples was accomplished using X-ray fluorescence with a Philips spectrometer PW 1220. The samples were prepared by melting with a flux (1 part of sample and 5 parts of Li-metaborate) at 1250 °C, and international standards were used for calibration (Schellmann 1986).

The analysed samples included a variety of different parent rock types. According to the available geological description (Schellmann 1974), the parent rocks were divided into igneous rocks and sediments. Weakly metamorphic rocks were assigned to one of the two groups, depending on their original material. The collection comprises the following rock types.

(1) Igneous rocks: gabbro, phonolite, serpentinite, amphibolite, andesite, basalts, charnockite, diabase, dolerite, granites and orthogneiss.
(2) Sediments including metasediments: sandstone, slate, shale, carbonaceous clay, various fine-grained clastic sediments, phyllite, quartzite and paragneiss.

The igneous rocks were further classified on the basis of their chemical analysis according to their silica content using the thresholds given by Le Maitre (1989) as ultramafic (<45 per cent SiO_2), mafic (45–52 per cent SiO_2), intermediate (52–63 per cent SiO_2) or felsic (>63 per cent SiO_2). Table 2 lists the countries where the samples originated from and provides the subdivision into parent rock groups, as well as the number of samples in each category.

Before describing and discussing magnetic susceptibility, a brief overview of the particular geochemical properties of the lateritic soil development of the samples is given. As an extract of the chemical analyses, Fig. 1 shows the SiO_2, Al_2O_3 and Fe_2O_3 content of the samples according to their parent rock material. The variation in the chemical composition of the samples reflects both the initial conditions of the parent rock and the changes that took place over time and through different grades of weathering, such as the enrichment of iron and aluminium and degradation of silica. The silica content increases from ultramafic to felsic igneous rocks while the iron content decreases. The sediments have values comparable to the felsic igneous rocks. The mean aluminium content is similar for all of the groups assessed, with exception of the ultramafic igneous rock group, which has lower values. The variability within the groups is higher for silica and iron than for aluminium.

As the groups in Fig. 1 contain material with different alteration states, the variability within the groups is high. This variability is especially evident for the silica and iron contents, because the

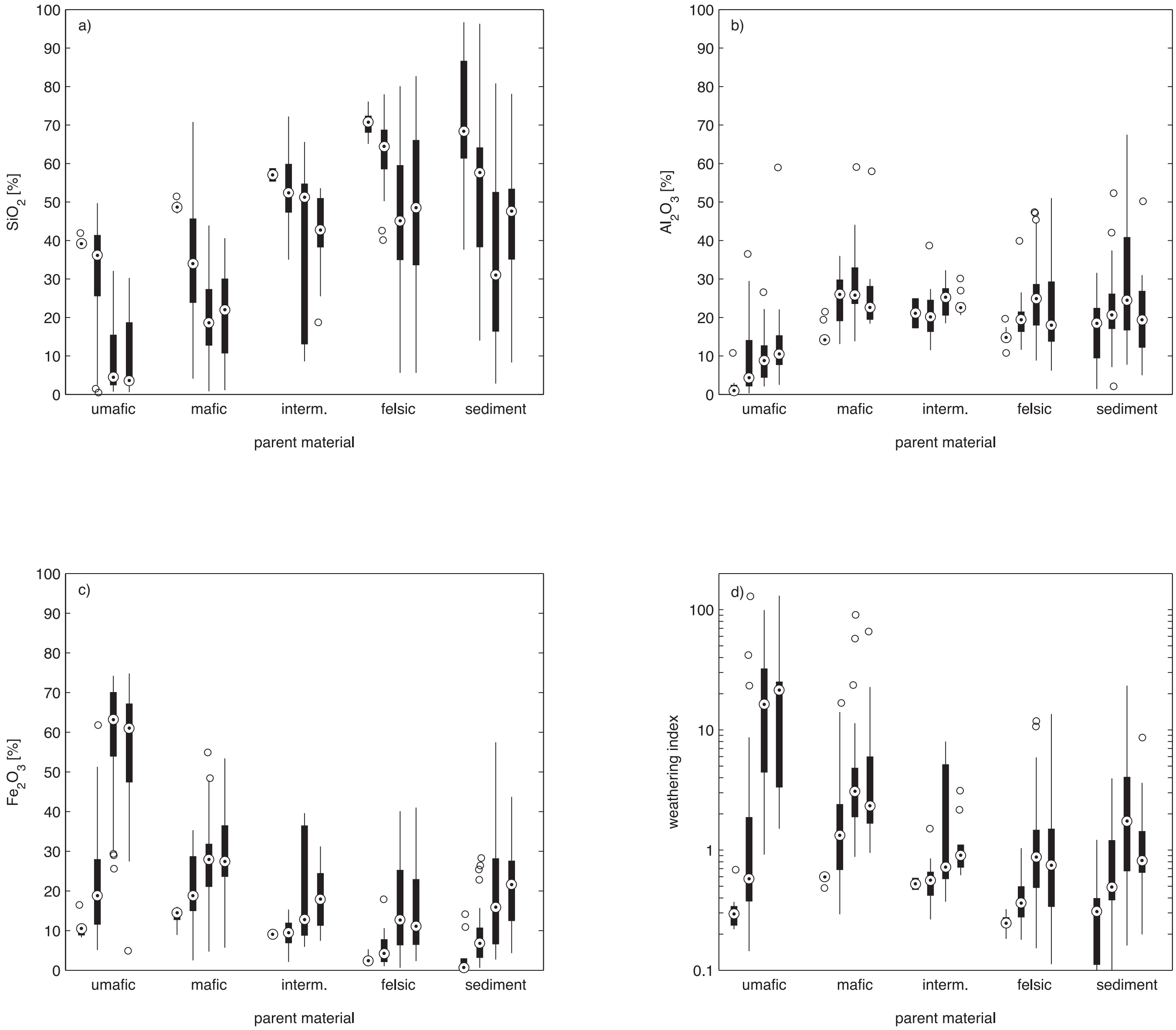

Figure 1. Critical major oxides (in weight per cent) (a–c) and weathering index calculated as (Fe_2O_3 + Al_2O_3)/SiO_2 (d). The samples are grouped by their parent material and the groups are further subdivided into subgroups of unweathered rock, weathered rock, subsoil and topsoil (from left to right). The black dots inside the white circles represent the medians, while the boxes themselves represent the lower and upper quartiles. The whiskers denote the most extreme values within the interval of the first quartile minus, and the third quartile plus 1.5 times the interquartile range, respectively. These correspond to a roughly 99 per cent coverage of the data. Outliers with values beyond the ends of the whiskers are displayed with circles.

strong chemical weathering in tropical conditions causes leaching of dissolved silica and residual enrichment of iron. There is less variability in the aluminium content, as it is generally less enriched than iron and as the parent material has a significant influence on the aluminium content of laterites (Schellmann 1986, 1994). The relationship Al_2O_3 + Fe_2O_3 and SiO_2 was previously used by Bennett (1926) to characterize lateritic soils and to describe the degree of desilification and the enrichment of Fe and Al (Fig. 1d). Within each parent material group, the index generally increases from unweathered rock to topsoil, that is from left to right. However, this index can only be used as a measure of weathering along individual soil profiles because the chemical composition of the parent material is significantly different across the various rock groups and even within the same group there is significant variability (Schellmann 1986, 1994).

