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FREQUENCY DEPENDENCE OF MAGNETIC SUSCEPTIBILITY OF WEAKLY CONTAMINATED SOIL SEDIMENTS

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ABSTRACT

This paper reports the frequency dependence of magnetic susceptibility of weakly contaminated soil sediments. Low field magnetic susceptibility measurements were carried out on soil sediments at Bomo irrigation dam, Samaru College of Agriculture, Ahmadu Bello University, (ABU), Zaria, using the MS2D field loop. Soil samples were also collected for laboratory analyses. The volumetric percentage composition of magnetite (Fe) in the soil was found to be about 0.02%. Frequency dependent magnetic susceptibility measured at two frequencies (0.465 kHz and 4.65 kHz) using MS2B sensor reveals a slight difference between magnetic susceptibility values with the higher frequency indicating lower values. The coefficient of frequency dependence (%) values varying between 2.37% and 7.39%, indicating the presence of a mixture of ultrafine superparamagnetic and coarse non-superparamagnetic grains or SP grains < 0.005 .m ferromagnetic minerals occurring as crystals in the top soil. The soil formation process was as a result of secondary ferromagnetic minerals occurring as a result of burning, biochemical and authigenic processes in the area under investigation.[1]

INTRODUCTION

Magnetic susceptibility measurements are a non-destructive and cost effective method of determining the presence of iron-bearing minerals within a given sample of rock or soil. The samples are exposed to an external magnetic field which causes them to become magnetized according to the amount of iron-bearing minerals present in the samples. The ease with which a particular sample, when exposed to a magnetic field is magnetized is referred to as the magnetic susceptibility (k) of the sample. The ease of magnetization is ultimately related to the concentration and composition (size, shape and mineralogy) of magnetisable materials within the sample. The total magnetic susceptibility of a sampled rock is therefore, given by the bulk contribution of its mineralogy, including paramagnetic (i.e. phyllosilicates, ferromagnesians, iron-bearing feldspars), diamagnetic (e.g., quartz, calcite) and ferromagnetic (i.e. magnetite, hematite) grains (Joseph, et al; 1992). In addition, fluids filling any porosity will contribute to a lesser extent, to the total bulk susceptibility of the sample. In natural environment, the magnetisability provides information about the minerals that are found in soils, rocks, dusts and sediments, particularly iron-bearing minerals. Tite and Mullins, (1971) placed bulk susceptibility on a footing of geology and physics in order to understand the enhancement process within an archeological context.

In this study, we present the frequency – dependent magnetic susceptibility k_{fd} and its mass adjusted form χ_{fd}. The magnetic susceptibility is measured at two frequencies, k_{lf} and k_{hf} and their mass adjusted form χ_{lf} and χ_{hf}.

The k_{lf} and χ_{lf} represent the degree to which samples placed in a low magnetic field enhance or detract from the field. k_{fd} quantifies the difference in susceptibility displaced by the sample placed in two fields of the same magnitude, but applied at two different frequencies. It is commonly thought of as a measure of the abundance of very fine (clay-size) superparamagnetic minerals (Dearing, 1999). It also is fundamentally a measure of the concentration of magnetic minerals, but may give additional information on magnetic grain size and species in combination with susceptibility.

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In soil studies, it has been shown (Dalan and Banerjee, 1998) that the iron phases which dominates the magnetic properties of the soil are environmentally sensitive and conservative. Applications within the recently developed field of environmental magnetism have demonstrated that contrasts in magnetic soil assemblages (in terms of the composition, concentration and grain size of the magnetic minerals) can be used to identify and characterize different soil types and layers (Rummery et, al; 1979; Maher, 1986; Thompson and Oldfield, 1986)

