

Tropical Soils and Landmine Detection—An Approach for a Classification System

Holger Preetz*

Leibniz Institute for Applied Geosciences
Stilleweg 2
D-30655 Hannover
Germany

Sven Altfelder

Federal Inst. for Geosci. and Natural Resour.
Stilleweg 2
D-30655 Hannover
Germany

Jan Igel

Leibniz Institute for Applied Geosciences
Stilleweg 2
D-30655 Hannover
Germany

Electromagnetic induction is the most common technique used in landmine detection. In soils exhibiting high magnetic susceptibility, metal detectors based on this method may become useless for landmine detection. Currently, no soil classification system exists that allows a prediction of negative effects on metal detectors. A total of 511 tropical soil samples from 15 different countries were investigated with regard to their susceptibility and some basic chemical parameters. Samples were separated into six classes based on their chemistry and their parent material. Soils derived from ultrabasic to basic parent material, on average, exhibited the highest susceptibilities because both rock types often contain a large amount of weathering-resistant magnetite. Independent of the origin, the variance of the susceptibilities is large. Even in soils derived from rocks initially low in magnetite, high susceptibilities may develop with pedogenesis. This may be due to either the enrichment of residual magnetite or the formation of maghemite. In addition to a soil's parent material, its degree of weathering should also be considered in a proper classification scheme. We used a coefficient based on soil chemistry that correlates with the degree of weathering. Based on this coefficient and the soil parent material, we determined the median and the 90th percentile of the corresponding distribution of soil susceptibilities for each combination of the classification factors. The resulting classification scheme has the form of a matrix and may serve as a first approximation of expected susceptibilities when only parent material and degree of weathering are known.

Landmines are one of the cheapest weapons used in armed conflicts, and represent a deadly hazard to civilians even many years after the end of an armed conflict. It is estimated that nearly 50 million antipersonnel mines still litter the soil in approximately 90 countries around the world, maiming or killing between 15,000 and 20,000 victims each year (MacDonald et al., 2003). Many of the countries affected are in the tropics. Efforts have been made around the world in recent years to reduce the impact and risks associated with landmines. In addition to other activities, this includes the clearing of mine fields (International Campaign to Ban Landmines, 2001).

Despite the large number of detection methods that have been developed over the years, metal detectors are still the most widely used devices when clearing mine fields. Metal detectors function on the principle of electromagnetic induction. The response to the signal generated by the detector is influenced by the various properties of the object, the detector technology, and very considerably also the soil itself. The most important soil parameters influencing the depth at which buried objects can be detected are the magnetic susceptibility and, to a lesser

extent, the electrical conductivity. The negative effects of soil properties on detection are as follows:

1. The sensitivity of the detector can be reduced to such an extent that the object can no longer be detected at the required depth.
2. False alarms can be generated.
3. Some detectors can be made totally unusable in extreme cases (Das et al., 2002).

That a whole series of ferrimagnetic and antiferromagnetic minerals are responsible for the magnetic properties of soils has been known for a long time. The minerals involved include Fe oxides and hydroxides, Fe–Ti oxides, and Fe sulfides. Soils with susceptibilities high enough to have a deleterious effect on metal detectors primarily contain minerals consisting of magnetite, titanomagnetite, and maghemite. The first two of these Fe minerals responsible for susceptibility have lithogenic origins. Basalts and andesites in particular can contain high proportions of magnetite or titanomagnetite. They are often only present in small quantities in other magmatites. The unanimous opinion in the pedological literature is that maghemite is formed pedogenically as a new mineral (Matsusaka and Sherman, 1961; Mullins, 1977; Singer and Fine, 1989). It is therefore obvious that there is a serious pedogenic influence on the magnetic susceptibility of the soil and thus on the detectability of landmines (cf. van Dam et al., 2005).

The obvious pedogenic influence as well as the influence of the parent material on magnetic susceptibility raises the question of whether it is possible to classify soils with respect to these parameters. Only a small number of studies so far have pursued this approach (e.g., Hanesch and Scholger, 2005; Dearing et al., 1996). There are practically no studies at all explicitly looking at the detectability of landmines. The exception is the study performed by Hannam and

Soil Sci. Soc. Am. J. 72:151-159

doi:10.2136/sssaj2007.0065

Received 15 Feb. 2007.

*Corresponding author (Holger.Preetz@gga-hannover.de).

© Soil Science Society of America

677 S. Segoe Rd. Madison WI 53711 USA

All rights reserved. No part of this periodical may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopying, recording, or any information storage and retrieval system, without permission in writing from the publisher.

Permission for printing and for reprinting the material contained herein has been obtained by the publisher.

Bellamy (2005), which classified the susceptibility of soils in Bosnia with respect to the detection of landmines.

Mine-clearing organizations have expressed considerable interest in research into this issue. Das et al. (2002) pointed out that conventional soil classifications, such as the FAO-UNESCO soil map of the world, do not contain any directly derivable information useful for the detection of landmines. There is, however, a need for a database and soil maps containing information on the crucial soil properties, i.e., magnetic susceptibility and electrical conductivity. This information would have the following benefits:

- Demining organizations could select detectors specifically according to the soil properties and predict their effectiveness.
- Equipment developers and scientists could assess the application potential of their equipment in different soil regions around the world.
- Scientists would have the information required to set up more suitable test beds simulating the properties of different soils around the world.

Das et al. (2002) also reported that demining experts are already well aware that certain soils cause problems for landmine clearance. There is confusion in the demining community, however, about the causes and the classification. Ambiguous terms such as conductive soils, lateritic soils, red soils, Fe-rich soils, mineralized soils, etc., are used to describe the problematic soils. Typical soil classification frequently involves only grain size analysis and chemical analysis instead of analysis of the crucial electromagnetic properties.

Finally, it was also proposed by Das et al. (2002) that the number of investigated parameters should be reduced to susceptibility alone because it has the dominant effect on metal detectors and leads to a reduction in the effort involved in data acquisition.

The problems described above initiated this study, which investigated the susceptibility of a large number of soil samples restricted to laterite soil types, which are widespread in the

tropics. Our aim was to look at the question of whether the influence of pedogenesis and the parent rock are identifiable and whether the results can be used to help classify soils and help solve the problems described above.

