Magnetic soil properties in Ghana

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ABSTRACT

In this paper we present the results of a study of some soil magnetic properties in Ghana. The soils sampled formed in different parent materials: Granites, Birimian rocks, and Voltaian sandstones. We discuss the role of environmental controls such as parent material, soil drainage, and precipitation on the magnetic properties. The main conclusion of this reconnaissance study is that the eight different soil types sampled have their own unique magnetic signature. Future research will have to confirm whether this conclusion holds for other soils in Ghana. If it does, the measurement of magnetic soil properties may become a viable complement for the investigation of soil erosion, land degeneration, and pedogenesis. The magnetic soil properties measured would probably not pose any limitations for the use of electromagnetic sensors for the detection of land mines and UXO.

1. INTRODUCTION

Many soils worldwide exhibit magnetic properties that result from the presence of iron oxides in different forms and quantities. Ferrimagnetic minerals such as magnetite and maghemite are the most magnetic of the iron oxides while paramagnetic and antiferromagnetic iron oxides such as goethite and hematite play a minor role in determining the magnetic character of a soil. Several sources of magnetic minerals are recognized: (i) The parent material from which the soils are developed; (ii) In situ formation by pedogenetic processes[1, 2]; (iii) Aeolian deposition of dust[3]; (iv) anthropogenic processes such as industrial fly ashes[4, 5]; (v) Flood deposition. Most research on magnetic soil properties is driven by two research questions: "How can magnetic minerals be exploited as natural tracers for a variety of geological processes such as climate change and soil erosion[6, 7]?" and "How do those minerals affect the behavior of electromagnetic waves in field soils?"

The lack of adequate soil data to drive landscape evolution models have been a major drawback throughout Africa as well as in other parts of the world. These models are needed to quantify soil-induced environmental problems such as erosion and land degradation[8-12]. Currently, the use of radio nuclides such as cesium (^{134}Cs) and lead (^{210}Pb) are being considered for wide application under the GLOWA VOLTA project[13] to trace soil dynamics, river sediments, atmospheric dusts and nutrient flows over periods from 20 to 30 years. However, the use of radioactive tracers has its limitations due to the need for special laboratories with costly gamma-counting equipment[14].

Soil properties have been widely used to characterize surface stability in many different environments since they show systematic changes in profile morphology over time. In young soils, there is no change in the distribution of weathering

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products with depth, termed an isotropic profile. As soils develop weathering products accumulate at different depths within the soil profile. Over time there is a systematic change in soil profile characteristics and an increase in profile anisotropy. Usually there is a gradual increase in weathering products to a maximum concentration in a B horizon, followed by a decline to the original parent material value with increasing depth. One of the major soil weathering products for tropical soils are iron oxides, which may have significant magnetic properties. We believe that the depth distribution of the magnetic properties of soils can be used to characterize the amount of erosion or deposition that a soil has undergone. Magnetic properties can be measured quickly and cheaply using magnetic susceptibility meters.

The main objective of this study is to provide information on the presence of magnetic properties in Ghanaian soils. This work is a first step to investigate how quick and inexpensive measurements of magnetic soil properties can be exploited for environmental soil research in Africa. In addition, since magnetic properties of tropical soils can seriously hamper the performance of electromagnetic sensors for the detection of buried land mines and unexploded ordnance[15], this work may have relevance for land mine and unexploded ordnance clearance operations in Africa.

2. MAGNETICS

2.1. Theory

The physical basis for magnetic behavior in minerals is the magnetic moment produced by electrons orbiting their nucleus and spinning around their axis. In many types of material the overall magnetic moment is zero because the orbital and spin components even out. When a mineral with zero magnetic moment is exposed to a magnetic field, its electron motions will be rearranged in such a way that a small net magnetic moment is created. If this magnetic momentum works in a direction opposite to the applied field, the mineral is called *diamagnetic*. In contrast, when the small net magnetic moment attempts to line up in the direction of the magnetic field, the mineral is called *paramagnetic*. Minerals in which the electron interaction leads to magnetic moments being aligned in opposite directions so that a net magnetic moment of zero results, are called *antiferromagnetic*. In some minerals, the interaction between electron spin and orbital movement in adjacent atoms causes these minerals to behave as active magnets. These types of minerals are called *ferromagnetic* when all magnetic moments line up in the same direction, or *ferrimagnetic*, when one-third of the magnetic moments line up in the opposite direction. Some ultra fine grains of iron oxides (<0.03 μm) may exhibit *superparamagnetic* behavior where magnetization is strong but unstable[16]. These ultra fine grains are formed as a result of burning, pedogenic processes, or bacterial processes. Many books and review papers have addressed the physical background of magnetic minerals in general [17, 18] and magnetic soils in particular [19-21].