Recently, rock magnetic methods have been found useful in environmental studies of modern soil. It has been applied by (Strzyszcz, 1993; Kapicka et, al; 1999; Hoffman et, al; 1999, and Petrovsky et, al; 2000) to delineate areas with concentrations of deposited anthropogenic ferrimagnetics significantly above background values, especially around local pollution sources. These studies showed that in polluted areas, the magnetic susceptibility of surface soil layers is considerably higher. A study of areas with relatively high concentrations of industry (Le Borgne, 1955; Thompson and Oldfield, 1986; Dalan and Banerjee, 1998; Heller et, al; 1998; Kapicka et, al; 1999, and Kapicka, 2003), in which the annual amount of atmospherically deposited dust and fly ash particles from coal burning power plant, reaches several thousand of tons per year, reveals that these particles can significantly influence magnetic properties of soils in the surrounding areas, thereby providing evidence of processes affecting iron minerals during pedogenesis, and of specific effects such as gleying.

The main objective of this work is to study the frequency dependence of magnetic susceptibility considered at two frequencies 0.465 kHz and 4.65 kHz, using the Bomo irrigation dam at Samaru College of agriculture farm, Ahmadu Bello University, Zaria (Fig.1) as case study. The result is then used to characterize the magnetic mineral type and the mode of formation of the soil at the dam.

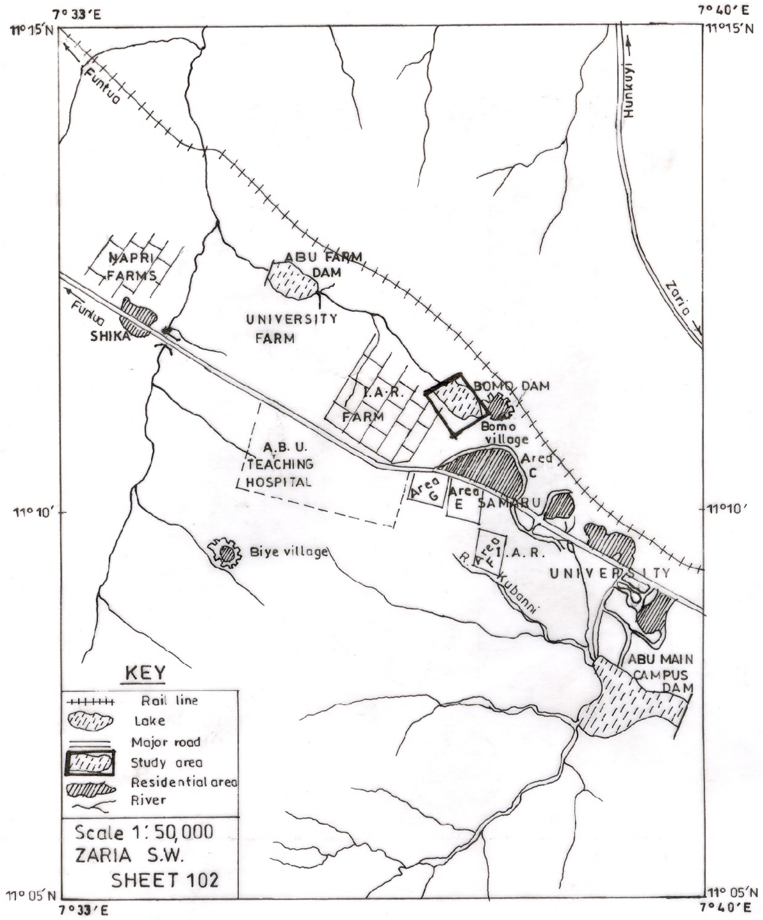

Fig. 1: Map of Samaru Showing the Study Area

METHODS

Field Method

The magnetic susceptibility was measured in the field using the MS2D loop sensor attached to a Bartington MS2 system, with a 2 x 10^{-6} [SI] sensitivity, operating at a frequency 0.958 kHz. The measurements were taken at regular intervals along the river bank. The loop sensor is designed for rapid assessment of the concentration of ferromagnetic, paramagnetic or diamagnetic minerals in the top 100 mm (approximately) of the soil surface (MS2 manual, 1993). Measurements taken with good contact between the loop and the ground are measured in SI units per volume. At each locality where the loop readings were taken, soil samples were collected for laboratory analyses.