3.2 Magnetic susceptibility measurements

All 466 samples, which were already dried and mechanically crushed, were used to fill 10 mL plastic boxes. Volumetric magnetic susceptibility was measured at room temperature with a Bartington MS2B kappa-bridge (Bartington Instruments, Witney, UK) in a magnetic field of $\sim$80 A m^{-1} at two frequencies: 465 and 4650 Hz. The instrument works according to the same principles of EMI that metal detectors use. According to Dearing (1999), the measurement accuracy of the device is 0.1×10^{-5} SI or 1.0×10^{-5} SI when using the sensitive and standard measuring range, respectively. All samples were measured in the sensitive measuring range with exception of those with susceptibilities significantly higher than 100×10^{-5} SI; these were instead measured in the standard range. The instrument was regularly reset, and an empty sample box was measured in between each individual reading to determine and remove the temporal drift of the instrument. To ensure high reproducibility and to assess the precision of the susceptibility values, each sample was measured 10 times. The mean of the repeated measurements was used for further analysis, and we provide the 95 per cent confidence bounds corresponding to twice the standard deviation of the mean. All samples were weighed, and the mass-specific susceptibility was calculated by dividing the volume-specific susceptibility by the bulk density of the samples.

4 RESULTS

The results of susceptibility measurements are depicted in Fig. 2 as a cross-plot of volume-specific susceptibility κ_{LF} versus absolute frequency dependence $\Delta\kappa$. The error bars show that the measurement of absolute susceptibility is quite precise but that the determination of its frequency dependence is prone to errors for low $\Delta\kappa$ values. The error in frequency dependence is high for very low and moderate susceptibilities, while the error is smaller between these ranges and for very high susceptibilities. This is because the sensitive measuring range was used up to susceptibilities of approximately 100×10^{-5} SI and the instrument was switched to the less sensitive range, which covers a wider span of values, for higher susceptibilities. The average error of all measurements is 0.2×10^{-5} SI and 0.5×10^{-5} SI, derived by using the sensitive and standard measuring ranges of the instrument, respectively, and includes both fluctuations caused by the instrument itself and fluctuations caused by slightly varying the positions of the sample in the holder when repeating the measurement. The measured error is similar to the values given by Dearing (1999), that is 0.1×10^{-5} SI and 1×10^{-5} SI for the two measuring ranges. Both κ_{LF} and $\Delta\kappa$ span a wide range of several decades. The histograms on the respective axes indicate that the distributions of susceptibility and absolute frequency dependence are similar to a log-normal distribution, that is, they are symmetric on a logarithmic scale. Thus, we used logarithmic scales for the purpose of depiction and classification. Relative frequency dependence is generally limited by the 15 per cent line, with only a few samples reaching higher values. Even when neglecting the samples with low susceptibilities ($\kappa_{LF} < 20 \times 10^{-5}$ SI), for which the measured frequency dependence might be affected by the measurement inaccuracy of the instrument (Dearing *et al.* 1996a), approximately 20 samples remain with a frequency dependence of greater than 15 per cent.

In Fig. 3, the data set is grouped according to parent rock (unweathered and weathered samples) and soil sample (topsoil and subsoil) of the various rock types. In general, within each group, the rock samples show a lower susceptibility and frequency dependence than do the soil samples. Furthermore, the variability of the magnetic susceptibility among the rocks and soils belonging to a single parent material group is still high. There is a general correlation between magnetic susceptibility and absolute frequency dependence, and the two are more tightly related for sediments than for the other parent materials.

Fig. 4 gives a statistical overview of susceptibility and its frequency dependence within each parent material group. The variability within the individual groups is high, and some high values occur in each group. The mean absolute susceptibility is much higher for the group with ultramafic and mafic parent material than for the group with intermediate, felsic and sedimentary material (Fig. 4a). Mass-specific susceptibilities were calculated and are summarized in Fig. 4(b); these show the same trends and correlations with parent material and weathering. This finding indicates that the variation in bulk density is small compared to the variation in susceptibility, the latter of which covers several decades in our data. For this reason and because metal detectors are influenced by volume-specific susceptibility, we restrict our presentation and discussion to volume-specific susceptibilities in the remainder of the paper.

The distribution of absolute frequency dependence of susceptibility $\Delta\kappa$ is summarized in Fig. 4(c). Again, ultramafic and mafic rocks and the associated soils have significantly higher means than

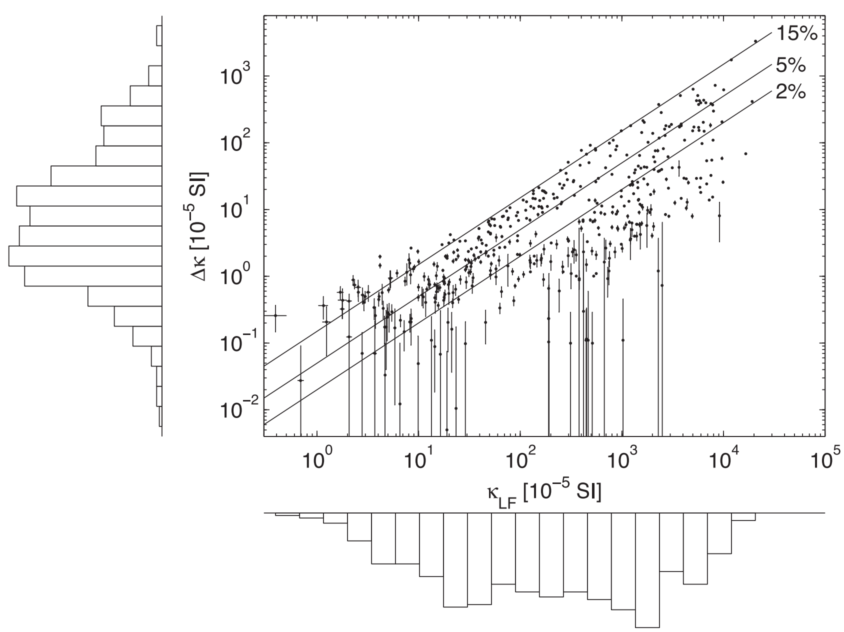

Figure 2. Frequency-dependent susceptibility $\Delta\kappa$ versus low-frequency susceptibility κ_{LF} of all 466 samples. The error bars correspond to the 95 per cent confidence bounds. The lines correspond to 2, 5 and 15 per cent relative frequency dependencies. The histograms are plotted on the respective axis.