2.2. Magnetic soil properties

Magnetic properties in soils are largely a consequence of the presence of different forms of iron. Although pure iron can occur naturally in rocks and soil, it is very rare. Specific types of iron oxides, iron-titanium oxides and iron sulfides are the predominant causes of magnetic soil characteristics. In abundance, iron (Fe) is the fourth element in the earth crust. Although the most abundant minerals in the earth’s continental crust are essentially Fe-free (plagioclase, feldspar, quartz), many other minerals contain significant amounts of iron [18]. Iron-containing minerals can be found in igneous rock such as basalt, gabbro, and granite, but also in metamorphic and sedimentary rocks. Therefore, it is no surprise that iron occurs in one form or another in many soils. The concentration of (magnetic) iron oxides is affected by the parent material, soil age, pedogenic processes, biological activity, and soil temperature [2, 22].

Table 1 shows magnetic susceptibilities for several iron- and iron-titanium-oxides, iron-sulfides and other soil constituents. Water and quartz are diamagnetic and have a small negative magnetic susceptibility. Hydrated iron oxides like goethite, which is the most abundant iron oxide in soils around the world, ferrihydrite, and lepidocrocite, play a minor role in determining the magnetic character of soils. Also hematite, which is the most abundant iron oxide in tropical soils, pyrite, and ilmenite hardly affect the magnetic soil characteristics. The magnetic character of soils is dominated by the presence of ferrimagnetic minerals such as magnetite and maghemite, and to a lesser degree by pyrrhotite [23].

Table 1. Magnetic susceptibilities for several iron oxides and soil constituents. Data from [18] and [24].

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

Although iron oxides occur in most environments throughout the world [25] some locations are more favorable for the formation and/or maintenance of significant amounts of (magnetic) iron oxides than others. Unfortunately, soil maps and available laboratory data at best contain information on the amount and not the type of iron oxides [26]. Tropical soils often contain large amounts of iron oxides [27]. 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 with an abundance of iron oxides are soils developed from parent material of volcanic origin. The volcanic origin ensures in many cases the abundance of (ferri)magnetic iron oxides. Volcanic derived soils have a much smaller acreage than Fe-rich soils in the tropics but can be found on all continents. They may be present everywhere where geologically young volcanic rock is found (e.g., near continental margins and subduction zones as well as in rift environments).

2.3. Characterization of magnetic soil properties

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

Remanent magnetization – Remanent magnetization exists in the absence of an applied field. The remanent magnetization must be added to any magnetization effects resulting from an applied magnetic field. Remanent magnetization occurs within ferrimagnetic and ferromagnetic minerals that have a natural alignment of the magnetic moments. This type of magnetization directly affects magnetic sensors. Also, remanent magnetization can be the result of alignment and subsequent 'locking' of magnetic moments in the weak magnetic field of the Earth. Locking can occur due to cooling from high temperatures through the mineral-specific Curie temperature, due to critical-size crystal growth, or due to compaction and consolidation [18]. These thermoremanent, chemical-remanent, and detrital-remanent magnetizations are small and affect only the most sensitive magnetic sensors.

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

Viscous remanent magnetization – Viscous remanent magnetization refers to the effect that occurs when the secondary magnetic field gets delayed relative to the primary magnetic field [18]. This effect differs from the standard induced magnetization, where the magnetization is instantaneous, and the secondary magnetic field is in-phase with the primary magnetic field. Viscous remanent magnetization occurs in ferrimagnetic materials with a range of different shapes (anisotropy) and especially grain sizes. Under these circumstances, the application or removal of a magnetic field to/from a sample causes a delayed change in the direction of magnetization. The time needed for the direction change to occur is known as the Neel relaxation time. One consequence of viscous remanent magnetization is that the susceptibility becomes frequency dependent. This effect has important implications for both time- and frequency-domain electromagnetic sensors [15, 28]. Viscous remanent magnetization can be measured using dual-frequency magnetic susceptibility sensors.

