Conceptual model for prediction of magnetic properties in tropical soils

Remke L. van Dam*[a], Jan M.H. Hendrickx[a], J. Bruce J. Harrison[a], Brian Borchers[b]
[a]Dept. of E&ES, New Mexico Tech, 801 Leroy Place, Socorro, NM 87801, USA
[b]Dept. of Mathematics, New Mexico Tech, 801 Leroy Place, Socorro, NM 87801, USA

ABSTRACT

In recent years it has become apparent that the performance of detection sensors for land mines and UXO may be seriously hampered by the magnetic behavior of soils. In tropical soils it is common to find large concentrations of iron oxide minerals, which are the predominant cause for soil magnetism. However, a wide range of factors such as parent material, environmental conditions, soil age, and drainage conditions control soil development. In order to predict whether magnetic-type iron oxide minerals are present it is important to understand the controlling factors of soil development. In this paper we present a conceptual model for predicting magnetic soil characteristics as a function of geological and environmental information. Our model is based on field observations and laboratory measurements of soils from Hawaii, Ghana, and Panama. The conceptual model will lead to the development of pedotransfer functions that quantitatively predict the occurrence and nature of magnetism in soils.

Keywords: land mine detection, UXO detection, magnetic iron oxides, tropical soils, climate, Hawaii, Ghana, Panama

1. INTRODUCTION

The performance of electromagnetic (EM) and magnetic sensors, which are frequently used for detection of buried landmines and unexploded ordnance (UXO), degrades significantly at sites with magnetic soils and rocks[1, 2]. In environments with highly magnetic soil, magnetic and electromagnetic sensors often detect anomalies that are of geologic or pedogenic, rather than metallic, origin[3]. Dealing with these false alarms in UXO and landmine surveys cost time and money and should be avoided as much as possible. Improved detection and discrimination performance can only be achieved when the natural variability in magnetic soil properties is understood and can be predicted.

Soils are complex bodies, which result from the interplay of a number of factors that contribute to the soil development. These factors include parent material, climate, topography, organisms and time. It has long been recognized that these five factors drive and/or affect. These factors have been combined into Jenny's Fundamental Soil Equation[4]:

$$S = f\,(c, o, r, p, t)$$

where S is the state of the soil, c is the climate, including rainfall and temperature, o is the activity of organisms, r is the relief/topography, p is the parent material and t is time. The rate of physical weathering, chemical weathering and alteration in soils depends on the relative importance of each these factors. Understanding of these processes is complicated by the fact that they occur on different timescales. Additional factors that influence S are the influx of eolian material[5] and soil erosion[6].

In humid ecosystems three stages of soil development are recognized[7]: 1) Building; the chemical weathering of easily-soluble primary minerals in young substrates, which releases elements into soluble and biologically available forms. These can be used by organisms, leached by percolating water, or neo-formed / retained as secondary minerals in the soil. 2) Sustaining; when the most soluble primary minerals have been depleted, weathering of more resistant primary minerals continues to contribute to the pool of minerals available for biochemical processes in the soil column.

---

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

Secondary clay particles keep cations available for ionic exchange. 3) Degrading; virtually all primary minerals have been used. Although the building process keeps contributing minerals to the pool available for biochemical processes (increasing the thickness of the soil column), the minerals are too deep in the soil column to contribute significantly to the ecosystem. Soils acidify (concentration of Al and Fe sequioxides increases) and biological activity is constrained by the low availability of useful cations and anions.

To meet the challenge of improving detection and discrimination of landmines and UXO in magnetic soils it is our objective to develop and test a conceptual model to predict the occurrence and nature of magnetism in tropical soils. We focus on the effects of climate gradients (mean annual rainfall), parent material, and soil age. Input for the conceptual model comes from measurements in tropical soils in Hawaii[8-10], Ghana[11], Panama, and data presented in the literature. We propose methods for quantification of the conceptual model and parameter testing.

2. SOIL MAGNETICS

The presence of iron oxides in different forms and quantities is the predominant cause for magnetic properties of soils. Iron oxide minerals can be both pedogenic (i.e., a product of soil formation) and lithogenic (i.e., unweathered minerals from the parent material) in origin. Although pure iron can occur naturally in rocks and soil, it is very rare. Specific types of iron oxides, iron-titanium oxides and iron sulfides are the predominant causes of magnetic soil characteristics. Iron (Fe) is the fourth most common element in the crust of the earth. Iron-containing minerals can be found in igneous rock such as basalt, gabbro, and granite, but also in metamorphic and sedimentary rocks. The concentration of (magnetic) iron oxides in soils is affected by the parent material, soil age, soil forming processes, biological activity, and soil temperature[12-14].

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

Table 1. Magnetic susceptibilities for several iron oxides and soil constituents. Data from Maher[15] and Thomson and Oldfield[16].

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

Three types of magnetization are used to describe the magnetic behavior of a material: (1) Remanent magnetization exists in the absence of an applied field and must be added to any magnetization effects resulting from an applied magnetic field. Remanent magnetization occurs within ferromagnetic and ferrimagnetic minerals and affects only the most sensitive magnetic sensors. (2) Induced magnetization or magnetic susceptibility results from a magnetic field being applied to a magnetically susceptible object. In the low-intensity field region, the net magnetic moment or magnetization, M, is proportional to the strength of the applied field (H). Therefore, the low-field magnetic susceptibility, defined as M/H is a material-specific property. The magnetic induction of a sample, measured by a magnetic or electromagnetic sensor, is the sum of all the different entities of induced magnetization, corrected for volume, distance to the sensor, and magnitude of the susceptibility. The magnetic susceptibility is either expressed per unit volume (κ) or per unit mass (χ). (3) Viscous remanent magnetization (VRM) refers to the effect that the secondary magnetic field gets delayed relative to the primary magnetic field due to the presence of superparamagnetic grains[17]. This effect differs from the standard induced magnetization, where the magnetization is instantaneous, and the secondary magnetic field is in-phase with the primary magnetic field. One important consequence of VRM is that the susceptibility becomes frequency dependent. This effect has important implications for both time- and frequency-domain electromagnetic sensors[1, 18].