MATERIALS AND METHODS

Soil Samples

Soil samples were retrieved from the archive of the Federal Institute for Geosciences and Natural Resources in Hannover, Germany. The sample archive includes a collection from the beginning of the 1970s of samples of lateritic soils from the world's tropical belt. They were collected as part of a research project looking at material alterations under intensive tropical weathering and the basic laws controlling such alterations. The objective at the time was to investigate the principles behind the genesis of mineral deposits (Schellmann, 1974). The collection consists exclusively of laterites with silicic parent rocks, and totals 1475 samples.

The investigated soils were termed *laterites* in accordance with the older nomenclature. This was the term used for the products of humid, tropical, lithological weathering characterized by significant Fe enrichment and frequently also Al enrichment compared with the parent rock. Modern terminology in the latest international classification system (FAO, 2006) would classify these soils as Ferralsols or Plinthosols, while they would be classified as Oxisols according to the U.S. Soil Taxonomy (NRCS, 2006).

A total of 511 samples were selected from this collection and their magnetic susceptibility was measured. The most important criteria for sample selection were the clear identification of the parent rock and the existence of geochemical analysis so that research could also be done on the relationships between the material composition and susceptibility. The selection included topsoil and subsoil from various depths, as well as samples of weathered parent rocks. The sample spectrum ranged from altered parent rocks to fully developed and strongly weathered tropical soils.

Lateritic soils generally occur on ancient land surfaces, some dating to the Tertiary period. Many of them are subject to strong erosional processes under current climate conditions. Hence, topsoil, subsoil, and weathered parent rock appear side by side in those landscapes (Mulcahy, 1960). For this reason, the vertical variability of many laterite profiles is comparable to the horizontal variability of topsoils in a region.

The sample selection was aimed at guaranteeing that, in addition to the parent rock, it would be possible to record the influence of the various degrees of weathering.

Soil samples that are >30 yr old can be used without any reservations to investigate magnetic susceptibility because this parameter is completely unaffected by the long period of storage of the dried samples.

Table 1 lists the countries where the soils originated and the subdivision into parent rocks, as well as the number of samples in each category.

The rock groups listed in Table 1 contain the following rock types:

Ultrabasic igneous rocks: gabbro, phonolite, and serpentinite

Basic igneous rocks: amphibolite, andesite, basalt, olivine-feldspar-basalt, charnockite, diabase, dolerite, gabbro, gneiss, and phonolite

Table 1. Country of origin and parent rocks of the soil samples.

Country of origin	Ultrabasic	Basic (intermediate)	Acid	Clays, clay slates	Phyllites	Sandstones	Σ
Australia		10	39	26		10	85
Brazil	20	31	9	11	14		85
El Salvador		10					10
Ghana			17	10	7	9	43
Guatemala	8						8
Hawaii		19					19
India		9	36	10			55
Madagascar	15	16	16				47
Mexico			4				4
New Caledonia	20						20
Philippines	8						8
Puerto Rico	23	4					27
Sri Lanka		4	20				24
Uganda		8	23	17			48
Venezuela	13	8	7				28
Σ	107	119	171	74	21	19	511

Acid igneous rocks: charnockite, dolerite, gneiss, biotite–gneiss, granitic gneiss, granite, and pisolite

Clays and clay slates: pisolite, slate, shale, quartzitic slate, clay slate, carbonaceous clay, and tertiary sediments

Phyllites: phyllite

Sandstones: sandstone and quartzite

Some of the igneous parent rock types appear in more than one rock group. This is because they were classified on the basis of chemical analysis. Even though individual rocks belong to one rock type, they may be assigned to different rock groups depending on their silica content.

Geochemical Analysis

For the aforementioned investigation in 1974, elemental concentrations were quantified by x-ray fluorescence analysis using a Philips spectrometer PW 1220. The samples were prepared by melting with a flux (1:5 sample/Li metaborate) at 1250°C, whereby international standards were used for calibration (Schellmann, 1986).

Determining Magnetic Susceptibility

All selected samples had already undergone preparation for geochemical analysis (i.e., were dried, mechanically crushed, and homogenized).

The measurement of the volumetric magnetic susceptibility (κ) was conducted using an MS2B laboratory apparatus (Bartington Instruments, Witney, UK) (Dearing, 1999). Appropriate 10-mL plastic bottles were filled with the soil samples, which were then measured three times at low frequency (465 Hz) and at a field strength of approximately $H = 80 \text{ A m}^{-1}$. Between each measurement, the samples were rotated in the apparatus by approximately 120° each time to ensure that any possible anisotropy within the samples was also taken into account. Anisotropy was found to be low. The average value was then derived from the resulting measurements.

The κ measurement results are converted in many publications into mass-related susceptibility (χ). This was not performed in our study to ensure direct comparability with the application-related classification system given in Table 2 (European Committee for Standardization, 2003) and field measurements conducted with the Bartington magnetic coil. The dimensionless κ measurements were recorded as $\times 10^{-5}$ (SI unit) because this unit has established itself among mine clearance experts and is the most frequently used.

In addition, the bulk densities, ρ_b , of the pulverized soil samples were predominantly in the same range ($\rho_b = 1.0 \pm 0.19 \text{ g cm}^{-3}$) so that the relative mutual differences between the samples remain the same for both parameters, i.e., achieve the same results.

Statistics

The measured susceptibilities of the soil samples were classified on the basis of the parent rock and the degree of weathering and were statistically evaluated. This involved determining the median, as well as the selected quantiles (quartiles, deciles, etc.). The equation for calculating the median \tilde{x} of an ordered random sample ($x_1, x_2, x_3, \dots, x_n$) of n measurements is

$$\tilde{x} = \begin{cases} x_{(n+1)/2} & n \text{ odd} \\ \frac{1}{2}(x_{n/2} + x_{n/2+1}) & n \text{ even} \end{cases}$$

There is no comparable clear and conventional regulation for calculating percentiles or quantiles from measurements. Hyndman

Table 2. Classification of susceptibility with respect to its negative effect on the functioning of metal detectors.