3. GEOGRAPHICAL SETTING

Ghana lies on the Gulf of Guinea just above the equator between latitudes 4º44'N and 11º11'N and covers an area of about 239,500 square kilometers (Fig. 1). Ghana can be subdivided in the following broad regions[29]: (1) The low-lying coastal plain, which stretches along the entire coastline, extends from the border with Ivory Coast in the west to that with Togo in the east. From the coastline it extends 24 to 100km inland. The area has an altitude ranging from sea level to around 130m. The geology in the western part is similar to that on (2) the southwestern plateau. This plateau has a triangular shape and extends from around the northwest of Accra to Banda in the Northern Region of the country. The geology is characterized by roughly southwest-northeast trending ranges of Tarkwaian Quartzite, Upper- and Lower Birimian metamorphosed rocks, and granitic complexes. The plateau is bordered to the northeast by (3) the Voltaian highlands, which trend southeast-northwest. The town of Ejura is located in these hills, mostly made up of sand- and mudstones and shales, which have an average elevation of around 780m. (4) The interior Voltaian basin covers the east-central region of the country. The Volta reservoir covers a significant part of this region, in which Tamale is one of the biggest cities. The basin is a relatively flat area with a height ranging from 100 to 200m above sea level. The geology is dominated by clastic parent material. The area to the west and north of the Voltaian basin is known as the (5) northwestern plateau. The geology is characterized by granitic, clastic and metamorphosed rocks.

The climate in Ghana can be characterized as tropical wet-and-dry, or tropical savanna climate (Köppen, Aw)[30]. Ghana is characterized by a strong and clear north-south rainfall gradient. The mean annual precipitation changes from over 2000 mm/yr in the south near Tarkwa to below 1000 mm/yr in the north near Bolgatanga. The rainfall pattern for Ghana is unimodal in the northern part which comprises the interior savanna agro-ecological zone[31]. It is, however, bimodal in the southern part which consists of the forest and coastal savanna agro-ecological zones of the country[32]. Our four study sites are located along the climatic transect running south to north (Fig. 1, Table 1). Around Tarkwa we have collected surface samples in September 2003 on Tarkwaian rocks, which can be quartzites, phyllite, grit, conglomerates and schists. In March 2004 we have sampled one soil pit near Ejura and two soil pits near Tamale. Soils in both areas have been formed on clastic parent materials. In August 2004 we have studied of soils in the area around Bolgatanga. These well-described soils have been formed on a variety of parent materials (Table 1)[33, 34].

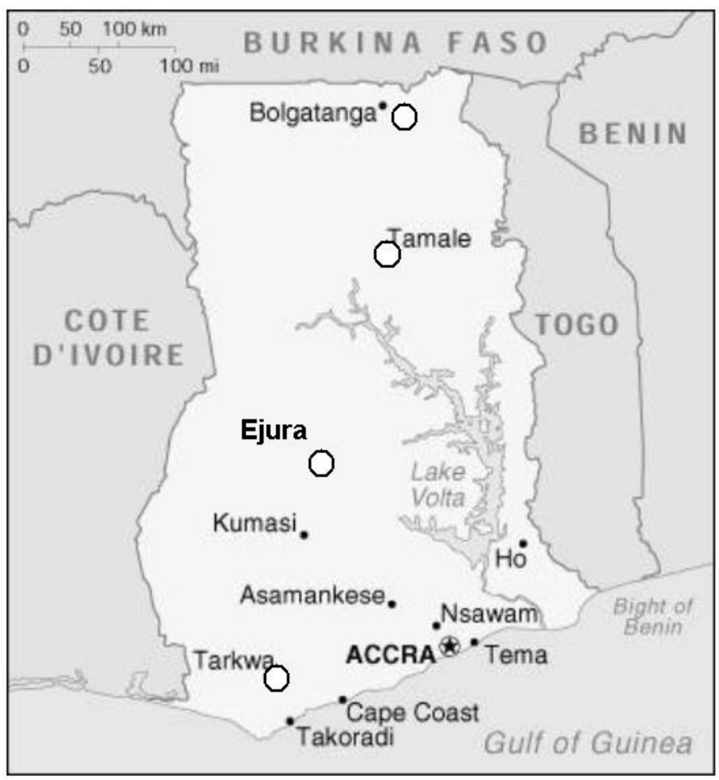

Figure 1. Location of soil sample sites in Ghana.