Many books and review papers have addressed the physical background of magnetic minerals in general[16, 19] and magnetic soils in particular[20-22]. The physical background for the existence of magnetic behavior in minerals is the magnetic moment produced by electrons orbiting their nucleus and spinning around their axis[21]. In many types of material the overall magnetic moment is zero because the orbital and spin components even out. When such a material is placed in a magnetic field the electron motions will rearrange so that a small net magnetic moment either opposes (diamagnetic behavior) or corresponds with (paramagnetic behavior) the direction of the applied field. Examples of materials are given in Table 1. In other minerals, interaction between electrons causes the individual magnetic moments to line up. In antiferromagnetic minerals the magnetic moments line up opposite directions so that the net magnetic moment is zero. In ferrimagnetic minerals two-thirds of the magnetic moments line up in one direction and one-third in the opposite direction. These minerals behave as tiny magnets and are of primary importance for describing the magnetic properties of a soil. Ferromagnets, where all magnetic moments line up in the same direction, do not occur naturally in a soil.

A special group of ferrimagnetic minerals are so-called superfine (<0.02μm) superparamagnetic (SP) grains. When placed in a magnetic field these magnetite grains exhibit a higher magnetic susceptibility than larger size grains but the effect gets smaller when the frequency of magnetic field is increased[17]. The formation of these SP magnetite and/or maghaemite grains is generally considered to be associated with processes occurring under normal pedogenic oxidation-reduction cycles[16, 21]. The exact processes leading to recrystallization of these SP grains are poorly understood. Organic matter, microorganisms, and normal chemical reactions may all play a role[16].

Although iron oxides occur in most environments throughout the world, tropical locations are among the most favorable for the formation and/or maintenance of significant amounts of secondary iron oxides in the soil column[20, 23-25]. Many tropical soils have deeply weathered profiles whose red and yellow colors result from an accumulation of iron and aluminum oxides. Large areas of these soils can be found in Africa and South America with minor acreages in South-East Asia. Another type of soil where iron oxides are abundant are relatively young soils developed from parent material of volcanic origin. The volcanic origin ensures in many cases the abundance of (ferri)magnetic iron oxides. Volcanic derived soils cover a much smaller total area than Fe-rich soils in the tropics but can be found on all continents. They may be present everywhere where geologically young volcanic rock is found (e.g., near continental margins and subduction zones).

3. MODEL FOR SOIL DEVELOPMENT

A model describing the processes and products leading to enhancement and decrease of magnetic soil properties is presented in Fig. 1. This model is adapted from a model originally proposed by Singer et al.[13]. Modifications to the original model have been made in Fig. 1 to make it better applicable for processes occurring in tropical soils. The model starts out with three types of iron-containing minerals inherited from the parent material: (1) ferrimagnetic minerals, such as magnetite, maghaemite, and titanomagnetite, (2) other iron oxides, such as hematite, and (3) other iron-bearing rocks and minerals, such as olivine, biotite, and ilmenite. The parent material of a soil can be both bedrock and unconsolidated material, such as sedimentary deposits and volcanic ash. The rate of soil formation, or pedogenesis, will be affected by the types and sizes of the individual minerals in the parent material, as well as by environmental factors mentioned earlier. The soil forming processes that lead to redistribution of soil constituents can be subdivided into seven groups[13], which will be discussed below.

Preferential accumulation is the relative enhancement of the magnetic soil fraction due to *leaching* of other soil minerals from the soil profile. The original ferrimagnetic minerals do not get altered nor do they relocate. The preferential accumulation can take place in both the A- and B-horizons.

Transformation is in-situ conversion of minerals. Although transformation can occur for any type of mineral we focus on this effect specifically for enhancement of magnetic properties. Four mineral transformation processes related to formation of magnetic minerals have been identified[21]: (1) low temperature transformation of magnetite into maghaemite, which does not lead to an enhancement of magnetic properties, (2) high temperature transformation (usually through burning, which is limited to the near surface) of non-magnetic minerals such as hematite into magnetite and maghaemite, (3) dehydration of lepidocrocite into maghaemite, which occurs in poorly-drained soils, and (4) transformation of weakly magnetic iron oxides into magnetite and maghaemite through normal oxidation-reduction cycles, which is possibly enhanced by micro-organisms. Under most conditions the latter transformation process is the most important[21].

Lessivage or colloidal migration is the vertical movement of particles within the soil profile. This process is usually associated with water movement through infiltration or evapotranspiration. Except for soils in arid and semi-arid regions lessivage is directed downward. Lessivage of clay minerals is a common process in many soils, leading to accumulation of clay films around particles in the B-horizon. Magnetic minerals, structurally or chemically bound to the clay minerals, may lead to enhancement of magnetic properties in the B-horizon.

Solubilization is the process in which crystallized minerals are solved in the soil pore water. Solubilization is a complex process, affected by solution pH, organic matter compounds, and chelation/complexiolysis. The iron that is in solution may lead to either *neoformation* of (magnetic) minerals or to downward movement *leaching* of the minerals from the soil column. Neoformation, which is related to the fourth transformation process (above), is considered an important mechanism for enhancement of (superparamagnetic) magnetic minerals[26]. In contrast to many less stable minerals leaching of iron and aluminum is uncommon in most well drained soils. Under reducing conditions Fe is more soluble and leaching of iron from the soil profile is more common.

Biosynthesis is a process by which magnetotactic bacteria produce magnetite. This process mainly occurs in anaerobic conditions below the ground water table and is considered of minor importance under most conditions, especially for well-drained soils.