Classification	Magnetic susceptibility $\times 10^{-5}$ (SI)
Neutral	0–50
Moderate	50–500
Severe	500–2000
Very severe	>2000

and Fan (1996) reported 10 standard methods for this calculation. The method used here was based on the assumption that a measured data value $x(i)$ can be considered to be the realization of the random variables $X(i)$. The corresponding random variable $FX[X(i)]$ is then β distributed with parameters $a = i$ and $b = n - i + 1$ (Randles and Wolfe, 1979). Useful characteristics for describing the calculated percentile $p(i)$ are the expectation, the mode, and the median. If the mode is selected as a suitable estimator, the percentile $p(i)$ is calculated as follows (Gumbell, 1958):

$$p(i) = \frac{(i-1)}{(n-1)}$$

Linear interpolation between the calculated percentiles $p(i)$ can now be used to calculate any quantile. Thus, the quantile associated with every percentile can be determined.

RESULTS

The most important results of the chemical analysis of the soil samples, the contents of Fe_2O_3 , Al_2O_3 , and SiO_2 , are listed in Table 3 and depicted in Fig. 1. The data reflect initial conditions in the parent rock as well as the enrichment due to the process of ferrallitization and were used to characterize the degree of soil weathering.

Before describing and discussing the results of the magnetic analysis, it is first necessary to introduce a reference parameter that is extremely important in landmine clearance in practice using metal detectors: the average value of the magnetic susceptibility of the soil above which there is a reduction in the functionality of most metal detectors. The values listed in Table 2 were derived from the European Committee for Standardization (2003) and up to now have been the only, albeit approximate, classification for this purpose. With this classification system, the interfering effect of soil magnetic susceptibility on metal detectors can be assessed.

The results of the susceptibility measurements are shown in Fig. 2 as a histogram and grouped in Fig. 3 with respect to the six different rock groups. The classification limits described in Table 2 are marked with dotted lines in the subsequent diagrams for comparison purposes.

The frequency distribution in the ungrouped results reveals that 33% of the investigated soils can be classified as “neutral,” while 21 and 15% of the samples are classified as “severe” and “very severe”, respectively. This means that considerable limitations in the search for landmines can be expected in more than a third of the investigated soils.

The susceptibilities are summarized in Table 4 with some statistical properties and grouped according to rock type. As shown in Fig. 2, the frequency distribution of the susceptibilities is strongly skewed to the right. This also applies to the separate results for each of the rock groups (not shown here).

Table 3. Summary of the sample geochemistry classified according to parent material with quantiles.

	Ultrabasic	Basic (intermediate)	Acid	Clay, clay slate	Phyllites	Sandstones
<i>n</i>	107	119	171	74	21	19
	%					
	SiO ₂					
Min.	0.6	0.5	5.6	1.3	3.1	39.4
Max.	86.5	55.3	82.7	86.7	54.7	85
Median	8.8	27.4	54.8	36.7	15.9	54.8
<i>I</i> ₅₀ †	32.2	28.2	26.9	28.8	36.5	27.4
<i>I</i> ₈₀ †	38.1	44.2	51.6	55.4	42.3	38.8
	Fe ₂ O ₃					
Min.	5.1	2.7	0.3	0.2	1.4	0.6
Max.	79.3	60.9	60.1	57.5	30.7	39.9
Median	58.7	23.7	8.5	15.8	10.9	14.9
<i>I</i> ₅₀	45.4	14	17.2	21.6	9.1	27.7
<i>I</i> ₈₀	61.32	24.1	29.9	30.8	24.9	32.7
	Al ₂ O ₃					
Min.	0.3	4.2	6.2	7.6	18.7	5
Max.	43	59.1	51	67.5	57.9	27.2
Median	5.1	24	20.7	22.7	38	9.9
<i>I</i> ₅₀	8.5	10.5	10.4	13.7	26.3	5.5
<i>I</i> ₈₀	13.72	24.3	18.5	38.3	32	11.9

† *I*₅₀, interquartile range (50% of measurements); *I*₈₀, interdecile range (80% of measurements).

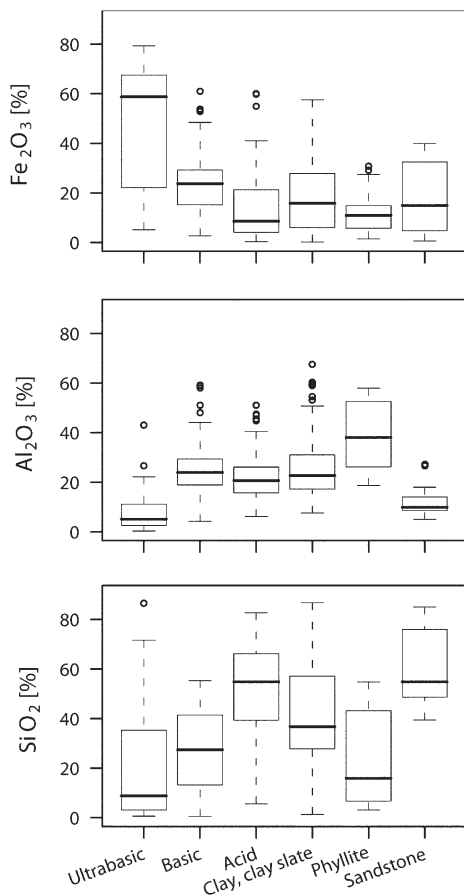


Fig. 1. Box plots of the sample geochemistry. The boxes show the upper and lower quartiles while the bars in the center show the median. The whiskers extend to the most extreme data point, with a distance from the box of no more than 1.5 times the interquartile range.

The median is therefore the most suitable location parameter, while the interquartile range *I*₅₀ (50% of the measurements, Q3 – Q1) is the most prudent measure for characterizing the scatter along with the broader interdecile range *I*₈₀ (80% of sample size, DZ9 – DZ1). These values are not affected by the extreme values at the edge of the distribution.

The results in Fig. 3 and Table 4 show very large variances for the measurements from all six groups, which is attributable, among other things, to the differences between the rock types subsumed within each group and their mineral compositions. Other factors that enhance variability are the different degrees of soil development and the associated enrichment or depletion of magnetic minerals, as well as redeposition of the soil and mixing with extraneous materials.

The median values in Fig. 3 confirm the varying mineralogy of the different rock groups. Medians of magnetic susceptibility for soils derived from ultrabasic and basic magmatites are around 1000×10^{-5} (SI) or higher. This is attributed to the Fe-rich magma of these parent rocks, which favors the formation of magnetite. Because of the weathering resistance of magnetite, its effect on susceptibility remains constant or even increases due to residual enrichment (Friedrich et al., 1992). Deterioration in the functionality of metal detectors can be expected at most localities with ultrabasic and basic soil parent materials.