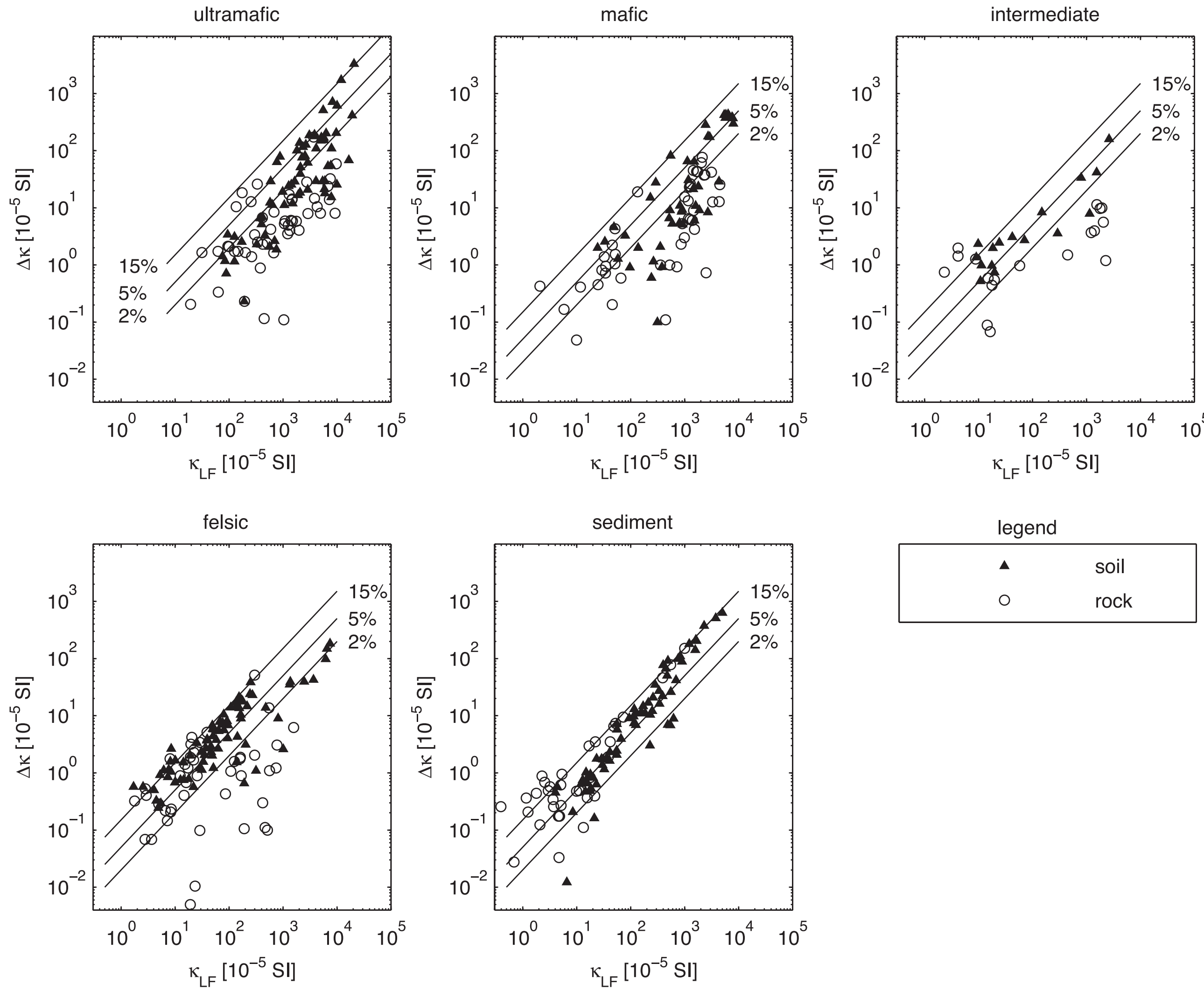

Figure 3. Absolute frequency dependence $\Delta\kappa$ versus low-frequency susceptibility κ_{LF} grouped for the different parent material. The symbols denote whether each sample is from the parent rock (unweathered and weathered) or soil (subsoil and topsoil). The lines correspond to 2, 5 and 15 per cent relative frequency dependence.

the other groups, although the variability within the group is high. Thus, the trend is the same as for susceptibility κ_{LF}, in which the group with ultramafic and mafic parent material shows the highest values (see Fig. 4a).

Relative frequency dependence is prone to higher errors than absolute frequency dependence. For this reason, only samples with susceptibilities $\kappa_{LF} > 20 \times 10^{-5}$ SI are considered and reported in Fig. 4(d), resulting in 368 samples. The values are low for samples of ultramafic, mafic and intermediate origin and are high for samples originating from felsic rocks and sediments.

For a more detailed analysis, the grouping is refined by taking the material alteration into consideration. The samples are grouped according to their parent rock and the type of material, that is, whether the sample is unweathered rock, weathered rock, subsoil or topsoil (Fig. 5). The box plots give an overview of the distribution of absolute susceptibility and absolute and relative frequency dependence and are shown simplified for clarity. Within the individual parent material groups, absolute susceptibility generally increases from left to right; that is, with progressing alteration from the unweathered rock to the topsoil (Fig. 5a). Absolute frequency dependence shows a steady increase with alteration for all parent materials (Fig. 5b), with exception of unweathered intermediate rocks that do not follow the trend. However, the number of samples in this subgroup is very small, so these results may not be of statistical significance. As samples with very low susceptibilities were not used for analysing the relative frequency dependence, the number of samples within some of the subgroups in Fig. 5(c) is smaller, and the results for some of these may therefore not be representative. Relative frequency dependence increases continuously with alteration for all igneous parent materials. Unweathered rocks have the lowest values (<1 per cent), whereas their corresponding topsoils have the highest values. Of these, the lowest values are found in soils developed from ultramafic rocks (2.5 per cent), rising with the increasing silica content of the parent material and finally reaching 7 per cent for felsic parent rocks. In contrast, the relative frequency dependence of unweathered sediments is already quite high (8 per cent) and stays at this high level. However, it does not increase further with additional material alterations.