Table 1. Sampling locations and soil characteristics

No.	Location	Field_ID	GPS	Elevation (m)	Parent Material	P^a (mm/yr)	Sample type	Depth (cm)	# samples	Drainage Class[e]
1	Tarkwa	L2	5˚17.44'N 2˚00.26'W	87	Tarkwaian[c]	1700	Surface	-	7	-
2	Tarkwa	L3	5˚17.85'N 2˚00.33'W	87	Tarkwaian[c]	1700	Surface	-	7	-
3	Tarkwa	L4	5˚17.77'N 2˚00.38'W	84	Tarkwaian[c]	1700	Surface	-	20	-
4	Ejura	E1	7°20.45'N 1°16.58'W	200	UV[d]	1200-1500	Soil pit	105	6	well
5	Tamale	T1	9˚28.45'N 0˚55.70'W	174	UV[d]	1000-1200	Soil pit	110	6	poor
6	Tamale	T2	9˚29.55'N 0˚55.66'W	155	UV[d]	1000-1200	Soil pit	110	5	swp
7	Kolingu[b]	NBR15[34]	10˚47.33'N 0˚48.23'W	235	Granite	<1000	Soil pit	160	10	top 30 cm well; deeper swp
8	Mimi[b]	M	10˚37.19'N 0˚24.97'W	187	UV/LV[d]	<1000	Soil pit	120	12	well
9	Nangodi[b]	N	10˚50.55'N 0˚41.73'W	±200	Volcanic[f]	<1000	Soil pit	140	12	top 20 cm m well; deeper swp
10	Tanchera[b]	T	10˚50.53'N 1˚08.06'W	±200	Granite	<1000	Soil pit	140	14	swp
11	Pwalugo[b]	P-C	10˚35.24'N 0˚50.33'W	140	Fluvial Soil	<1000	Soil pit	60	4	poor
12	Pwalugo[b]	P-S	10˚35.20'N 0˚50.33'W	140	Fluvial Soil	<1000	Soil pit	70	5	swp

[a]Mean annual rainfall
[b]In Bolgatanga area (Fig. 1)
[c]Tarkwaian; quartzite, phyllite, grit, conglomerate and schist
[d]Upper/Lower Voltaian; mainly sandstone
[e]Estimated Drainage Classes: sw ex = somewhat excessively, well, m well = moderately well, swp = somewhat poorly drained, poor
[f]Birrimian greenstones, andesites, schists and amphibolites

4. METHODS

Samples were collected for laboratory analyses of soil texture, mineralogy and frequency dependent magnetic properties. Most samples taken in soil pits were taken with a 100 cm^3 cylindrical ring. Gravimetric samples were collected in Tarkwa and in the soil pits where volumetric sampling was too difficult due to gravel and/or rocks. In the laboratory the samples were dried for a minimum of 48 hours at a low temperature (<50ºC), so as not to cause any chemical reactions. Next, 10cm^3 pots were filled for measurement of the magnetic susceptibilities and their weight was measured on an A&D GR-120 balance with 0.1mg accuracy. The soil material was crushed (manually) to silt-sand grain sizes where necessary.

The magnetic susceptibility was measured at two frequencies (0.46/4.6kHz) using a Bartington MS2B sensor. All measurements were conducted at the most sensitive "0.1" setting. An air reading was performed before and after each measurement. Each sample was measured 1 to 3 times. The mass-specific magnetic susceptibility, χ, (m^3/kg) was calculated from the volume-specific susceptibility (κ) using:

$$\chi = 10\kappa / m \qquad [1]$$

where m is the sample weight[16] in grams. The (percent) difference (χ_{fd}%) between the higher frequency (χ_{hf}) and the lower frequency (χ_{lf}) readings can be used to estimate the viscous remanent magnetization of the samples. The frequency dependent susceptibility was calculated using[16]:

$$\chi_{fd}\% = ((\chi_{lf} - \chi_{hf}) / \chi_{lf}) \times 100 \qquad [2]$$

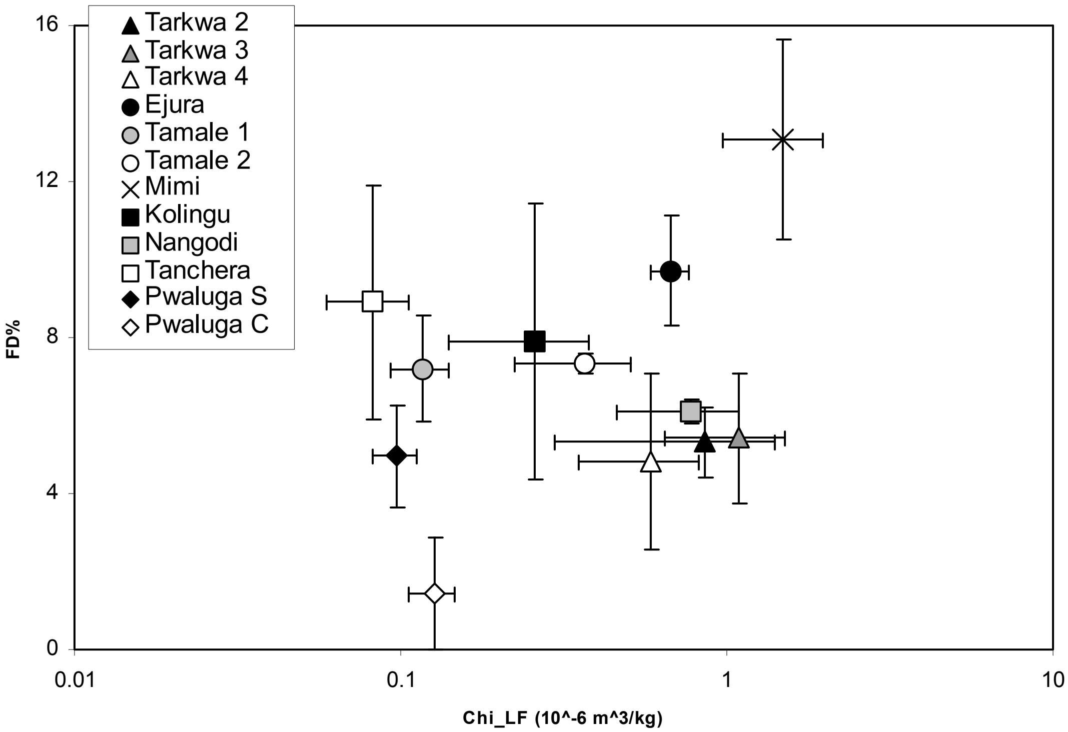

Figure 2. Cross plot showing average frequency dependent magnetic susceptibility and average low-frequency magnetic susceptibility for 12 soils in Ghana, measured at a Bartington MS2B sensitivity of 0.1. Data have been averaged over the top 50cm of each soil. The error bars represent 1 standard deviation. In the Nangodi soil an outlier in the top horizon (possibly related to burning of the vegetation) has been left out. The data show an overall positive correlation between χ_{lf} and χ_{fd}%. This correlation is somewhat "blurred" due to data from the Tarkwa region, all of which consist of surface samples rather than samples from soil pits.

Dual frequency magnetic susceptibility measurements have been made at a sensitivity setting of "0.1". Frequency dependent magnetic susceptibility values higher than 15% are considered rare. When samples have low frequency readings (χ_{lf}) less than $0.1 \cdot 10^{-6}$ m^3/kg large errors in χ_{fd}% can occur[5].

5. RESULTS AND DISCUSSION

5.1. Soil descriptions

In this section we present short descriptions of the soils sampled (Table 1). In bold italics we present the international soil name according to the Keys to Soil Taxonomy[35]. The classification presented in this study is quite general and only up to the Great Group level.

Tarkwa Area. This area is underlain by the Tarkwaian geological formations which consist of sandstones, phyllites, quartzites, schists, and conglomerates[36, 37]. The upland soils in the area are *Juaso* and *Mawso series* (***Haplustult***). They are deep, well to moderately well drained. Topsoil textures are sandy loams while the subsoils are gravelly and concretionary sandy clay loams[38].

Ejura Site. This site is underlain by Upper Voltaian sandstones. These rocks are flat–bedded and are fine–grained, massive and ferruginous or feldspathic[39]. The major upland soils are *Ejura* and *Amantin series* (***Kandiustalf***). These soils are deep to very deep, gravel–free and well–drained to moderately well–drained sandy loams to clay loams[40, 41].

Tamale Sites. The dominant geology of the area is Voltaian clay shales which are characteristically grayish–green and purple. Lenses of fine–grained micaceous sandstone, siltstone and mudstone occur within this geological formation[42]. Both soil pits are located on dryland rice fields. The *Volta series* are developed in alluvium on floodplains or old river beds in valley bottoms of streams. They are poorly drained. The topsoil is silty or very fine sandy loam; the subsoil is very fine sandy or silty clay. The *Lima series (**Albaqualf**)* have a morphology similar to the *Volta series (**Endoaquept**)* but light textured. They are developed from colluvio alluvial materials on floodplains or low terraces in the area. They are imperfectly or poorly drained and subject to seasonal waterlogging or flooding. The topsoil is fine sandy loam or loamy fine sand. Below this is a loose layer of common iron concretions which grade into silty or sandy clay layer with few iron concretions[42, 43].