Acid magmatites rarely contain magnetite, and then only very small quantities. This also applies in the same way to claystones and shales, phyllites, and particularly sandstones. As a consequence, the measured susceptibilities occurring most frequently in soils of this type lie in the unproblematic zone with values of $<50 \times 10^{-5}$ (SI). Because of the broad range in variation, however, it is also possible in some cases that soils derived from acid magmatites and even from sandstones may negatively affect the functionality of metal detectors. The reasons for the rarely occurring high susceptibilities in tropical soils derived from one of the four parent rocks that primarily contain little or no magnetite are as follows: Volcanic ash emissions can give rise to the accumulation of certain amounts of magnetite—which can be considered a coincidental result in this context. It is also possible that the small quantities of magnetite in these parent rocks can become relatively enriched as a result of strong weathering of the soil profile—which should be correlatable with the state of soil development.

The third reason is the formation of new maghemite. According to Evans and Heller (2003), maghemite may be formed by the oxidation of magnetite and is therefore dependent on the concentration of the latter in the parent rock. Another process is the neoformation of maghemite caused by the transformation of pedogenic Fe in the presence of very high temperatures and organic matter (Schwertmann, 1988; Hanesch et al., 2006). These conditions can exist during fires, which frequently occur in tropical regions.

Various researchers have also postulated the secondary formation of new magnetite as a result of bacterial activity, which should therefore be taken into consideration as another possible factor (Fassbinder et al., 1990). It is, however, unlikely

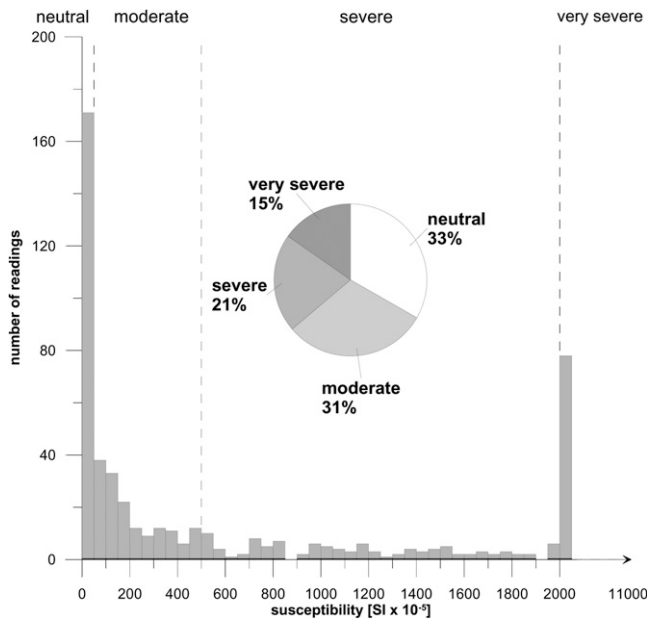


Fig. 2. Histogram showing the measured susceptibilities. The pie chart in the center shows the proportion of measurements with respect to the four classes described in Table 2.

that sufficient quantities would form in this case to have a deleterious effect on metal detectors (cf. Dearing et al., 1996).

The types of pedogenic neoformation or enrichment of magnetic minerals discussed here should correlate with the degree of soil development.

The main characteristic of lateritic soils is their intense and deep weathering, which is coupled with the accumulation of Fe and Al oxides and the depletion of silica. Thus the amounts of Fe_2O_3 , Al_2O_3 , and SiO_2 are widely used to describe and compare this soil type (e.g., Lecomte and Zeegers, 1992; Bestland et al., 1996).

The measure used here for the development of a ferralitic soil and its degree of weathering is an index based on its chemi-

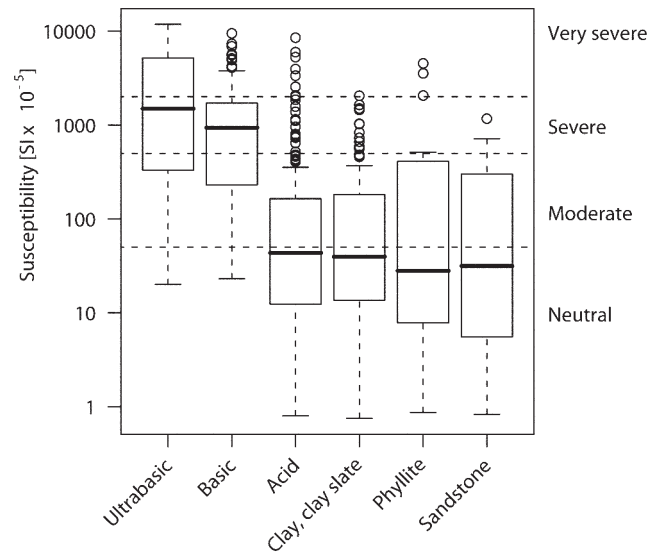


Fig. 3. Box plots of the susceptibilities. The boxes show the upper and lower quartiles while the bars in the center show the median. The whiskers extend to the most extreme data point, with a distance from the box of no more than 1.5 times the interquartile range.

Table 4. Summary of the susceptibilities with quantiles.

	Ultrabasic	Basic (intermediate)	Acid	Clays, clay slates	Phyllites	Sandstones
<i>n</i>	107	119	171	74	21	19
	$\times 10^{-5}$ (SI)					
Min.	20	23	1	1	1	1
Max.	11,819	9476	8527	2056	4541	1168
Median	1,496	937	44	40	28	32
I_{50}^\dagger	4,857	1479	151	161	402	295
I_{80}^\dagger	7,914	3142	728	706	2055	569

$^\dagger I_{50}$, interquartile range (50% of measurements); I_{80} , interdecile range (80% of measurements).

cal composition. The quotient of $SiO_2/(Al_2O_3 + Fe_2O_3)$ was used in the past to characterize lateritic soils (Bennett, 1926). This index is therefore a simple means of describing the degree of desilification as well as the degree of enrichment of Fe and Al. The smaller the index, the higher the degree of weathering, and values <2 in particular indicate extensive ferrallitization. Higher values at the end of the scale mean that the associated samples are not so much soils as parent rocks altered in situ.