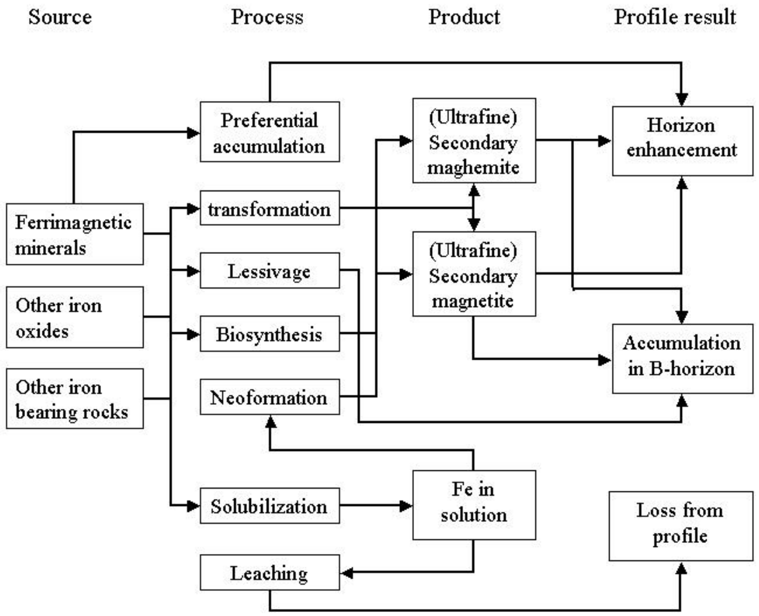

Fig. 1. A model describing soil processes leading to the enhancement or reduction of magnetic properties in the soil column (Adapted from Singer et al.[13]).

4. DATA

In this section we describe magnetic soils data obtained by our research group and additional data from literature. The magnetic data from our research group can be subdivided into Hawaii[8-10], Ghana[11], and new, previously unpublished data from Panama. Data from the literature is naturally wide in scope, orientation, and geographic location. Because of differences between magnetic sensors, published data of measurements under field conditions are not always comparable. However, data from laboratory sensors operating at low-intensity magnetic fields (<80 A/m) are usually comparable[27].

Data from Hawaii show that for soils with similar basaltic parent material and comparable soil ages there exists a strong correlation between mean annual rainfall and the low-frequency mass-specific magnetic susceptibility (χ_{lf}) and the frequency dependent magnetic susceptibility ($\chi_{fd}\%$), respectively (Fig. 2). These data show the effect of progressive weathering (as induced by increasing mean annual precipitation) on the soil magnetic properties. Starting out from the parent material, with low $\chi_{fd}\%$ values (<2%), and values for χ_{lf} between 7 and $9 \cdot 10^{-6}$ m^3/kg, initial soil development (Kohala 3) leads to an increase of both $\chi_{fd}\%$ and χ_{lf}. Higher χ_{lf} values result from leaching of easy soluble soil minerals and thus, preferential accumulation of primary ferrimagnetic minerals in the B-horizons (Fig. 1). Ultrafine secondary ferrimagnetic minerals cause higher values of $\chi_{fd}\%$, which may be the result of transformation and neoformation. With progressive weathering (mean annual rainfall increasing from 180 to 1300mm/yr), χ_{lf} decreases, which is the result of the processes in Fig. 1 impacting the relatively stable primary ferrimagnetic minerals. While χ_{lf} decreases, soil processes cause transformation to and neoformation of ultrafine secondary ferrimagnetic minerals, leading to a further increase in $\chi_{fd}\%$.

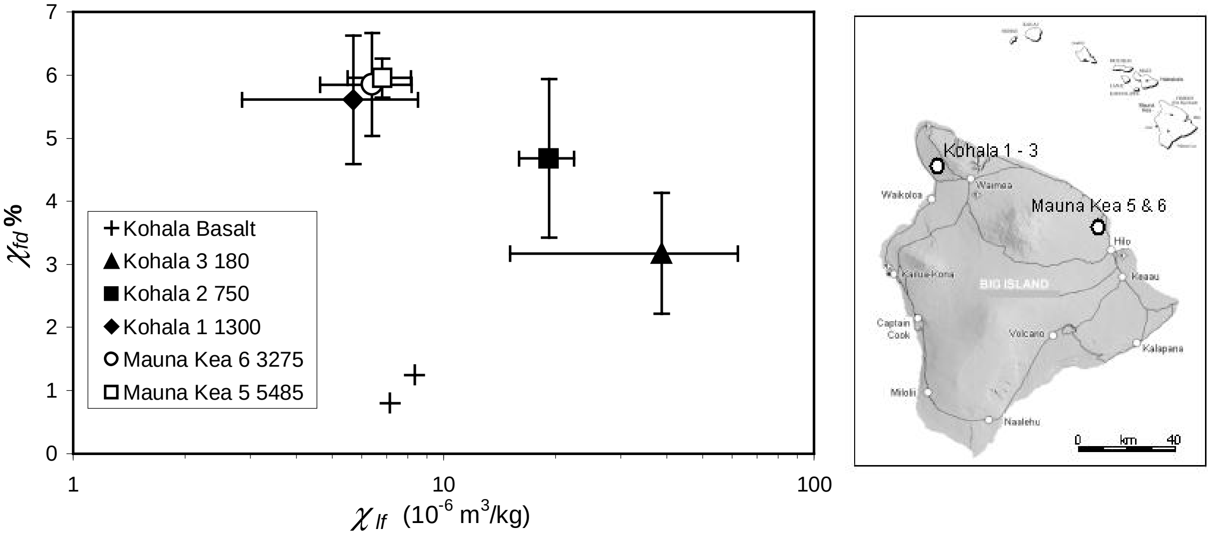

Fig. 2. Cross plot of the average low-frequency mass-specific magnetic susceptibility (χ_{lf}) and the average frequency dependent magnetic susceptibility ($\chi_{fd}\%$) of 5 soils on Kohala Volcano and Mauna Kea Volcano on the Big Island of Hawaii. The data have been averaged over measurements of the top 50cm of each soil. The error bars represent one standard deviation in the measurements. In addition, results for the measurements of 2 basalt samples from Kohala Volcano are given. The information in the legend stands for the volcano name, the number of the soil pit, and mean annual precipitation in millimeters. This plot is based on data in Van Dam et al.[10]. The data have been measured at the "1.0" sensitivity setting using a Bartington MS2B sensor.