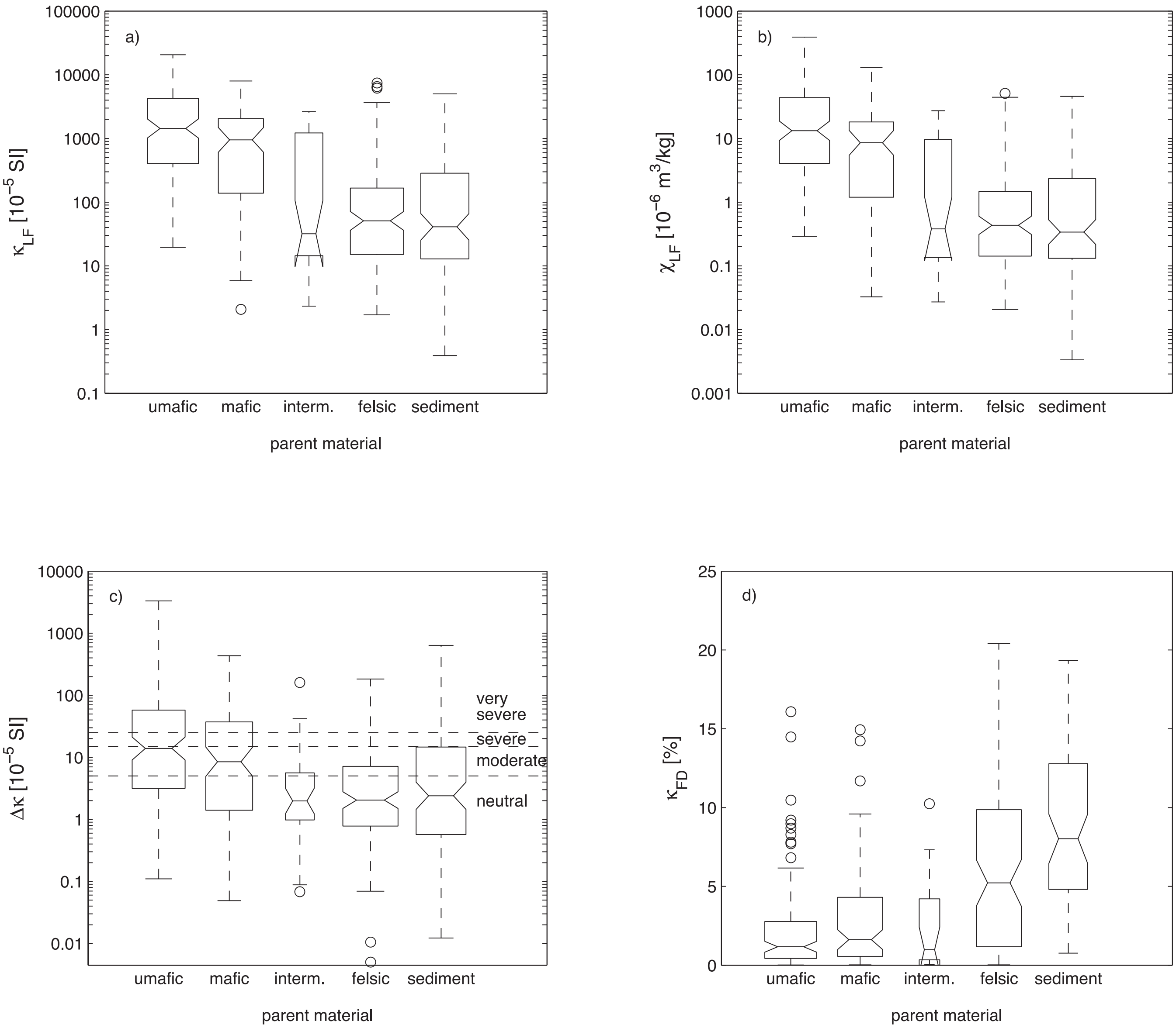

Figure 4. Box plots of volume-specific susceptibility (a), mass-specific susceptibility (b), absolute frequency dependence (c) and relative frequency dependence (d). The statistical analysis is based on the logarithms of susceptibility for (a)–(c). The samples with $\kappa_{LF} < 20 \times 10^{-5}$ SI are not shown in (d) as they are subject to large errors when expressing the relative frequency dependence, and a total of 368 samples remain. The boxes show the median and upper and lower quartiles. The whiskers denote the most extreme values within the interval of the first quartile minus and the third quartile plus 1.5 times the interquartile range, respectively. Outliers with values beyond the ends of the whiskers are displayed with circles. The widths of the boxes are scaled by the square root of the number of samples in the group. The notches surrounding the medians are a measure of the significance of the differences between the medians at a 95 per cent confidence level (McGrill *et al.* 1978). The influence on EMI detectors in (c) is rated according to the thresholds of Table 1.

5 INTERPRETATION AND DISCUSSION

5.1 Influence of parent material and alteration in the magnetic susceptibility of laterites

The variability of magnetic susceptibility and frequency dependence is high among unaltered and altered rocks and soils belonging to a single parent group (Figs 3 and 4). This variability can be attributed to the variability in chemical and mineralogical composition of the parent rocks as well as to differences in the states of soil development. With respect to susceptibility and absolute frequency dependence, we can distinguish two parent material groups. The notches in the boxes of Fig. 4 indicate that there is no significant difference in the medians of susceptibility and absolute frequency dependence between ultramafic and mafic rocks and their altered forms. Similarly, there is no difference between the intermediate rocks, felsic rocks and sediments and their altered forms. This finding was also confirmed by a rank-sum (Mann–Whitney–Wilcoxon) test at a 5 per cent significance level to reject the null hypothesis that two groups are independent samples from an identical distribution. The hypothesis could not be rejected by comparing the groups with ultramafic and mafic parent material as well as by comparing the groups with intermediate, felsic and sedimentary parent material, so that these two families are regarded to be similar with respect to susceptibility and absolute frequency dependence.

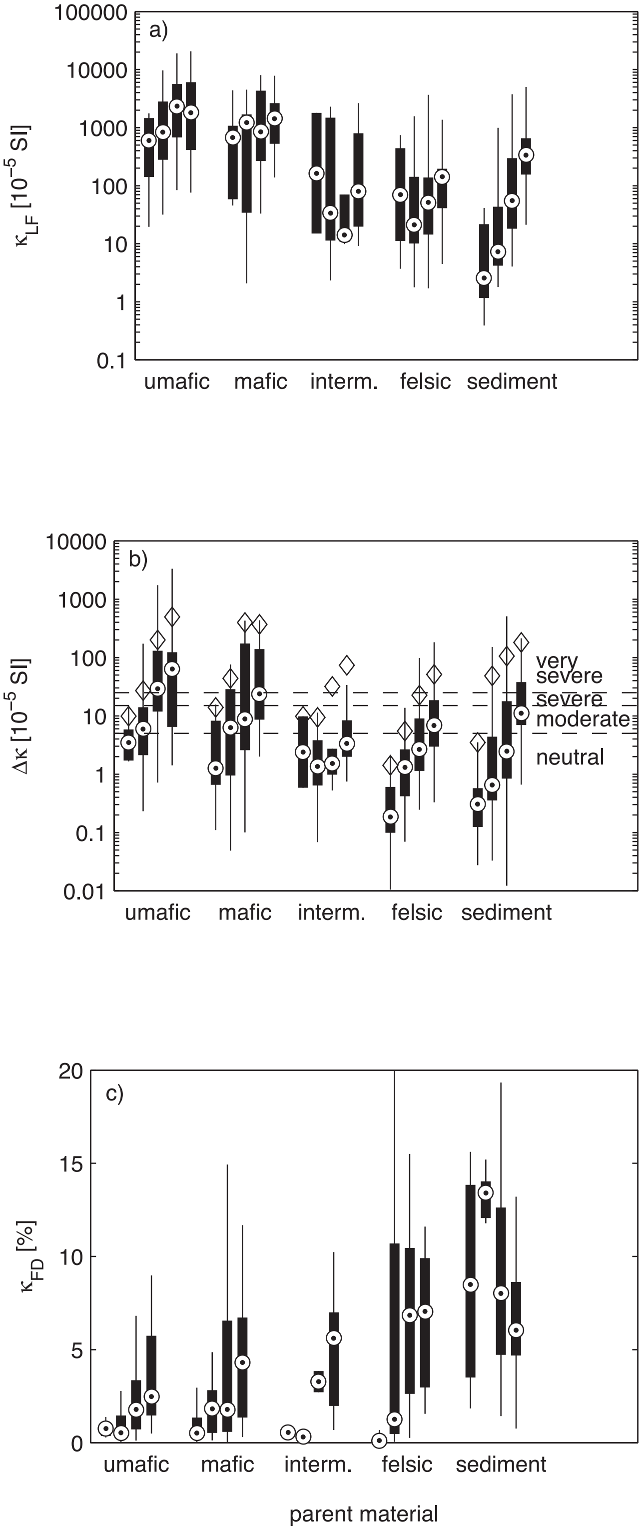

Figure 5. Box plot of volume specific susceptibility (a), absolute frequency dependence (b) and relative frequency dependence (c) for the different parent rock types. Within these groups the samples are subdivided into unweathered rock, weathered rock, subsoil and topsoil (from left to right). For a description of the boxes, see Fig. 1. For clarity, the outliers are not plotted. The numbers of samples represented by each box are listed in Table 3. In (b), the 90 per cent percentiles are also plotted with diamonds and the influence on EMI detectors is rated according to the thresholds of Table 1.

Table 3. Classification of samples by parent material and degree of weathering. The numbers represent the sample size within each subgroup.