Figure 4 shows, on the basis of the index, that most of the investigated soils can be considered to be strongly weathered. The soils that are strongly ferrallitized also have the highest susceptibilities. A reduction in weathering also corresponds with a nonlinear decline in the high susceptibilities. In principle, however, it is always possible for very low susceptibilities to be present independent of the degree of weathering. Values $>2000 \times 10^{-5}$ (SI), which are particularly problematic for metal detectors, are almost always linked to the strongest degree of weathering with an index <2 .

When samples are split according to parent material, magnetic susceptibilities are driven by the degree of weathering (Fig. 5). This indicates that weathering influences the sample

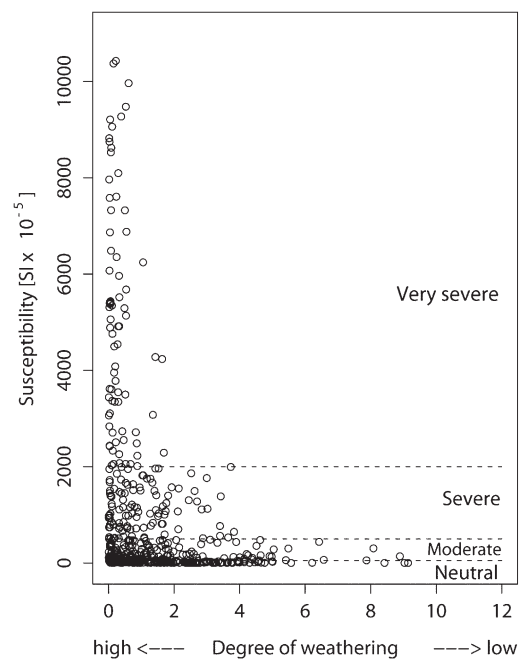


Fig. 4. Scatter plot of susceptibilities for soils derived from all rock groups. The susceptibility is plotted against the degree of weathering.

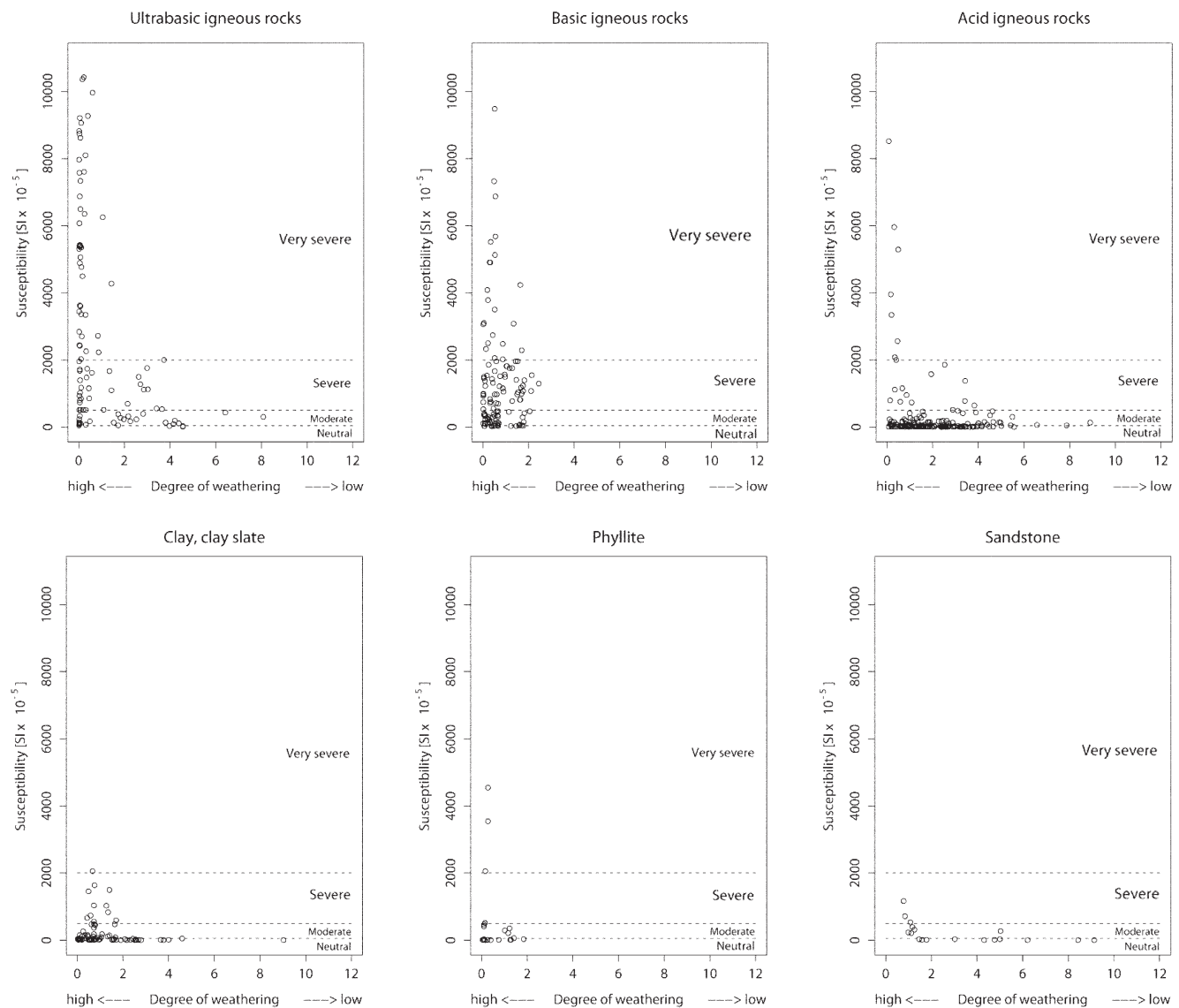


Fig. 5. Individual scatter plots of soil susceptibilities according to rock groups. The susceptibility is plotted against the degree of weathering.

susceptibilities in a similar manner, independent of the parent material. The main difference between the rock groups is that they are located at different sections along the curve describing the dependency relationship shown for the unsplit sample in Fig. 4. The group-dependent location on the curve is conditional on the initial chemical composition of the unaltered parent material.

Data in Fig. 4 and 5 support the thesis discussed above, which postulates that significant enrichments of magnetic Fe minerals can occur in tropical soils. This may be explained by the relative enrichment of magnetite originating from the parent rock, or the formation of new maghemite from pedogenic Fe (cf. Maher, 1986; Singer et al., 1996). Based on the existing data, neither process can be identified to be the dominant process; however, maghemite and magnetite contribute to magnetic susceptibility in the same dimension (Mullins, 1977). Therefore their influence on the metal detector is comparable and a differentiation of both minerals has minor significance in the context of landmine detection.