For a mean annual precipitation higher than 1300mm no significant variation in either χ_{lf} or $\chi_{fd}\%$ occurs. The average values for all three soils in this range (Kohala 1, Mauna Kea 5, Mauna Kea 6) lie within one standard deviation. These data seems to indicate that for high rainfall rates a steady state exists between weathering and magnetic susceptibility of soils. However, other data suggests that with increasing rainfall and progressive weathering the mineralogy, and sometimes the magnetic characteristics of soils do change. Soils developed in basaltic tephra on the Big Island of Hawaii, and ranging from 1000 to 3000 mm/yr annual rainfall show an increase in iron with increasing precipitation (measured by dithionite extraction, Fe_d, and XRF)[28]. For this dataset the iron species are unknown.

Other researchers have observed similar correlations between mean annual rainfall and χ_{lf} and $\chi_{fd}\%$, respectively. For a transect of soil profiles on Kohala Volcano on the Hawaii, Singer et al.[13] show that pedogenic magnetic susceptibility (obtained through chemical extraction of all maghaemite and large (>1µm) magnetite grains) shows a positive correlation with mean annual precipitation. For rainfall rates above 1300mm/yr Singer et al. observed a reversal of the trend, which is not found in our study (Fig. 2). Maher and Thompson[29] show that the magnetic susceptibility of topsoils in both warm and cool temperate climates in the Northern Hemisphere increases (from 0.1 to $5\cdot10^{-6}$ m^3/kg) with mean annual rainfall increasing from 0 to 1000 to 1500mm/yr. For higher rainfall rates the magnetic susceptibility decreases[29].

The magnetic signature of a soil is not necessarily correlated with that of the substrate, which is the result of magnetic enhancement of ferrimagnetic minerals through transformation and neoformation (Fig. 1). Magnetic data from soils in Ghana developed on sandstone and granites (both with few primary magnetic minerals) show that the low-frequency mass-specific magnetic susceptibility correlates positively with the frequency dependent magnetic susceptibility (Fig. 3)[11]. This indicates that the magnetic susceptibility is predominantly the effect of magnetic soil enhancement with superparamagnetic ferrimagnetic grains. Although for these soils the low-frequency mass-specific magnetic susceptibility (χ_{lf}) is relatively low, the frequency dependent magnetic susceptibility ($\chi_{fd}\%$) may be high. No clear correlation between mean annual precipitation and magnetic properties has been found[11]. However, the data suggest that χ_{lf} and $\chi_{fd}\%$ are lowest for young soils, and for soils that are poorly drained.

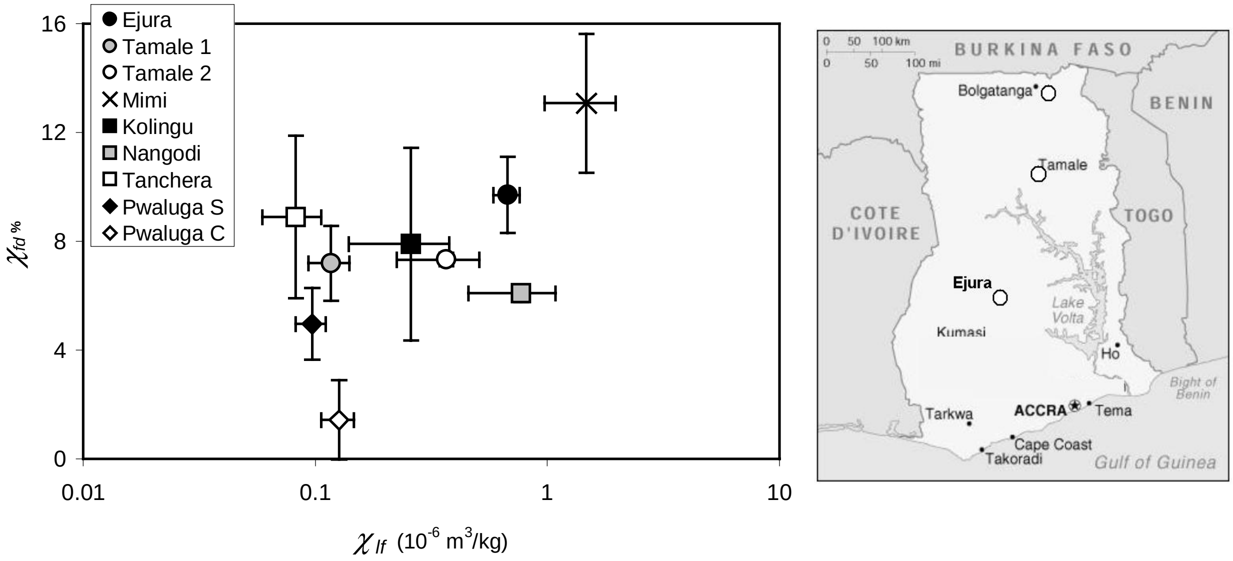

Fig. 3. Cross plot showing average frequency dependent magnetic susceptibility and average low-frequency magnetic susceptibility for 9 soils in Ghana, measured at a Bartington MS2B sensitivity of “0.1”. All soils, except for those around Ejura and Tamale, are from the Bolgatanga area. Data have been averaged over the top 50cm of each soil. The error bars represent 1 standard deviation. In the Nangodi soil an outlier in the top horizon (probably related to burning of the vegetation) has been left out. The mean annual precipitation ranges from 1000 to around 1500mm/yr. This plot is based on data in Hendrickx et al.[11].

Other researchers have made similar observations. Maher shows that magnetic susceptibility of parent material and soil horizons do not necessarily correlate[30]. Mathé et al.[31] use magnetic properties (measured using a Kappabridge KLY-2) to discuss soil development in Cameroon. No frequency dependence has been measured directly. These soils have developed under a tropical humid environment on gneissic rocks of the Precambrian basement. The iron oxide content ranges from 10 to 40%. The magnetic susceptibility (χ) varies from $<0.1\cdot10^{-6}$ m^3/kg for the parent material and saprolite, to around $0.5\cdot10^{-6}$ m^3/kg in the B-horizon, and $1\cdot10^{-6}$ m^3/kg in the topsoil (A-horizon). They show that correcting the measured magnetic susceptibility for iron oxide concentration of the sample (χ_{lf}) amount helps to explain the type of iron oxides present. In the saprolite layer χ_{lf} is about equal as the susceptibility value of goethite and hematite (~$0.5\cdot10^{-6}$ m^3/kg). In the A- and B-horizons, the higher values for χ_{lf} (1 to $10\cdot10^{-6}$ m^3/kg) indicate the presence of magnetic enhancement with (superparamagnetic) ferrimagnetic magnetite and maghaemite.