	Unweathered rock	Weathered rock	Subsoil	Topsoil	Σ
Ultramafic	9	40	49	17	115
Mafic	12	33	30	15	90
Intermediate	2	16	6	10	34
Felsic	12	32	58	23	125
Sediments	10	24	49	19	102
Σ	45	145	192	84	466

Within each parent material group, the rock material shows a lower susceptibility and frequency dependence than the soil material (Fig. 3). This is a clear indication of the influence of soil forming processes on magnetic susceptibility. In general, soils are richer in minerals with high magnetic susceptibility; in particular, they tend to be richer in SP minerals than their parent rocks. The accumulation of SP minerals is a direct indication of this process and of the degree of pedogenesis (*cf.* Fine *et al.* 1995). This finding is supported by the data shown in Fig. 5, where a general trend of increasing susceptibility, absolute frequency dependence and relative frequency dependence within the individual parent material group from left to right (i.e. with increasing weathering) can be seen. However, there are some differences depending on the parent material. It is obvious that soils formed on parent materials with a high initial magnetic susceptibility are different from soils formed on other parent rocks.

Ultramafic and mafic magma are Fe-rich and favour the formation of magnetite and titanomagnetite during crystallization; therefore, these are the rocks with the highest susceptibilities (Fig. 4). During pedogenesis, these groups show a moderate increase of κ_{LF}, a high increase of $\Delta\kappa$ and an increase of κ_{FD}, thus giving the highest susceptibilities and absolute frequency dependencies of the analysed samples (Fig. 5). These findings can in part be explained by the residual enrichment of ferrimagnetic minerals. Another contributing factor is the enhancement of ultrafine-grained minerals due to either the comminution of initially larger lithogenic ferrimagnetic minerals (*cf.* Maher 1998) or the neoformation of magnetite that is in turn favoured by high iron supplies and alternating redox conditions (*cf.* Dearing *et al.* 1996b) or the neoformation of maghemite (*cf.* Barron & Torrent 2002). However, relative frequency dependence remains at a fairly low level even after pedogenesis because the parent material originally contains a high amount of MD grains. The majority of ferrimagnetic minerals still have grains of this size even after soil formation processes, such that the relative proportion of SP minerals remains low even when the total amount is high. Therefore, for the group with the ultramafic and mafic parent materials and their derivatives, the level of magnetic susceptibility is dominated by MD lithogenic minerals.

In contrast, intermediate and felsic rocks are relatively poor in ferrimagnetic minerals; therefore, the magnetic susceptibility and absolute frequency dependence of these rocks and their derivatives are lower. The trend in absolute susceptibility is not that clear, but the absolute and relative frequency dependence both increase steadily with alteration. Furthermore, soils derived from these rocks show higher relative frequency dependence than soils derived from mafic and ultramafic material. It is therefore likely that the main process enhancing the amount of hyperfine-grained ferrimagnetic minerals in these materials is neoformation, while comminution of MD minerals and residual enrichment only contribute to a lesser degree. Finally, the magnetic susceptibility of the soils derived from intermediate and felsic rocks is governed by SP secondary ferrimagnetic minerals.

Sediments have low susceptibilities and absolute frequency dependence as well. Both increase steadily with alteration. Relative frequency dependence, however, is at high level for the parent material and does not change significantly during pedogenesis. Commonly, sediments have already gone through intense weathering before sedimentation and thus are often already enriched with SP minerals. Maher & Taylor (1988) describe that ultrafine-grained magnetic minerals formed during soil development contribute significantly to the magnetic fraction of such sediments. In fact, they show a high relative frequency dependence of susceptibility, which is significantly higher than that of most soils developed directly from the igneous rock groups. This high frequency dependence is not further increased during subsequent weathering, as sediment is converted to soil. Thus, magnetic susceptibility of sediments is mainly due to SP mineral deposition. During soil formation, the total amount of SP minerals is increased mainly by residual enrichment, explaining why the susceptibility and absolute frequency dependence increase while the relative frequency dependence remains constant.

Generally, three processes can cause an accumulation of hyperfine-grained minerals during weathering: the comminution of MD ferrimagnetic minerals, the residual enrichment of ferrimagnetic minerals (including the SP fraction) and the neoformation of SP minerals. All groups show a steady increase in absolute frequency dependence with weathering, implying that the total amount of SP minerals rises. If only residual enrichment of ferrimagnetic minerals contributed without changing the grain size distribution, an increase in susceptibility and absolute frequency dependence would be expected, without a corresponding change in the relative frequency dependence. This result can only be observed for the group of sediments for which residual enrichment most likely plays the main role (Fig. 3). Hence, this group also shows the clearest correlation between susceptibility and absolute frequency dependence. For all other groups, the correlation is not as tight, and absolute and relative frequency dependence increases with pedogenesis, leading to the conclusion that the concentration of SP minerals with respect to the total magnetic fraction is changed by either the comminution of large minerals or by the neoformation of SP minerals. As soils derived from ultramafic and mafic materials show the highest absolute frequency dependences and as it is not likely that comminution is the only responsible process, there is evidence that the high iron content within these parent materials favours the neoformation of superfine-grained ferrimagnetic minerals (*cf.* Dearing *et al.* 1996b). As for the relative frequency dependence, there is a steady increase with the alteration of igneous rocks. The smaller the initial amount of ferrimagnetic minerals in the parent rock material (e.g. related to a low iron content of the igneous rock forming magma), the higher the increase in the relative frequency dependence.

5.2 Classification system

Bulk magnetic susceptibility has an influence on EMI-based landmine detectors, particularly on older CW detectors, and has already been analysed in prior work (Preetz *et al.* 2008). In this study, classifications are made according to the absolute frequency dependence of magnetic susceptibility (see Figs 4c and 5b), as this is the critical property for a variety of EMI-based landmine detectors. We deduce two statistical values within each group of material to characterize them (Table 4). Although the median describes the average behaviour of a group, the 90 per cent-quantile is used to assess a maximum value that is to be expected in extreme cases. A total of 10 per cent of the samples within a group have higher $\Delta\kappa$ than given by this limit. If the group is small, the deduced statistical values are assigned a high degree of uncertainty. This is especially true for the 90 per cent quantiles in which the estimates are very uncertain for sample sizes smaller than 10 (Gumbel 1958). However, we present the values for reasons of completeness.

In Table 5, the characteristic frequency dependence of susceptibility is transformed to characteristic impairment of EMI detectors using the thresholds listed in Table 1. The first index is based on the median and describes the average expected influence of a given soil/rock group in the field. The second index is based on the 90 per cent quantiles and is a more conservative appraisal that can be used to err on the side of caution. In at least 10 per cent of the cases, the ground will have a larger influence than indicated by this index.

We merged groups that had a relatively small number of samples and similar frequency-dependent susceptibilities. This approach gives more reliable values of the deduced statistical parameters and yields a simpler classification system that may also be used by non-geoscientists. A rank-sum (Mann–Whitney–Wilcoxon) test was performed to test whether the medians of $\Delta\kappa$ of two groups are similar and thus if the groups may be merged with statistical rigour. For a given degree of alteration, the groups relating to different parent materials were compared (Fig. 6a), and for a given parent material, the groups relating to different alterations were compared (Fig. 6b). A white box indicates that the hypothesis that the two groups are independent samples from identical distributions with equal medians is rejected at the 5 per cent significance level, whereas a black box indicates a failure to reject this hypothesis, meaning that the groups can be regarded as being similar and can be merged. The plots are symmetric with respect to the main diagonal, as comparing group A to B is the same as comparing group B to A. Overall, the four plots in Fig. 6(a) and the five plots in Fig. 6(b)

Table 4. Medians and 90 per cent quantiles of absolute frequency dependence of susceptibility for different groups of material and parent rock [10^{-5} SI]. The numbers of samples within each group are listed in Table 3. Values of frequency dependence that are prone to high uncertainties due to a small number of samples (<10) are indicated in italic numbers.