Soils derived from ultrabasic parent rocks exhibit the greatest scatter in susceptibilities. This group contains the highest

values of up to $11,000 \times 10^{-5}$ (SI), but the group also contains a series of values that remain in the neutral range of $<50 \times 10^{-5}$ (SI) with respect to their influence on mine detectors (see Table 2). The ultrabasites are present in all weathering classes from altered magmatite all the way through to residual enriched Fe and Al crusts. Because the largest values—apart from a few exceptions—are associated with the strongest degrees of weathering, the susceptibilities of soils derived from this rock group can be said to be strongly influenced by their lithogenic origin and the pedogenic processes as well.

The same applies to basic parent rocks, subject to the reservation that this group consists mainly of samples with a high degree of weathering. Basic and ultrabasic rocks often contain high amounts of magnetite because Fe-rich magmas provide the best conditions for the development of magnetite (Philpotts, 1991).

In the other four groups, the magnetite concentrations of the parent rocks are much lower than the basic and ultrabasic magmatites for different reasons. Concerning the acid igneous rocks, Fe concentration of the magma is low and thus only a few magnetic minerals crystallize during the cooling of the

magma. The material and mineral content of clastic sediments like clay and sandstone depends on factors like origin, conditions of transport, deposition, and sorting, and weathering processes as well. The mineral content of the weakly metamorphosed clay slates and phyllites is related to their source rocks, which commonly also contain a marginal amount of magnetite. In total, the sediments and metamorphites in our sample collection predominantly contain small amounts of magnetite.

There are still instances in these four groups, however, of high, and in some cases very high, values brought about by very strong weathering. This indicates the formation of new magnetic minerals because the original magnetite concentrations are small or even absent. In addition, it is still possible, particularly in the case of acid magmatites, that the high values are due to the residual enrichment of originally very low concentrations of magnetite.

In conclusion, it is clear that, in addition to the direct influence of the parent rock, the degree of weathering also plays a crucial role in the degree of susceptibility of the soil (Singer et al., 1996). It is therefore essential to take both of these factors into consideration when classifying soils in terms of the detectability of landmines.

CLASSIFICATION

As discussed above, the parent rocks as well as the degree of weathering are important for the classification of susceptibilities. Unlike the parent rock, which is relatively easy to assess on the basis of geological maps, precisely determining the degree of weathering in the field can be problematic. It is therefore prudent to classify the degree of weathering in a way that allows correlation with field results. Given the fact that the extreme values of the measured susceptibilities increase exponentially with an increase in weathering, the degree of weathering is subdivided approximately logarithmically to produce three classes ranging from high to low degrees of weathering. The selected intervals are 0 to 1, 1 to 3, and 3 to 10.

As can be seen in Fig. 5, a high degree of weathering does not necessarily mean that magnetic susceptibility of a weathered sample is high. The probability that a highly weathered sample also has a high susceptibility is increased, however, compared with weakly weathered samples or unaltered material. Quantifying this increase in probability, which is of importance for classification purposes, can be achieved by deriving quantiles of the susceptibility distribution of samples corresponding to a certain degree of weathering.

Figure 6 demonstrates the relationship between selected distribution quantiles (10%, median, 90%, maximum) and

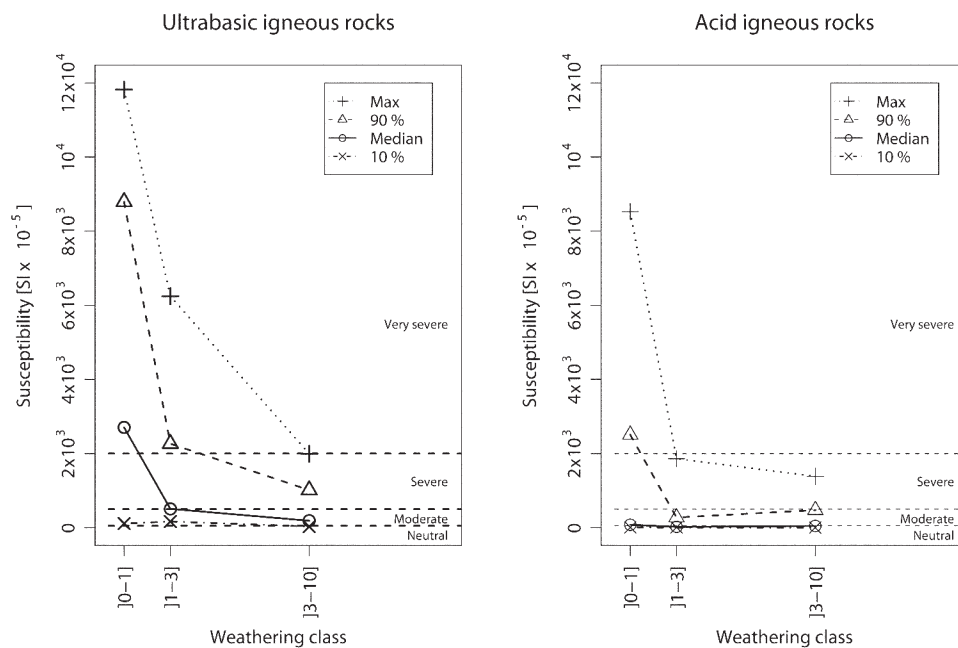


Fig. 6. Scatterplot of selected statistical parameters of the susceptibility distribution corresponding to the weathering classes of soils for two exemplary rock groups.

the degree of weathering for two selected parent rocks (ultrabasic and acid magmatites).

For ultrabasic parent rocks, high susceptibilities in particular correlate with the degree of weathering. While the 10% quantile is independent of the weathering index, the median demonstrates considerable dependence. This is even more pronounced for the 90% quantile and the measured maximum. For acid parent rock, the 10% quantile is independent of the degree of weathering as well; however, for this rock group the same applies to the median. Clear dependence is first shown with the 90% quantile and the measured maximum.