Laboratory Analysis

The magnetic measurements conducted allow three properties to be determined: concentration, grain size, and magnetic mineral type. For the present study all measurements are carried out at room temperature. The Bartington sensor used is the MS2B dual frequency sensor operating at 0.465 kHz (low frequency), and 4.65 kHz (high frequency). Measurements at these two frequencies provide an indication of the form, nature and size distribution of the magnetic minerals in the sample, as well as distinguish magnetic enhancement due to man from that of natural origin. Magnetic susceptibility measurements over a field may vary significantly, but if the frequency dependence is constant and low these are probably due to varying concentration of natural magnetic minerals in the soil. Sites of human activities are usually distinguished as areas of high susceptibility accompanied by increased frequency dependence (Anthony, 1990). The results obtained can be used for archaelogical purposes. Samples were prepared using 10 ml cylindrical bottle available with the Bartington instrument. The samples were dried at room temperature to remove the percentage contribution of water to the magnetic susceptibility values.

The Multisus software supplied with the system was used for measuring the low and high frequencies in the laboratory. This Windows software runs on the user's PC and provides data capture from the MS2 meter, via the RS232 serial port. When used with the MS2B sensor the program allows volume or mass specific susceptibility measurements with corrections for sample volume or mass where appropriate, and calculation of the frequency dependent susceptibility.

THEORY

Fine grained minerals exhibit frequency dependent susceptibility. This is significant where grains of the single domain (~ 0.03:m diameter) order are present and where very rapid changes in frequency dependent occur with relatively small changes in diameter. In naturally occurring materials, these grains are widely distributed in sizes and give rise to a fairly uniform frequency dependence of susceptibility in the low frequency range in which the MS2 operates (MS2 manual, 1993). The coefficient of frequency dependence (Π_{FD}) can be expressed as the change in susceptibility per decade frequency divided by the low frequency susceptibility (Π_{LF}) where the low frequency susceptibility is always of higher value. Therefore the percentage (%) frequency dependence magnetic susceptibility (Tite and Mullins, 1971) is given by:

$$\chi_{FD}\,\% = \frac{\chi_{LF} - \chi_{HF}}{\chi_{LF}} \times 100$$

where LF and HF are in the ratio 1:10

The assessment of the relative iron abundance in a sample soil or rock containing magnetic minerals is given by the empirical formula (Dearing, 1999).

$$k = 0.15p$$

Where p is the percentage volumetric concentration of magnetite and,
k is the volume susceptibility.

RESULTS

The results of the field measurements of magnetic susceptibility of top soils taken at the dam site indicate that the top soils are weakly contaminated with ferromagnetic minerals. The volume magnetic susceptibility values ranges from 3.08 x 10^{-5} SI to 120.0 x 10^{-5} SI along the river bank, with an average value of 14.23 x 10^{-5} SI thus giving a volumetric concentration of about 0.02% magnetite in the soil. Though field susceptibility surveys can be used to characterize rapid variations of susceptibility across a site, they suffer from certain drawbacks that can only be investigated through laboratory study (Dalan and Banerjee, 1998). First, field instruments measure a volume magnetic susceptibility (k) which can not be conveniently normalized by mass as is done in the laboratory. For comparative purposes, k is an imprecise measure, as one does not know how closely the sediment or soil is packed, or how much air, water, or other inclusion are present, all of which affect susceptibility values. It is only through sample preparation in the laboratory that all these factors can be controlled and measured, hence the need for the laboratory analyses. This research work employs the frequency dependence of some magnetic minerals to characterize and determine the mode of formation of the soil at the site been investigated. The results of frequency dependence of magnetic susceptibility conducted on 59 sub-samples are shown in tables 2 and 3. Table 2 shows the volume magnetic susceptibility (k, which is dimensionless), while table 3 is that of mass specific magnetic susceptibility, (Π, in m^3kg^{-1} units). A look at the tables reveal a slight difference in susceptibility values at low and high frequencies, with the high frequency indicating slightly lower values. This is an indication of the presence of ultrafine (< 0.03) superparamagnetic ferromagnetic minerals (Dearing, 1999).