	All samples[a]		Unweathered rock		Weathered rock		Subsoil		Topsoil	
Parent material	Median	90 per cent quantile	Median	90 per cent quantile	Median	90 per cent quantile	Median	90 per cent quantile	Median	90 per cent quantile
Ultramafic	14	173	*3.5*	*9.9*	6.0	27	29	198	64	495
Mafic	8.5	291	1.3	14	6.3	44	8.8	397	24	371
Intermediate	2.0	13	*2.4*	*9.8*	1.4	9.4	*1.5*	*32*	3.3	73
Felsic	2.0	19	0.2	1.4	1.3	5.5	2.7	23	6.8	51
Sediments	2.3	94	0.3	3.5	0.7	48	2.5	106	11	181

[a]All samples regardless of the degree of weathering.

Table 5. Classification of the absolute frequency dependence of magnetic susceptibility according to the ground influence on EMI detectors (1, neutral; 2, moderate; 3, severe; 4, very severe). The first index is deduced from the median and the second from the 90 per cent quantile of Table 4. Italic numbers are used for numbers that base on a small number of samples (<10) and that are not that reliable.

Parent material	All samples[a]	Unweathered rock	Weathered rock	Subsoil	Topsoil
Ultramafic	2–4	*1–2*	2–4	4–4	4–4
Mafic	2–4	1–2	2–4	2–4	3–4
Intermediate	1–2	*1–2*	1–2	*1–4*	1–4
Felsic	1–3	1–1	1–2	1–3	2–4
Sediments	1–4	1–1	1–4	1–4	2–4

[a] All samples regardless of the degree of weathering.

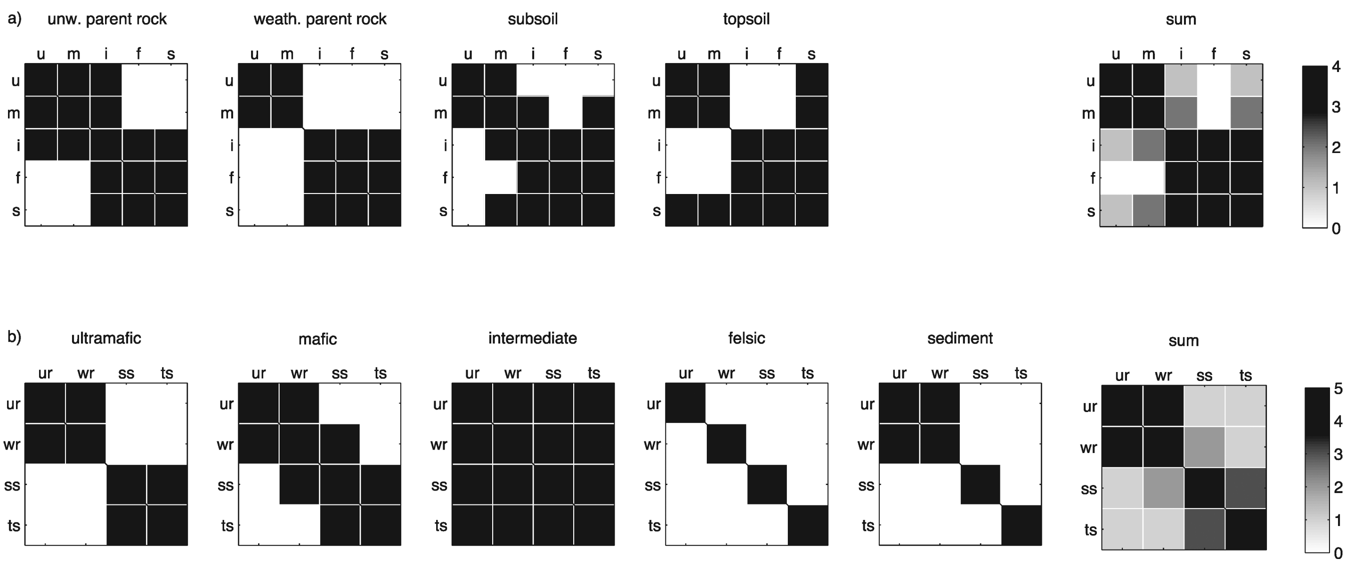

Figure 6. Summary of the rank-sum (Wilcoxon–Mann–Whitney) tests of absolute frequency-dependent susceptibility comparing the subgroups of Fig. 5: with the same degree of alteration but different parent material in (a) and with the same parent material but different alteration in (b). Black boxes indicate that the two groups are independent samples from identical distributions with equal medians, whereas white boxes indicate that they descend from different distributions. The rightmost plot is the sum of the plots to the left to depict the mean trend. Abbreviations: u, ultramafic; m, mafics; i, intermediate; f, felsic; s, sediment; ur, unweathered rock; wr, weathered rock; ss, subsoil; ts, topsoil.

Table 6. Simplified classification system: medians and 90 per cent quantiles of absolute frequency dependence of susceptibility [10^{-5} SI] for simplified data grouping and classification according to the ground influence on EMI detectors (1, neutral; 2, moderate; 3, severe; 4, very severe). The first index is deduced from the median and the second from 90 per cent quantile. The number *n* represents the sample size of the subgroups.

	Rock				Soil			
Parent material	*n*	Median	90 per cent quantile	Classification	*n*	Median	90 per cent quantile	Classification
Ultramafic and mafic	94	5.1	37	2/4	112	26	390	4/4
Intermediate, felsic and sediments	96	0.9	7.2	1/2	165	4.3	67	1/4

show a similar pattern with only a few exceptions. For instance, in Fig. 6(b), the group with intermediate parent material is small (36 samples), which is the main reason the test always gives a failure to reject the null hypothesis at the chosen 5 per cent significance level. To visualize the general trend, the individual test results are summed (rightmost plots). Regarding the parent rock, materials of ultramafic and mafic origin show similar frequency-dependent susceptibilities as materials of intermediate, felsic and sedimentary origin (Fig. 6a). Furthermore, regarding the degree of alteration, unweathered and weathered parent materials show clearly different values compared to subsoils and topsoils (Fig. 6b).

Based on these test results, we define a simplified classification system that can also be used by laymen in the field: two parent material groups (ultramafic and mafic rocks versus intermediate, felsic rocks and sediments) and two degrees of alteration (rocks versus soils) are therefore differentiated.

The medians and 90 per cent quantiles of the absolute frequency dependence of the simplified system are depicted in Table 6 as well as the classification regarding the influence on detectors. One can deduce that the intermediate and felsic rocks or sediments have no influence on EMI detectors on average and only weak influence in extreme cases. The average soils derived from these rocks also display neutral behaviour, although in extreme cases such soils can actually have such high-frequency dependence of susceptibility that they can have a very severe influence on detectors. Ultramafic and mafic rocks typically have a more moderate influence but may also have a very severe influence in extreme cases. Furthermore, soils developed from these rock groups generally show a very severe influence on detectors.

5.3 Application and limitation

These results clearly indicate that the frequency dependency of susceptibility depends on both the parent material and on the degree of weathering or soil development.