An evaluation of the expected susceptibilities at a given site in relation to mine detection should primarily consider the probability that susceptibility is high, which leads to a negative effect on the metal detector. Ideal parameters quantifying this part of the distribution are the median and quantiles above the median. Against the background of the sample size of the soils classified according to parent rock and degree of weathering, we chose the 90th percentile as a viable parameter, in addition to the median, for characterizing each of the different weathering classes.

Table 5 gives both parameters for each combination of weathering class and parent rock. No quantiles can be given for those factor combinations for which there is no measurement data. Samples with a low degree of weathering are underrepresented because only ferrallitic soils were analyzed, which are typically characterized by strong weathering. In some cases, sample size was so small that the 90% quantiles must be assigned a high degree of uncertainty (values in italic in Table 5). The rule defined by Gumble (1958) for quantile estimation produces very uncertain quantile estimates, particularly for quantiles with percentiles larger than $1 - 1/n$ and smaller than $1/n$.

If no information is available on the degree of weathering, it is still possible to estimate the susceptibility based on the soil parent rock only. Table 6 shows the median and the 90% quantile of soil samples belonging to a parent rock. Please note that

Table 5. Ninety percent quantile and median of susceptibilities against degree of weathering and parent rock, *n* represents the sample size on which the figures are based. Quantiles shown in italics are those where the sample size was too small in principle to calculate the 90% quantile.

Rock type	Degree of weathering								
	[0–1]			[1–3]			[3–10]		
	90% quantile	Median	<i>n</i>	90% quantile	Median	<i>n</i>	90% quantile	Median	<i>n</i>
	— × 10 ⁻⁵ (SI) —			— × 10 ⁻⁵ (SI) —			— × 10 ⁻⁵ (SI) —		
Ultrabasic	8793	2706	75	2266	508	19	1014	187	13
Basic (intermediate)	3962	743	85	1963	1051	34	—	—	—
Acid	2506	78	52	273	23	77	474	46	42
Clay, clay slates	716	54	43	713	28	26	37	11	5
Phyllites	3100	21	14	317	61	7	—	—	—
Sandstones	<i>1077</i>	715	3	<i>432</i>	122	8	<i>108</i>	4	8

especially for extreme cases (either very strongly or very weakly weathered soils), these values deviate significantly from the quantiles corresponding to the specific degree of weathering. It is still clear, however, that in the cases of clay and clay slates, sandstones, and acid magmatites as soil parent rocks, it is unlikely that the susceptibilities will fall into the “very severe” category.

The final classification scheme compiling the previous results and classifications is shown in Table 7. The indices listed there are based on the median and the 90% quantile. The latter is the more conservative, i.e., safe, estimation. In case the degree of weathering is unknown, the left column of Table 7 can be used to evaluate a soil’s susceptibility based on its parent rock alone. A more sophisticated evaluation is possible using the next three columns when the degree of weathering is known.

APPLICABILITY OF THE RESULTS AND OUTLOOK

The results clearly show that there is a close correlation between the degree of susceptibility of tropical soils and the nature of the parent rock. The second influencing factor is the degree of weathering of the soil. The effect of increasing weathering and ferrallitization on soil susceptibility is plain to see even though the underlying mechanisms are not clearly understood. The mechanisms may involve the relative enrichment of magnetite or the neoformation of maghemite. Although the mechanisms cannot be explained in detail, the effects of the weathering process are unequivocal.

The classification of sites for landmine clearance exclusively according to parent rock can be undertaken on the basis of Table 6. This can be performed by people with no geoscientific training by referring to geological maps, which are available for all countries around the world, although the quality

varies. Field mapping to identify the rocks in situ would naturally be very prudent where possible.

Taking into consideration the degree of weathering on site is a complicated matter. The classification presented in Table 8 was undertaken with the help of geochemical analysis. As a first approach, we propose to use the coloration of the soil for an approximation of the degree of weathering. According to Schwertmann (1988), hematite is the most dominant of the Fe minerals formed during weathering in tropical soils and its fraction accumulates with increasing weathering. Due to its low magnetic susceptibility, hematite does not contribute appreciably to the magnetic properties of soil. It can be used, however, as a proxy parameter for weathering.

As demonstrated by Barron and Torrent (1986), the intensity of red in tropical soils increases with the amount of hematite (Torrent et al., 1983, 1980). The color intensity of the soils should therefore be used as a first approach to classifying soils in the field according to Table 7. In this context, consideration should also be given to the fact that soils affected by the highest degrees of ferrallitization can also be affected by the formation of Fe–Al crusts in the subsoil. Because even in the recent tropics these soils are usually very old and the topsoil is eroded, these crusts are frequently visible at the surface. This gives rise to the following preliminary classification of the degree of weathering, which can also be applied by non-geoscientists.

The aforementioned classification of the degree of weathering from the condition of the soil in the field is poorly differentiated and should be used at this stage to supplement the sound classification given in Table 6. Because there is a serious shortage at the present time of means of evaluating the susceptibility of soils (Das et al., 2002), the uncertainties inherent in the system should be overlooked for the time being. The method presented here should be considered as a first approach, with the objective of developing it further in the future. The

possibility of classifying the degree of weathering in particular on the basis of a simple and reproducible method of determining the color of soils in the field with the help of Munsell soil color charts should be investigated. If this proves successful, it would be the key to establishing a simple but differentiated classification system that could be used in practice by mine clearance experts to assess in advance whether the soil at a particular location will have a detrimental effect on metal detectors.

Table 6. Ninety percent quantile and median of susceptibilities against parent rock alone, *n* represents the sample size on which the values are based.

Rock type	<i>n</i>	Median	Classification	90% quantile	Classification
		× 10 ⁻⁵ (SI)		× 10 ⁻⁵ (SI)	
Ultrabasic	107	1496	severe	8018	very severe
Basic (intermediate)	119	937	severe	3187	very severe
Acid	171	44	neutral	733	severe
Clay, clay slates	74	40	neutral	710	severe
Phyllites	21	28	neutral	2059	very severe
Sandstones	19	32	neutral	572	severe

Table 7. Final classification of the susceptibilities, where 1 is neutral, 2 is moderate, 3 is severe, and 4 is very severe. Limitations for metal detectors are based on the median and the 90% quantile. The first index represents the median, the second index the 90% quantile.