Soils formed on parent materials low in iron-bearing materials usually have a lower absolute magnetic susceptibility (χ_{lf}) as well as a lower pedogenic enhancement (which may be approximated by $\chi_{fd}\%$) of the magnetic character, as was shown for soils in Northern California[32]. In the tropical state of Paraná, Brazil, soils developed on basic volcanic parent material (high concentration of ferrimagnitic minerals) have a higher average mass-specific magnetic susceptibility (12.2 to $57.7 \cdot 10^{-6}$ m^3/kg; measured with a Bartington MS2B sensor) than soils developed on volcanic rocks with a low concentration of ferrimagnetic minerals (14.3 to $17.5 \cdot 10^{-6}$ m^3/kg)[33].

Similar behavior is observed in magnetic data from Panama (Fig. 4). Here, magnetic data from multiple soil pits in two first-order drainages basins in the Rio Chagres watershed show distinct differences related to the parent material. The Rio Chagrecito soils (open diamond in Fig. 4), which are formed in volcanic parent material, have values for χ_{lf} that are comparable to those in Hawaii (Fig. 1). The low values of $\chi_{fd}\%$ may be attributed to the abundance of mass movements on the steep slopes of this drainage basins, preventing soil stabilization and the development of pedogenic superfine magnetic minerals[34]. In contrast to the Rio Chagrecito soils, the Upper Piedras soils (open square in Fig. 4) have been formed in granites, and are characterized by low values for χ_{lf}. For χ_{lf} values below $1 \cdot 10^{-6}$ m^3/kg, significant errors in frequency dependent magnetic susceptibility ($\chi_{fd}\%$) may occur[11]. Therefore, the variability in $\chi_{fd}\%$ values in the Upper Piedras soils in Fig. 4 cannot be used quantitatively. The other soils that were studied in Panama are located near the Technological University of Panama (UTP) and near the town of Achiote, and have been formed in volcanic parent material and sandstone, respectively [35].

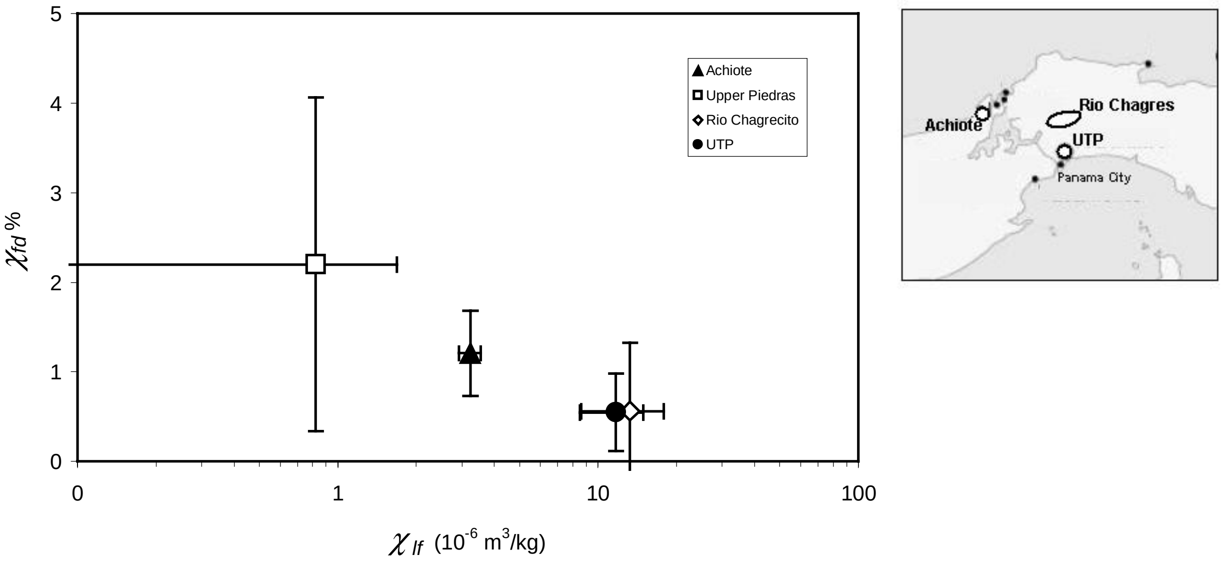

Fig. 4. Cross plot of low-frequency mass-specific magnetic susceptibility (χ_{lf}) and the frequency dependent magnetic susceptibility ($\chi_{fd}\%$) for 10 soils from Panama. The data have been averaged over measurements of the top 50cm of each soil. The error bars represent one standard deviation in the measurements. The Upper Piedras (5 soils) and the Rio Chagrecito (3 soils) are first order drainage basins in the watershed of the Rio Chagres[34]. These data have been measured at "1.0" sensitivity using a Bartington MS2B sensor.

5. CONCEPTUAL MODEL

In this section we describe a conceptual model for the prediction of magnetic characteristics in soils. Several mechanisms for the enhancement of magnetic properties have been proposed[15, 20, 21, 32]. Our model, based on measurements from soils in Hawaii, Ghana, Panama, and on data from the literature, includes the effects of rock type, precipitation, and soil age to predict the relative effects of the mass-specific magnetic susceptibility (χ_{lf}) and frequency dependent magnetic susceptibility ($\chi_{fd}\%$) (Fig. 5). Several of the definitions have been kept flexible because not enough data are available at this point to make concrete statements. The data from our studies as well of those from other researchers make it clear that basic volcanic rocks lead to a distinctly different magnetic signature in soils than other rock types. Therefore, this is the first decision in the model. Currently, insufficient data exist that allow for a subdivision to be made between other types of parent material. Our studies and published data show that a mean annual precipitation has a strong effect on magnetic soil behavior. Fire can have an effect of magnetic enhancement in the top horizons. This effect is overprinted in soils with a large inherited magnetic character (i.e., developed on basalts), but may be significant in soils developed on all other substrates[11]. The description of soil age (young or old) needs improvement, but we believe the current indication can be used when the context of a soil is understood. Other (environmental) factors that can have an effect on the magnetic characteristics of soils such as accumulation of material (atmospheric fallout of dust) and soil erosion[8, 36, 37] have not been incorporated in this model.