When planning a demining campaign, the organization or the responsible supervisor must gather information on the geology of the minefield area to specify the parent rock from which the ground material originates. This can be conducted by asking a geoscientist who is familiar with the region or by consulting geological or soil maps based on the FAO classification system (FAO 2006), which are available for all regions of the world, albeit in different scales and quality. The next step is to obtain information on the weathering of the material, by consulting the soil map and deducing the degree of weathering from the soil type or by going to the field and exploring the terrain to determine if there is soil or rock prevalent on the ground surface. With this information, we can predict soil influence on detectors that are influenced by the frequency dependence of magnetic susceptibility. Preetz & Hennings (2010) proved the practicability of predicting soil magnetic susceptibility for Angola by means of easily available FAO soil maps using their own evaluation algorithm. This algorithm may be easily adapted for application to our data on the frequency-dependent susceptibility.

Experts with geoscientific backgrounds may use Table 5 for more subtle predictions. If more information is available on the specific detector models that are under consideration (such as the critical values of frequency-dependent susceptibility at which the detector is impaired), one can use the $\Delta\kappa$ medians and 90 per cnet quantiles of Table 4 or Table 6 to deduce a detector-specific rating. By predicting the frequency dependence that is to be expected in the field, a suitable detector model can be chosen that is able to function in the presence of the specific ground material.

The proposed classification system is based on a set of 466 samples of laterites and their parent material, which to our knowledge represents the largest data set on frequency-dependent magnetic susceptibility of this soil type. However, it is important to note that we only obtain the average soil effect on demining when applying the system. The system provides information on a general trend according to the most probable behaviour of the subsurface; however, in rare cases, the soil impact can actually be much higher. This also holds true for geological/soil maps that can be used as input information to specify the parent rock material and the degree of weathering. Depending on its scale, a map always represents a generalized picture of the real field conditions. An additional factor that may be very important in determining detector performance is the small-scale spatial variability of soil properties that cannot be deduced from geoscientific databases. That is, when adjusting the ground compensation of a metal detector at one location, the compensation may not work just a few metres away because the soil properties may have already changed. Van Dam *et al.* (2004) carried out measurements along transects in different tropical/subtropical countries and found the magnetic susceptibility to vary by a factor of 2–5. This finding is consistent with our measurements of the spatial distribution of soil susceptibility on former landmine fields in Mozambique, showing the same variability with correlation lengths between one and a few metres (Igel & Preetz 2009). To the best of our knowledge, no measuring devices are available that can be used to determine the frequency dependence of susceptibility in the field, and there is a lack of measurements on the spatial variability of this property. Our own measurements (unpublished) with the Bartington MS2B on soil samples collected every 40 cm along a 20-m long transect in Mozambique show that the spatial variability of frequency-dependent susceptibility is comparable to the variability of absolute susceptibility. Hence, the small-scale variability of magnetic susceptibility and its frequency dependence must be further analysed in the future.

One significant cause of heterogeneity across short distances is the presence of stones and rocks, for instance in the cases where the soil is interspersed with solid components of its parent rock due to strong erosional processes. These stones usually have smaller frequency dependence of magnetic susceptibility, as shown by Table 4. For a metal detector, an abrupt decrease in the frequency dependence that occurs as it is moved over a large stone embedded in the soil causes significant problems and may lead to both, a false alarm or the none-detectability of a landmine beside the stone (Guelle, personal communication, 2006). Thus, the absolute level of frequency dependence as well as the variability in the field scale must be considered, especially if there are stones in the topsoil.

The proposed prognosis system is restricted to the tropics and to tropical palaeosols in the adjacent subtropical zones, as only tropical soils and their parent material were analysed. If sample collections from further soil types were available, the prognosis system could easily be expanded to cover further regions. However, tropical soils are highly weathered and are the soils with the most distinct magnetic susceptibilities and therefore cause most problems to electromagnetic detectors. Furthermore, from a worldwide perspective, the tropics and the subtropics are the regions which are most affected by landmines, and therefore most of the humanitarian demining activities are concentrated in these regions.

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REFERENCES

Barron, V. & Torrent, J., 2002. Evidence for a simple pathway to maghemite in Earth and Mars soils, *Geochimica cosmochim. Acta.,* **66**(15), 2801–2806.

Béget, J.E., Stone, D.B. & Hawkins, D.B., 1990. Paleoclimatic forcing of magnetic susceptibility variations in Alaskan loess during the late Quaternary, *Geology,* **18,** 40–43.

Bennett, H.H., 1926. Some comparisons of the properties of humid-tropical and humid-temperate American soils, with special reference to indicated relations between chemical composition and physical properties, *Soil Sci.,* **21,** 349–375.

Bloodworth, T.J., Logreco, A., 2004. Identifying and obtaining soil for metal-detector testing, JRC, Ispra/IPSC/SERAC Unit Technical Note No. I.04.117, available at: http://www.itep.ws/pdf/Technical_Note_I.04.117_JRC_Bloodworth.pdf (last accessed 2012 June 4).

Butler, R.F., 1992. *Paleomagnetism: Magnetic Domains to Geologic Terranes,* Blackwell, Boston, pp. 319.

CEN (European Committee for Standardization), 2003. Humanitarian mine action – Test and evaluation – Part 1: Metal detectors, CEN Workshop Agreement (CWA) 14747–1. Available at: http://www.itep.ws/pdf/CWA_metal_detectors.pdf (last accessed 2012 June 4).

CEN (European Committee for Standardization), 2008. Humanitarian mine action – Test and evaluation – Part 2: Soil characterization for metal detector and ground penetrating radar performance. CEN Workshop Agreement (CWA) 14747–2. Available at: http://www.itep.ws/pdf/CWA_soil_characterization.pdf. (last accessed 2012 June 4).

Das, Y., 2006. Effects of soil electromagnetic properties on metal detectors, *IEEE Trans. Geosci. Remote Sens.,* **44**(6), 1444–1453.

Das, Y., McFee, J.E. & Cross, G., 2002. Soil properties database for humanitarian demining: a proposed initiative, in *17th World Congregation of Soil Sci.,* Bangkok, Thailand, pp. 1–9.

Dearing, J.A., 1999. *Environmental Magnetic Susceptibility: Using the Bartington MS2 System,* 2nd edn, Chi Publishing, Kenilworth.

Dearing, J.A., Dann, R.J.L., Hay, K., Lees, J.A., Loveland, P.J., Maher, B.A. & O'Grady, K., 1996a. Frequency-dependent susceptibility measurements of environmental materials, *Geophys. J. Int.,* **124,** 228–240.

Dearing, J.A., Hay, K.L., Baban, S.M.J., Huddleston, A.S., Wellington, E.M.H. & Loveland, P.J., 1996b. Magnetic susceptibility of soil: an evaluation of conflicting theories using a national data set, *Geophys. J. Int.,* **127,** 728–734.

Dunlop, D.J. & Özdemir, Ö., 1997. *Rock Magnetism: Fundamentals and Frontiers,* Cambridge University Press, Cambridge, 573pp.

Evans, M.E. & Heller, F., 2003. *Environmental Magnetism: Principles and Applications of Enviromagnetics,* Elsevier, Amsterdam, 299pp.

FAO (Food and Agriculture Organization of the United Nations), 2006. World Reference Base for Soil Resources 2006. World Soil Resources Reports 103, ftp://ftp.fao.org/agl/agll/docs/wsrr103e.pdf (last accessed 2012 June 4).