Rock type	Ignoring weathering	Degree of weathering		
		[0–1]	[1–3]	[3–10]
Ultrabasic	3–4	4–4	3–4	2–3
Basic (intermediate)	3–4	3–4	3–3	–
Acid	1–3	2–4	1–2	1–2
Clay, clay slates	1–3	2–3	1–3	1–1
Phyllites	1–4	1–4	2–2	–
Sandstones	1–3	3–3	2–2	1–2

ACKNOWLEDGMENTS

This work was supported by the German Federal Ministry of Education and Research (BMBF) under contract no. 01 RX 0310. We thank the students Thomas Putzmann and Henning Schröder for carrying out the measurements.

REFERENCES

Barron, V., and J. Torrent. 1986. Use of the Kubelka–Munk theory to study the influence of iron oxides on soil colour. *J. Soil Sci.* 37:499–510.

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.

Bestland, E.A., G.J. Retallack, A.E. Rice, and A. Mindszenty. 1996. Late Eocene detrital laterites in central Oregon: Mass balance geochemistry, depositional setting, and landscape evolution. *Geol. Soc. Am. Bull.* 108:285–302.

European Committee for Standardization. 2003. Humanitarian mine action—Test and evaluation—Metal detectors. CWA 14747. Available at www.gichd.ch/fileadmin/pdf/publications/CWA_metal_detectors1.pdf (verified 11 Oct. 2007). European Committee for Standardization, Brussels.

Das, Y., J.E. McFee, and G. Cross. 2002. Soil properties database for humanitarian demining: A proposed initiative. p. 1–9. *In* World Congr. of Soil Sci., 17th, Bangkok, Thailand. Soil and Fertilizer Soc. of Thailand, Bangkok.

Dearing, J.A. 1999. Environmental magnetic susceptibility: Using the Bartington MS2 system. 2nd ed. Chi Publ., Kenilworth, UK.

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

Evans, M.E., and F. Heller. 2003. Environmental magnetism: Principles and applications of enviromagnetics. Academic Press, Amsterdam.

FAO. 2006. World reference base for soil resources 2006: A framework for international classification, correlation and communication. World Soil Resour. Rep. 103. Available at www.fao.org/ag/Agl/agll/wrb/doc/wrb2006final.pdf (verified 11 Oct. 2007). FAO, Rome.

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

Friedrich, G., A. Marker, and M. Kanig. 1992. Heavy mineral surveys in exploration of lateritic terrain. p. 483–498. *In* C.R.M. Butt and H. Zeegers (ed.) Handbook of exploration geochemistry. Vol. 4. Regolith exploration geochemistry in tropical and subtropical terrains. Elsevier, Amsterdam.

Gumbell, E.J. 1958. Statistics of extremes. Columbia Univ. Press, New York.

Hanesch, M., and R. Scholger. 2005. The influence of soil type on the magnetic susceptibility measured throughout soil profiles. *Geophys. J.*

Table 8. Rough estimation of the degree of weathering.

Degree of weathering	Condition of the soil
0–1	presence of an Fe–Al crust or crust fragments
2–3	intense red color of the soil
4–10	weak red color of the soil or any other color

Int. 161:50–56.

Hanesch, M., H. Stanjek, and N. Petersen. 2006. Thermomagnetic measurements of soil iron minerals: The role of organic carbon. *Geophys. J. Int.* 165:53–61.

Hannam, J., and P. Bellamy. 2005. Assistance with magnetic susceptibility measurements: Soil samples from the archive of the Agropedology Institute, Sarajevo. Available at www.itep.ws/pdf/Bosnia2005.pdf (verified 11 Oct. 2007). Cranfield Univ., Silsoe, UK.

Hyndman, R.J., and Y. Fan. 1996. Sample quantiles in statistical packages. *Am. Stat.* 50:361–365.

International Campaign to Ban Landmines. 2001. Landmine monitor report 2001: Toward a mine-free world. Available at www.icbl.org/lm/2001/ (verified 11 Oct. 2007). Human Rights Watch, New York.

Lecomte, P., and H. Zeegers. 1992. Humid tropical terrains (rainforests). p. 241–294. *In* C.R.M. Butt and H. Zeegers (ed.) Handbook of exploration geochemistry. Vol. 4. Regolith exploration geochemistry in tropical and subtropical terrains. Elsevier, Amsterdam.

MacDonald, J., J.R. Lockwood, J. McFee, T. Altshuler, T. Broach, L. Carin, R. Harmon, C. Rappaport, W. Scott, and R. Weaver. 2003. Alternatives for landmine detection. RAND, Santa Monica, CA.

Maher, B.A. 1986. Characterization of soils by mineral magnetic measurements. *Phys. Earth Planet. Inter.* 42:76–92.

Matsusaka, Y., and D. Sherman. 1961. Magnetism of iron oxide in Hawaiian soils. *Soil Sci.* 91:239–245.

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

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

NRCS. 2006. Keys to Soil Taxonomy. 10th ed. Available at soils.usda.gov/technical/classification/taxonomy/. NRCS, Washington, DC.

Philpotts, A.R. 1991. Principles of igneous and metamorphic petrology. Prentice Hall, Englewood Cliffs, NJ.

Randles, R.H., and D.A. Wolfe. 1979. Introduction to the theory of nonparametric statistics. John Wiley & Sons, New York.

Schellmann, W. 1974. Abschlussbericht zum Forschungsvorhaben Nr. 1630 “Laterit”, Teil 1: Allgemeine Forschungsergebnisse. Archive report of the Federal Inst. for Geosci. and Nat. Resour., Hannover.

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

Schwertmann, U. 1988. Occurrence and formation of iron oxides in various pedoenvironments. p. 267–308. *In* J.W. Stucki et al. (ed.) Iron in soils and clay minerals. Reidel Publ., Dordrecht, the Netherlands.

Singer, M.J., and P. Fine. 1989. Pedogenetic factors affecting magnetic susceptibility of northern California soils. *Soil Sci. Soc. Am. J.* 53:1119–1127.

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

Torrent, J., U. Schwertmann, and H. Fechter. 1983. Quantitative relationships between soil color and hematite content. *Soil Sci.* 136:354–358.

Torrent, J., U. Schwertmann, and D.G. Schulze. 1980. Iron oxide mineralogy of some soils of two river terrace sequences in Spain. *Geoderma* 23:191–208.

van Dam, R.L., J.M.H. Hendrickx, J.B.J. Harrison, and B. Borchers. 2005. Conceptual model for prediction of magnetic properties in tropical soils. *Proc. SPIE* 5794:177–187.