Bolgatanga Area. Four soil pits where sampled: Kolingu, Mimi, Nangodi, and Tanchera series. These soils are described in detail in a report of the Soil Research Institute (CSIR) of Ghana[34]. The *Kolingu series* (***Haplustalf***) occurs on upper to middle slopes and is developed over granites. They do not have a high water retention: rain water percolates easily through the thin gravelly top layer to the slowly permeable clayey decomposing rock below; then, the water moves laterally downslope to valley bottoms. The *Mimi series* (***Rhodustalf***) have developed over Voltaian sandstones and occur as a piedmont soil developed from colluvium on upper to middle slopes. The profile consists of about 30 cm or less of porous loamy fine sand grading into 120 cm or more of uniform porous sandy clay loam. The soil is well drained. The *Nangodi series* (***Ustorthent***) is developed over volcanic rocks which are mainly Birimian greenstones, andesites, schists and amphibolites. It occurs on the foot slopes of hill ranges. It consists of abundant greenstone brash with quartz stones in a silty clay matrix. The *Tanchera series* (***Haplustalf***) has developed over hornblide granite and occurs on slopes with gradients of 2-3 percent. It consists of about 5-8 cm of loamy sand underlain by 60 to 100 cm of loamy coarse sand or dandy loam. External drainage is low.

5.2. Magnetic measurements

The average magnetic susceptibilities measured in the soils cover a range from about $0.09 \cdot 10^{-6}$ to $2 \cdot 10^{-6}$ m^3/kg but most soils have values less than $1 \cdot 10^{-6}$ m^3/kg (Fig. 2). These values are typical for top soils derived from parent materials that do not contain large quantities of magnetic iron oxides[16]. The increase of the frequency dependent magnetic susceptibility with increasing low frequency magnetic susceptibility is typical for the formation of secondary minerals during the course of pedogenetic processes (Fig. 2). The value of 13% for the Mimi series is relatively high[16]. An important result from this preliminary study is the distinct magnetic signature observed for each of the twelve soils sampled. Each soil has it own unique location on the cross plot between average frequency dependent magnetic susceptibility and average low-frequency magnetic susceptibility (Fig. 2). The young fluvial soils at Pwalugo cluster nicely together as do the three Tarkwa surface samples and the two soils at Tamale. If future studies confirm this unique magnetic susceptibility signature of different soils or soil horizons, magnetic susceptibility measurements may become a cost-effective complement to the more elaborate radio-nuclides measurements for erosion, land degeneration, and soil development studies in Ghana.

Figures 3 and 4 present the profiles of magnetic susceptibility (solid symbols) and the frequency dependent magnetic susceptibility (open symbols) for the nine depth sampled soil pits. All nine profiles have a definite low frequency magnetic susceptibility signature and demonstrate relatively small internal variability of the measurements. The robust low-value magnetic susceptibility profiles are not caused by a lower sensitivity of the MS2 meter at low values since it can measure repeatable χ_{lf} to about $0.001 \cdot 10^{-6}$ m^3/kg or smaller[16].

The *parent material* of the soils is most likely the cause for the relatively low susceptibility values. None of the soils sampled was formed on basic or ultrabasic rocks so that the susceptibilities of the parent materials is probably less than about $1 \cdot 10^{-6}$ m^3/kg; the increase in magnetic susceptibility is due to pedogenic processes. Clearly, the youngest soils are the Pwalugo soils on the flood plain of the White Volta: both their frequency dependency and magnetic susceptibility are very low (Fig. 2). The magnetic susceptibility is somewhat higher in the upper 10 cm but then remains rather constant to a depth of about 50 cm (Fig. 3B). This may indicate that these flood plain soils have been formed in the same sedimentary parent material. All other soil profiles show more soil development and are older which is expressed in increased frequency dependence. For example, the Tanchera soils have a rather low magnetic susceptibility but their increased frequency dependency is evidence of a longer period of soil formation.

A) B)