Fassbinder, J.W.E., Stanjek, H. & Vali, H., 1990. Occurrence of magnetic bacteria in soil, *Nature,* **343,** 161–163.

Fine, P., Verosub, K. & Singer, M.J., 1995. Pedogenic and lithogenic contributions to the magnetic susceptibility record of the Chinese loess/paleosol sequence, *Geophys. J. Int.,* **122,** 97–107.

Forster, Th., Evans, M.E. & Heller, F., 1994. The frequency dependence of low field susceptibility in loess sediments, *Geophys. J. Int.,* **118,** 636–642.

Friedrich, G., Marker, A. & Kanig, M., 1992. Heavy mineral surveys in exploration of of lateritic terrain, in *Handbook of Exploration Geochemistry,* Vol. 4, pp. 483–498, eds Butt, C.R.M. & Zeegers, H., Elsevier, Amsterdam.

Guelle, D.M., Lewis, A.M. & Ripka, P., 2006. Metal detector trials, test results and their interpretation, European Commission, Joint Research Centre Ispra, ISSN 1018–5593. Available at: http://www.itep.ws/pdf/STEMD+OtherTrialsJRCNov2006.pdf (last accessed 2012 June 4).

Gumbel, E.J., 1958. *Statistics of Extremes,* Columbia University Press, New York, NY, 400pp.

Hannam, J.A. & Dearing, J.A., 2008. Mapping soil magnetic properties in Bosnia and Herzegovina for landmine clearance operations, *Earth planet. Sci. Lett.,* **274**(3–4), 285–294, doi:10.1016/j.epsl.2008.05.006.

ICBL (The International Campaign to Ban Landmines), 2010. Landmine monitor 2010. Available at: http://www.themonitor.org/index.php/publications/display?url=lm/2010/ (last accessed 2012 June 1).

Igel, J. & Preetz, H., 2009. Small-scale variability of electromagnetic soil properties and their influence on landmine detection: how to measure, how to analyze and how to interpret?, in *Detection and Sensing of Mines, Explosive Objects, and Obscured Targets XIV,* Proc. SPIE Vol. 7303, 730312, doi:10.1117/12.819392.

Kletetschka, G. & Banerjee, S.K., 1995. Magnetic stratigraphy of Chinese loess as a record of natural fires, *Geophys. Res. Lett.,* **22,** 1341–1343.

Knudsen, M.F., Abrahamsen, N. & Riisager, P., 2005. A rock- and palaeomagnetic study of geologically recent lavas and 1995 volcanic glass on Fogo (Cap Verde Islands), *Bull. Geol. Soc. Denmark,* **52,** 39–52.

Le Maitre, R.W. (ed.), 1989. A classification of igneous rocks and glossary of terms, in *Recommendations of the International Union of Geological Sciences, Subcommission on the Systematics of Igneous Rocks,* Blackwell Publications, Oxford, 193pp.

Maher, B.A., 1998. Magnetic properties of modern soils and Quaternary loessic paleosols: paleoclimatic implications, *Palaeogeog. Palaeclimat. Palaeoecol.,* **137,** 25–54.

Maher, B.A. & Taylor, R.M., 1988. Formation of ultrafine-grained magnetite in soils, *Nature,* **336,** 368–370.

McGrill, R., Tukey, J.W. & Larsen, W.A., 1978. Variations of box plots, *Am. Stat.,* **32**(1), 12–16.

Mulcahy, M.J., 1960. Laterites and lateritic soils in South-Western Australia, *J. Soil Sci.,* **11**(2), 206–224.

Mullins, C.E., 1977. Magnetic susceptibility of the soil and its significance in soil science: a review, *J. Soil Sci.,* **28,** 223–246.

Néel, L., 1949. Théorie du traînage magnétique des ferromagnétiques en grains fins avec applications aux terres cuites, *Ann. Géophys.,* **5,** 99–136.

NRCS (Natural Resources Conservation Service), 2006. *Keys to Soil Taxonomy,* 10th edn, NRCS, Washington, DC. Available at: soils.usda.gov/technical/classification/taxonomy/ (last accessed 2012 June 4).

Preetz, H. & Hennings, V., 2010. Predicting metal detector performance for landmine clearance—soil magnetic map of Angola, *Environ. Earth Sci.,* **60,** 1499–1508, doi:10.1007/s12665-009-0285-0.

Preetz, H., Altfelder, S. & Igel, J., 2008. Tropical soils and landmine detection—an approach for a classification system, *Soil Sci. Soc. Am. J.,* **72,** 151–159.

Schellmann, W., 1974. Abschlussbericht zum Forschungsvorhaben Nr. 1630 "Laterit", Teil 1: Allgemeine Forschungsergebnisse, Archive Report of the Federal Institute for Geosciences and Natural Resources, Hanover.

Schellmann, W., 1986. On the geochemistry of laterites, *Chem. Erde,* **45,** 39–52.

Schellmann, W., 1994. Geochemical differentiation in laterite and bauxite formation, *Catena,* **21,** 131–143.

Schwertmann, U., 1988. Occurence and formation of iron oxides in various pedoenvironments, in *Iron in Soils and Clay Minerals,* pp. 267–308, eds Stucki, J.W., Goodman, B.A. & Schwertmann, U., Reidel Publishing, Dordrecht.

Singer, M.J. & Fine, P., 1989. Pedogenic factors affecting magnetic susceptibility on Northern California soils, *Soil Sci. Soc. Am. J.,* **53,** 1119–1127.

Singer, M.J., Verosub, K.L., Fine, P. & TenPas, J., 1996. A conceptual model for the enhancement of magnetic susceptibility in soils, *Quarternary Int.,* **34–36,** 243–248.

Thompson, R. & Oldfield, F., 1986. *Environmental Magnetism,* Allen & Unwin, London, 227pp.

Torrent, J., Barrón, V. & Liu, Q., 2006. Magnetic enhancement is linked to and precedes hematite formation in aerobic soil, *Geophys. Res. Lett.,* **33,** L02401, doi:10.1029/2005GL024818.

Van Dam, R.L. *et al*., 2004. Spatial variability of magnetic soil properties, in *Detection and Remediation Technologies for Mines and Minelike Targets IX,* Proc. SPIE Vol. 5415, pp. 665–676, doi:10.1117/12.540693.

Van Dam, R.L., Hendrickx, J.M.H., Harrison, J.B.J. & Borchers, B., 2005. Conceptual model for prediction of magnetic properties in tropical soils, in *Detection and Remediation Technologies for Mines and Minelike Targets X,* Proc. SPIE Vol. 5794, pp. 177–187.

Van Dam, R.L., Harrison, J.B.J., Hirschfeld, D.A., Meglich, T.M., Li, Y. & North, R.E., 2008. Mineralogy and magnetic properties of basaltic substrate soils: Kaho'olawe and Big Island, Hawaii, *Soil Sci. Soc. Am. J.,* **72**(1), 244–257.

Worm, H.-U., 1998. On the superparamagnetic–stable single domain transition for magnetite, and frequency dependence of susceptibility, *Geophys. J. Int.,* **133,** 201–206.

Worm, H.-U. & Jackson, M., 1999. The superparamagnetism of Yucca Mountain Tuff, *J. geophys. Res.,* **104**(B11), 415–425.

Zhou, W., Van der Voo, R., Peacor, D.R. & Zhang, Y., 2000. Variable Ti-content and grain size of titanomagnetite as a function of cooling rate in very young MORB, *Earth planet. Sci. Lett.,* **179,** 9–20.