DISCUSSION

Magnetic susceptibility measurements at dual frequency provide information of archeological value (Anthony, 1990). By sampling the frequency spectrum at two points, dual frequency measurement provides an indication of its form and thus the nature and size distribution of the magnetic minerals in the sample. Materials directly weathered from bed rock tend to consist of large, multi-domain grains and shows a low or no frequency dependence (Mullins, 1977). The processes of reworking by man tend to favour change to the smaller grain sizes, including those with high frequency dependence. Burning has this effect, and it has been observed (Anthony, 1990; Dearing, 1999) that fertile, well-drained top soils, often the product of cultivation, also encourage the precipitation of such ultra fine clay sized secondary iron oxides with relatively high frequency dependent susceptibility. These grains which are single domain (for magnetite, around 50 nanometers or 50 billionths of a meter) are the most stable and also possess the property of superparamagnetism, which readily align with an applied field, but are unstable when removed because of thermal disturbance.

Therefore, the measurement of frequency dependent susceptibility exploits this phenomenon by measuring the sample at least twice at two different magnetization frequencies. A low frequency (0.465 kHz) measurement (the standard susceptibility measurement Π_{lf}) allows the superparamagnetic (SP) crystals close to the boundary with stable single domain (SSD) grains to contribute fully to the susceptibility, whilst a high frequency measurement (4.65 kHz) does not. The higher frequency has the effect of shifting the domain boundary between SP and SSD crystals to smaller crystal sizes. The difference in the values of the two measurements at different frequencies indicates the presence of superparamagnetic minerals and samples without the minerals will show identical values when measured at high frequency (Oldfield et, al; 1985; Thompson and Oldfield, 1986; Maher, 1998; and Dearing, 1999). Dearing (1999), showed that all crystals smaller than ~0.03μm show reduced susceptibility values at high frequency measurement (see table 1). Based on Dearing, (1999) it is evidence that the soil samples collected at our site show the presence of ultrafine superparamagnetic ferromagnetic minerals occurring as crystals produced largely as a result of biochemical processes in the soil, burning, and diagenesis. The samples are a mixture of SP and coarser non-SP grains, or grains less than 0.005 μm.

Table1: Interpretation of frequency dependent susceptibility values (After Dearing, 1999)

Low Π_{fd}%	< 2.0 Virtually no or < 10% SP grains
Medium Π_{fd}%	2.0 – 10.0 admixture of SP and coarser non- SP grains or SP grains < 0.005 :m.
High Π_{fd}%	10.0 – 14.0 virtually all or > 75 % SP grains
Very high Π_{fd}%	>14.0 rare values, erroneous measurement, anisotropy, weak sample or contamination

CONCLUSION

This paper has examined the frequency dependency of magnetic susceptibility of magnetic minerals of soil sediments in the Bomo irrigation dam, Ahmadu Bello University, Zaria. The results have shown that the soil formation at the dam are as a result of secondary origin due to human activities such as farming and bush burning. The volumetric concentration of magnetite was found to be approximately 0.02%. The result of frequency dependence shows that there is a slight difference between magnetic susceptibility values measured at low and high frequencies with the coefficient percentage frequency dependency (Π_{fd} %) varying between 2.37 % and 7.39 %. This is an indication of the presence of a mixture of ultrafine (clay-size) superparamagnetic ferromagnetic minerals occurring as crystals produced largely as a result of biochemical processes in the soil, burning and other processes of soil formation.

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References:

Anthony, C. (1990). Seen Beneath the Soil: Prospecting methods in Archeology. B.T. Bastsford Ltd., London.

Dalan, R.A, and Banerjee, S.K; (1998). Solving Archaeological problems using Techniques of soil magnetism. Geo-archaeology; An international Journ; Vol, 13, No.1, Pp,3-36.

Dearing, J. A., (1999). Environmental magnetic susceptibility: Using the Bartington MS2 system. Kenilworth: Chi Publishing Ltd.