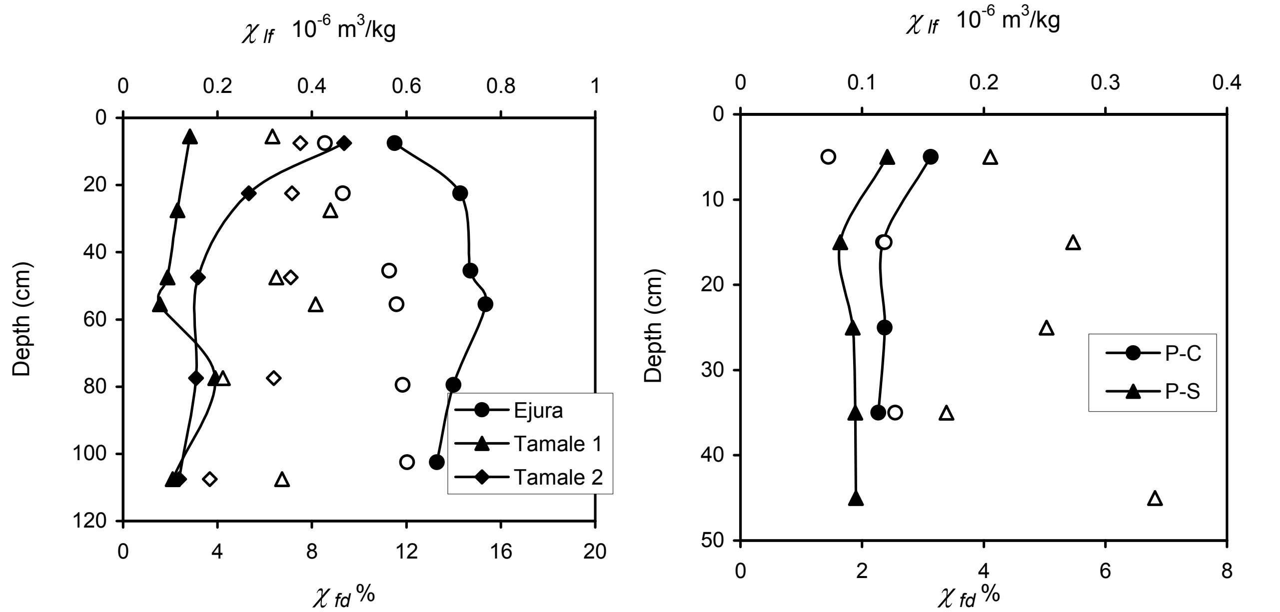

Fig. 3. Graphs showing magnetic susceptibility variations with depth for 5 soils in sandstone or fluvial sand. A) Soils from the Voltaian basin. B) Soils in fluvial sediment in the Bolgatanga area. Solid symbols represent low-frequency mass-specific susceptibility values. Open symbols stand for percent frequency dependency values.

A) B)

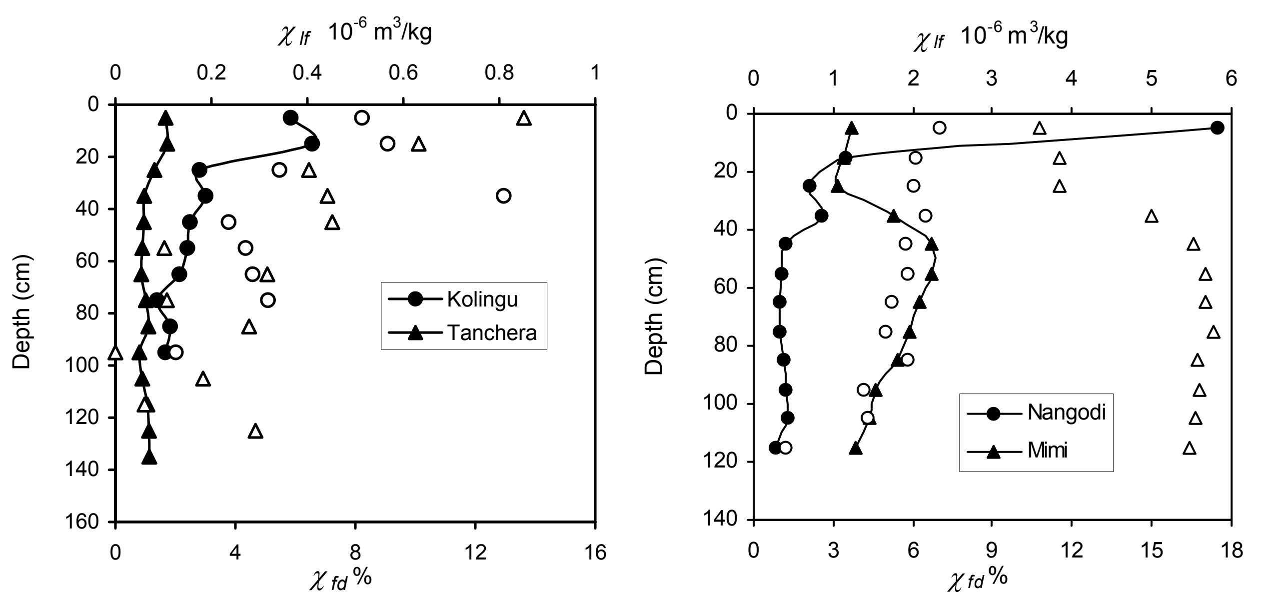

Fig. 4. Graphs showing magnetic susceptibility variations with depth for 4 soils in the Bolgatanga area. A) Soils developed in granite. B) The Nangodi soil was formed on Birimian phyllites, while the Mimi soil was developed in Upper/Lower Voltaian Sandstone. Solid symbols represent low-frequency mass-specific susceptibility values. Open symbols stand for percent frequency dependency values.