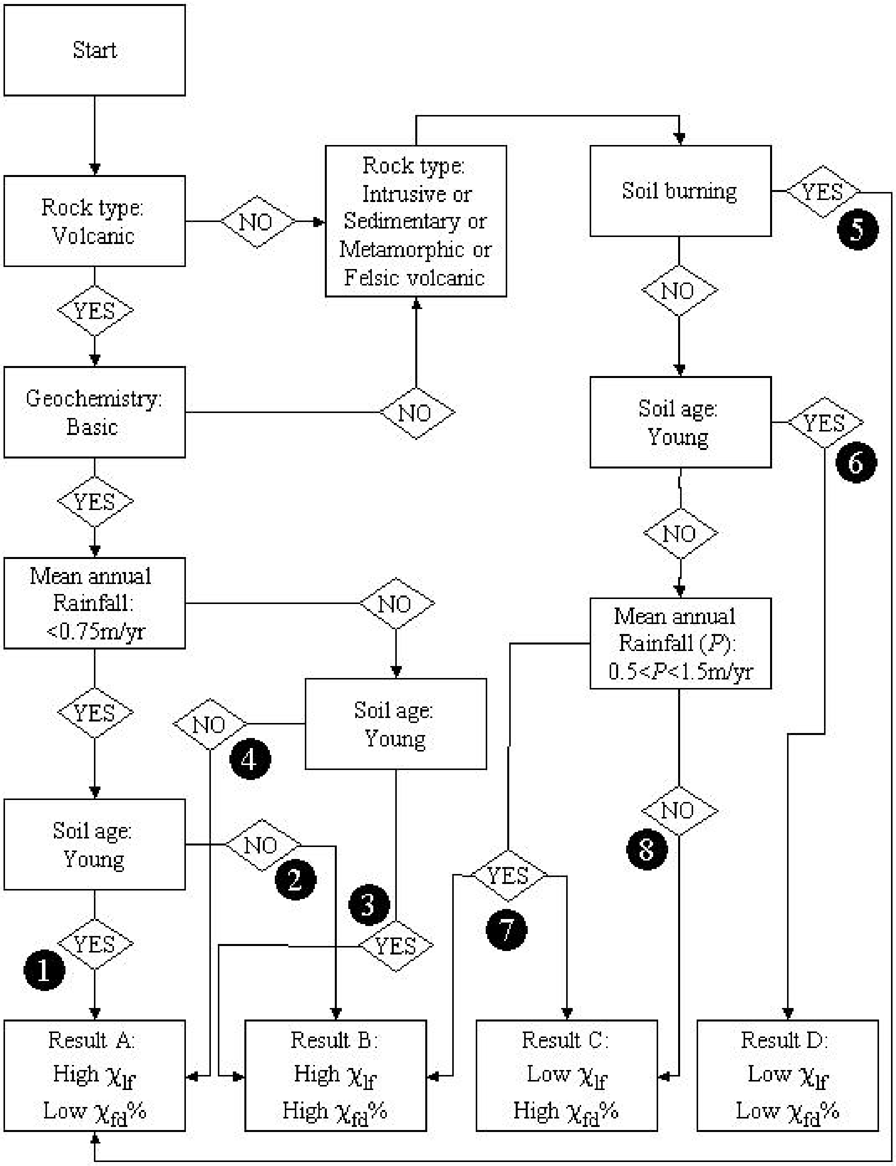

Fig. 5. Conceptual flow model describing how soil processes and environmental parameters control the pathways from parent material to different magnetic properties in a soil. Numbered pathways are discussed in the text.

The resulting magnetic properties in Fig. 5 have been classified into four groups (A-D) combining high and low values of χ_{lf} and $\chi_{fd}\%$, respectively. There are relatively few data that can be used to define exact boundaries between these groups. It has been reported that κ_{lf} values as low as $140\cdot10^{5}$ SI (equivalent to χ_{lf} values around $1\cdot10^{-6}$ m^3/kg for typical bulk densities of field soils may affect performance of metal detectors[38]. In a recent report the magnetic behavior of soils has been classified into neutral, moderately problematic, severely problematic soils, and extremely problematic soils[39]. The report suggests that boundaries between these categories lie at κ_{lf} values of 50, 500, and $2000\cdot10^{5}$ SI, measured using a Bartington MS2B sensor. For typical bulk densities of field soils these values equal mass-specific magnetic susceptibilities around 0.3, 3, and $12.5\cdot10^{-6}$ m^3/kg. As a rule of thumb in Fig. 5, the transition from low to high χ_{lf} values lies at around 3 to $4\cdot10^{-6}$ m^3/kg, while the transition from low to high $\chi_{fd}\%$ lies at around 4 to 5%.

In Fig. 5 the possible pathways for the prediction of soil magnetic characteristics have been numbered. Examples of pathway ① are the soils Kohala 3 (Fig. 2) and Rio Chagrecito (Fig. 4). Soils of pathway ② are found on Kaho'olawe Volcano[8]. Soils of pathway ③ are those found on other locations of Kohala Volcano (soils Kohala 1 and 2) and Mauna Kea Volcano (Fig. 2). One soil we have described on the island of O'ahu follows pathway ④[10]. High temperature transformation of hematite into magnetite through burning of vegetation can lead increased susceptibilities in the near surface of a soil (pathway ⑤), as was observed in the Nangodi soil in Ghana[11]. Possibly this effect can lead to situations with both high and low frequency dependent magnetic susceptibilities (results A and B; Fig. 5). Young soils developed on parent materials low in ferrimagnetic minerals typically have low (frequency dependent) susceptibility values as is shown for pathway ⑥. The soil Pwaluga-C, developed in floodplain sediments, is an example of this pathway. For older soils well-drained conditions and a mean annual rainfall between around 500 and 1500mm/yr is favorable for the neoformation of superparamagnetic ferrimagnetic grains[30]. Depending on the maturity of the soil these conditions can lead to χ_{lf} values between 1 and $5\cdot10^{-6}$ m^3/kg and soils can classify in both results B and C (pathway ⑦). This pathway is very common for many soils in temperate and warm climates[30], and most soils that we have studied in Ghana classify in this group (Fig. 3). Pathway ⑧, finally, is typical for situations where the environmental situations are unfavorable for the neoformation of large amounts superparamagnetic grains.

6. DISCUSSION AND CONCLUSIONS

In this paper we have discussed the major weathering and soil forming processes that play a role in the magnetic enhancement of soils in the tropics. Transformation to and neoformation of (superparamagnetic) ferrimagnetic grains occurs in most soils providing enough time and the correct environmental conditions. It seems apparent from our data, as well as information from the literature that there are clear correlations between soil magnetic properties and parent material, precipitation, and soil age. Low values for $\chi_{fd}\%$ are generally associated with poorly developed or young soils, while with increasing weathering and soil formation the frequency dependent magnetic susceptibility increases[17]. We attribute the observed inverse relation between χ_{lf} and mean annual precipitation for soils developed on basaltic substrates (Fig. 2) to an increase in transformation rates of primary ferrimagnetic minerals to other, less magnetic minerals. The positive correlation relation between $\chi_{fd}\%$ and mean annual precipitation (observed for soils developed on all types of parent materials) can be attributed to increased neoformation of superparamagnetic ferrimagnetic grains with higher rates of soil formation.

We have presented a conceptual model for the prediction of magnetic soil properties based on various environmental parameters. Some of the definitions in the model are currently poorly constrained. By expanding our dataset of magnetic soil properties we hope to improve our model and to develop a database of magnetic soil properties around the world[40]. In order to quantify the parameters in the conceptual model we are attempting to characterize the types and amount of iron oxides in the different soil horizons using a variety of chemical extraction techniques, X-Ray diffraction, X-Ray fluorescence, and thermogravimetry. Using this and other available databases[41, 42] we hope ultimately to be able to develop good pedotransfer functions to predict the magnetic characteristics of soils in the tropics and around the world.

ACKNOWLEDGMENTS

The research was funded by grants from the Army Research Office (DAAD19-02-1-027 and STIR19-02-1-027). Additional support has been received from the U.S. Army Research Tropical Testing Center at Yuma Proving Grounds.

REFERENCES

1. Billings, S.D., L.R. Pasion, D.W. Oldenburg, and J. Foley. *The influence of magnetic viscosity on electromagnetic sensors*. in *EUDEM-SCOT2, International Conference on Requirements and Technologies for the Detection, Removal and Neutralization of Landmines and UXO*. Brussels 2003.
2. Borry, F., D. Gulle, and A. Lewis. *Soil characterization for evaluation of metal detector performance*. in *EUDEM-SCOT2, International Conference on Requirements and Technologies for the Detection, Removal and Neutralization of Landmines and UXO*. Brussels 2003.
3. Butler, D.K., *Implications of magnetic backgrounds for unexploded ordnance detection.* Journal of Applied Geophysics. **54**(1-2): p. 111-125, 2003.
4. Jenny, H., *Factors of soil formation*. New York: McGraw-Hill, 1941.
5. Kennedy, M.J., O.A. Chadwick, P.M. Vitousek, L.A. Derry, and D.M. Hendricks, *Changing sources of base cations during ecosystem development, Hawaiian Islands.* Geology. **26**(11): p. 1015-1018, 1998.
6. Porder, S., A. Paytan, and P.M. Vitousek, *Erosion and landscape development affect plant nutrient status in the Hawaiian Islands.* Oecologia. **142**: p. 440–449, 2005.
7. Vitousek, P.M., O.A. Chadwick, T.E. Crews, J.H. Fownes, D.M. Hendricks, and D. Herbert, *Soil and ecosystem development across the Hawaiian Islands.* GSA Today. **7**: p. 1-8, 1997.
8. Van Dam, R.L., J.B.J. Harrison, J.M.H. Hendrickx, D.A. Hirschfeld, R.E. North, J.E. Simms, and Y. Li. *Mineralogy of magnetic soils at a UXO remediation site in Kaho'olawe Hawaii*. in *SAGEEP*. Atlanta, GA: EEGS 2005.
9. Van Dam, R.L., J.M.H. Hendrickx, B. Harrison, B. Borchers, D.I. Norman, S.A. Ndur, C. Jasper, P. Niemeyer, R. Nartey, D. Vega, L. Calvo, and J.E. Simms. *Spatial variability of magnetic soil properties*. in *Detection and Remediation Technologies for Mines and Minelike Targets IX*. Orlando: SPIE 2004.
10. Van Dam, R.L., J.B.J. Harrison, J.M.H. Hendrickx, B. Borchers, R.E. North, J.E. Simms, C. Jasper, C.W. Smith, and Y. Li. *Variability of magnetic soil properties in Hawaii*. in *Detection and Remediation Technologies for Mines and Minelike Targets X*. Orlando: SPIE 2005, this issue.
11. Hendrickx, J.M.H., J.B.J. Harrison, R.L. Van Dam, B. Borchers, D.I. Norman, C.D. Dedzoe, B.O. Antwi, R.D. Asiamah, C. Rodgers, P. Vlek, and J. Friesen. *Magnetic soil properties in Ghana*. in *Detection and Remediation Technologies for Mines and Minelike Targets X*. Orlando: SPIE 2005, this issue.
12. Kitayama, K., E.A.G. Schuur, D.R. Drake, and D. Mueller-Dombois, *Fate of a wet montane forest during soil aging in Hawaii*. Journal of Ecology. **85**: p. 669-679, 1997.
13. Singer, M.J., K.L. Verosub, P. Fine, and J. TenPas, *A conceptual model for the enhancement of magnetic susceptibility in soils.* Quaternary international. **34-36**: p. 243-248, 1996.
14. Fabris, D., J.M.D. Coey, and W.D.N. Mussel, *Magnetic soils from mafic lithodomains in Brazil*. Hyperfine Interactions. **113**: p. 249-258, 1998.
15. Maher, B.A., *Magnetic properties of modern soils and Quaternary loessic paleosols: paleoclimatic implications.* Palaeogeography Palaeoclimatology Palaeoecology. **137**: p. 25-54, 1998.
16. Thompson, R. and F. Oldfield, *Environmental magnetism*. London: Allen & Unwin. 227, 1986.
17. Dearing, J.A., *Environmental magnetic susceptibility: using the Bartington MS2 system*. Kenilworth: Chi Publishing. 104, 1994.
18. Pasion, L.R., S.D. Billings, and D.W. Oldenburg. *Evaluating the effects of magnetic susceptibility in UXO discrimination problems*. in *SAGEEP* 2002.
19. Lindsley, D.H., ed. *Oxide minerals: petrologic and magnetic significance*. Reviews in mineralogy, ed. P.H. Ribbe. Vol. 25. Mineralogical Society of America: Chelsea. 506 1991.
20. Cornell, R.M. and U. Schwertmann, *The iron oxides: structure, properties, reactions, occurrences and uses*. Second ed. Weinheim: Wiley-VCH. 664, 2003.
21. Mullins, C.E., *Magnetic susceptibility of the soil and its significance in soil science* **-** *a review.* Journal of Soil Science. **28**: p. 223-246, 1977.
22. Stucki, J.W., B.A. Goodman, and U. Schwertmann, eds. *Iron in soils and clay minerals*. Reidel: Dordrecht. 893 1988.
23. Driessen, P.M. and M. Dudal, *The major soils of the world*. Zutphen, The Netherlands: Koninklijke Wöhrmann B.V. 310, 1991.