Our data confirm earlier observations[44] that there is a relation between the *drainage condition* of a soil and its magnetic susceptibility in Ghana. The uni-modal precipitation pattern in northern Ghana probably causes reduction of minerals such as hematite in anaerobic conditions (wet season from April through September) followed by oxidation to (magnetic) maghemetite during aerobic intervals[1]. There also is evidence that “ferrimagnetics” are not synthesized in water-saturated soils, i.e. poor drainage, instead they seem to form during a short period between wetting and drying soil conditions[45]. The well drained Mimi and Ejura soils (Table 1, Figs. 2, 3, and 4) have the highest magnetic susceptibility and frequency dependent magnetic susceptibility of the nine soil profiles. In addition, the Kolingu and Nangodi soils have a higher magnetic susceptibility in the top soil where drainage conditions are favorable in comparison with the sub soils.

Significant variability occurs in the frequency dependence of the sample material. All soils formed on granite substrates in the Bolgatanga area show increasing values of χ_{fd}% towards the top horizons, which may be due to neoformation of small-grained, so-called superparamagnetic, minerals in the top horizons (Fig. 4)[1, 16, 21, 46]. In the B horizon of the soil developed on Upper/Lower Voltaian sandstone (Fig. 4B) the frequency dependent magnetic susceptibility is higher than what is usually considered the upper limit (15%)[16].

The Nangodi soil (Fig. 4B) has an anomalously high value in the top horizon. This may be due to relative enrichment with and neoformation of ferrimagnetic minerals, which has been described in earlier research[1, 21, 46], or because of a contaminated or polluted sample[47]. However, since burning is so prevalent in Ghana[48], effect of fire is the most likely explanation[16]. In the Bolgatanga area the Mimi soil has formed in an alternative parent material (Upper/Lower Voltaian sandstone) that has a significantly higher frequency magnetic susceptibility than the soils developed in granite (Fig. 4B). The increased magnetic susceptibility and magnetic frequency dependency of the Mimi soils with depth may have been caused by the fact that the A horizon of sand (0-30 cm) originates from a different parent material than the deeper B horizons.

Figure 5 shows a weak negative correlation between the mean annual precipitation and the low frequency magnetic susceptibility. We do not have enough data to fully separate the effects of rainfall amounts and parent material but –at least our data seem not do differ from general trends established in the warm temperate zone[49].

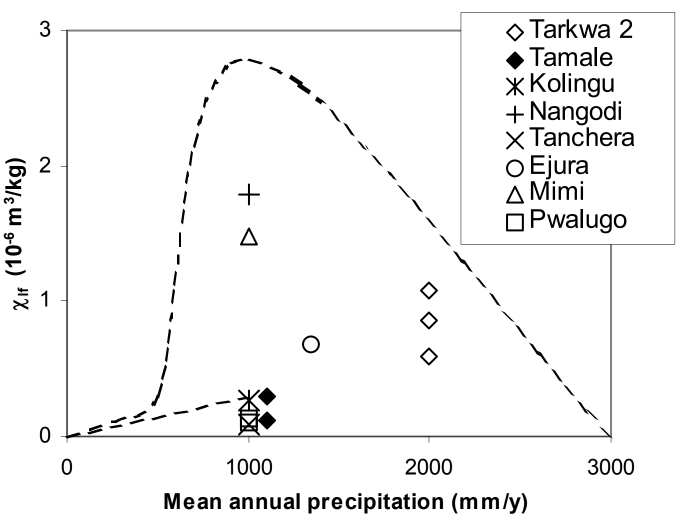

Figure 5. Graphs showing the relation between mean annual precipitation and mass-specific low frequency magnetic susceptibility. Individual symbols have been given per area (above) and parent material (below). The dashed lines in the graphs represent observed trends in a dataset of ~50 soils in the warm temperate zone by Maher and Thompson[49].

6. CONCLUSIONS

I. The main conclusion of this preliminary study is that the eight different soil types sampled in Ghana have their own unique magnetic signature, i.e. combination of average magnetic frequency and low frequency magnetic susceptibility. Future research will have to confirm whether this conclusion holds for other soils in Ghana. If it does, the measurement of magnetic soil properties may become a viable complement to the more expensive measurements of radio-nuclides for the investigation of soil erosion, land degeneration, and pedogenesis.

II. This study seems to confirm previous studies on the effect of topographic location or drainage condition on the formation of magnetic iron minerals in a soil profile. Future work will include the detailed study of multiple soils at different locations along a hill slope or catena.

III. The magnetic soil properties measured in nine different Ghanaian soils would probably not pose any limitations for the use of electromagnetic sensors that are used in other African countries for the detection of land mines and UXO.

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