24. Goulart, A.T., J.D. Fabris, M.F. De Jesus Filho, J.M.D. Coey, G.M. Da Costa, and E. De Grave, *Iron oxides in a soil developed from basalt.* Clays and clay minerals. **46**(4): p. 369-378, 1998.
25. Aleva, G.J.J., *Laterites - concepts, geology, morphology and chemistry*, ed. D. Creutzberg. Wageningen: ISRIC. 169, 1994.
26. Maher, B.A. and R.M. Taylor, *Formation of ultrafine-grained magnetite in soils.* Nature. **336**: p. 368 - 370, 1988.
27. Lecoanet, H., F. Lévêque, and S. Segura, *Magnetic susceptibility in environmental applications: comparison of field probes.* Physics of the Earth and Planetary Interiors. **115**: p. 191-204, 1999.
28. Parfitt, R.L., C.W. Childs, and D.N. Eden, *Ferrihydrite and Allophane in four Andepts from Hawaii and implications for their classification.* Geoderma. **41**: p. 223-241, 1988.
29. Maher, B.A. and R. Thompson, *Paleorainfall reconstructions from pedogenic magnetic susceptibility variations in the Chinese loess and paleosols.* Quaternary Research. **44**: p. 383–391, 1995.
30. Maher, B.A., *Comments on "Origin of the magnetic susceptibility signal in Chinese loess".* Quaternary Science Reviews. **18**: p. 865-869, 1999.
31. Mathé, P., P. Rochette, D. Vandamme, and F. Colin, *Volumetric changes in weathered profiles: iso-element mass balance method questioned by magnetic fabric.* Earth and Planetary Science Letters. **167**: p. 255-267, 1999.
32. Singer, M.J. and P. Fine, *Pedogenic factors affecting magnetic susceptibility of Northern California soils.* Soil Science Society of America Journal. **53**: p. 1119-1127, 1989.
33. Da Costa, A.C.S., J.M. Bigham, F.E. Rhoton, and S.J. Traina, *Quantification and characterization of maghemite in soils derived from volcanic rocks in Southern Brazil.* Clays and Clay Minerals. **47**(4): p. 4660473, 1999.
34. Harrison, J.B.J., J.M.H. Hendrickx, D. Vega, and L.E. Calvo Gobbetti, *Character and spatial variability of soils in two small first order drainage basins, Upper Rio Chagres watershed, Panama*, in *The Rio Chagres, Panama*, R.S. Harmon, Editor. Springer, In press.
35. Panama, *Mapa Geologicó de República de Panamá*. Ministerio de Comercio e Industrias 1991.
36. Olson, K.R., A.N. Gennadiyev, R.L. Jones, and S. Chernyanskii, *Erosion patterns on cultivated and reforested hillslopes in moscow region, Russia.* Soil Science Society of America Journal. **66**: p. 193-201, 2002.
37. Royall, D., *Particle-size and analytical considerations in the mineral-magnetic interpretation of soil loss from cultivated landscapes.* Catena. **57**(2): p. 189-207, 2004.
38. Das, Y., J.E. McFee, K. Russell, G. Cross, and T.J. Katsube. *Soil information requirements for humanitarian demining: the case for a soil properties database*. in *Detection and Remediation Technologies for Mines and Minelike Targets VIII*. Orlando: SPIE 2003.
39. Billings, S.D., D. Guelle, and A. Lewis. *Soil influence and ground compensation: summary of breakout session 2*. in *ITEP-workshop, reliability tests for demining (http://www.kb.bam.de/ITEP-workshop-03/)*. Federal Institute for Materials Research and Testing (BAM), Berlin 2003.
40. Das, Y., J.E. McFee, and G. Cross. *Soil properties database for humanitarian demining: a proposed initiative*. in *17th World Congress of Soil Science*. Bankok, Thailand: The International Union of Soil Science 2002.
41. Batjes, N.H., *Development of a world data set of soil water retention properties using pedotransfer rules.* Geoderma. **71**(1-2): p. 31-52, 1996.
42. Hendrickx, J.M.H., R.L. Van Dam, B. Borchers, J.O. Curtis, H.A. Lensen, and R.S. Harmon. *Worldwide distribution of soil dielectric and thermal properties*. in *Detection and Remediation Technologies for Mines and Minelike Targets VIII*. Orlando: SPIE 2003.