Heller, F. Strzyszcz, Z and Magiera, T. (1998). Magnetic record of industrial pollution in forest soils of Upper Silesia, Poland. Jour. of Geophys Res. Vol. 103, No. 17, 767 – 774.

Hoffman, V., Knab, M. and Appel, E. (1999). Magnetic susceptibility mapping of roadside pollution. Jour of Geochan Explor. Vol. 66, 313 – 326.

Josep M. Pares and Ben A. vander pluijm, (2002) Phyllosilicate fabric characterization by Low-temperature Arisotropy of magnetic susceptibility (LT – AMS). Geophy. Res. letter, Vol. 29, 24 pp. 2215 – 2219.

Kapicka A. Jordanora . N, Petrovsky. E, and Podrazsky V., (2003). Magnetic Study of weakly contaminated forest soils water, air, and soil pollution, Kluwer Academic Publ., Vol. 148 pp. 31 – 44.

Kapicka, A., Petrovsky, E., and Machackova, K. (1999). Proxy mapping of fly-ash pollution of soils around a coal-burning power plant: A case study of Czech. Republic, Jour. of Geochem Explor. Vol 66. pp 291-297.

LeBorgne, E. (1955). Susceptibilities Manistique anomale du sol superficial. Ann. Geophys Vol. II, 399 – 419.

Maher, B. A. (1986). Characterization of Soils by mineral magnetic measurements. Physics of the Earth and Planetary Interior.

Operation manual for MS2 magnetic susceptibility system: Barrington Instruments Ltd. Oxford, England. http://www.bartington.com/

Oldfield, G., Krawiecki, A., Mhaer, B., Taylor, J.T., and Twigger, S. (1985). The role of mineral magnetic measurements in Archacology. In N.R.J Fieller, D.D. Gilbertson, and N.G.A. Ralph, (eds)., Palaeoenviron. Investigations: Research Design, Methods and Data Analysis, pp. 29 – 43.

Petrovsky, E., Kapicka, A., Jordanova, N., Knab, M. and Hoffmaun, V., (2000). Low – field magnetic susceptibility: a proxy method of estimating increased pollution of different environmental systems. Environ. Geol. Vol 39. 312 – 318.

Rummery, T.A., Bloemendal, J., Dearing, J., and Oldfield, F. (1979). The persistence of fire induced magnetic oxides in solids and lake sediments. Annals of Geophysics Vol; 35, pp 103-107.

Strzyszcz, Z., (1993).Magnetic susceptibility of soils in the areas influenced by Industrial Pollution, in J. B. Bucher and I. Bucher – Wallin (eds); Air Pollution and forest decline, Birmensdorf. pp. 201 – 207.

Thompson, R. and Old field, F., (1986). Environmental Magnetism, Allen and Unwin, London.

Tite, M.S., and Mullins, C. (1971). Enhancement of the magnetic Susceptibility of Soils on Archeological sites. Archaeometry. Vol 13, pp.209 – 219.

Table 2: Volume Specific Magnetic Susceptibility

Sample	Low-freq magnetic Susceptibility (x 10^{-5} SI)	High-freq magnetic Susceptibility (x 10^{-5} SI)	Coeff. of Freq-Dependence(%) Π_{fd}
A1	12.72	12.00	5.66
A2	52.60	50.32	4.41
A3	30.80	30.00	2.60
A4	110.16	106.52	3.30
A5	30.32	29.24	3.56
A6	2.12	1.92	9.43
A7	17.24	16.32	5.34
A8	38.28	37.60	1.78
A9	87.04	84.72	2.67
B1	19.16	18.44	3.76
B2	6.68	6.36	4.79
B3	6.16	5.92	3.90
B4	8.24	7.88	4.37
B5	10.04	9.76	2.79
B6	5.80	5.48	5.52
B7	9.64	9.28	3.73
C1	4.76	4.56	4.20
C2	4.68	4.48	4.27
C3	5.32	5.04	5.26
C4	9.56	9.20	3.77
C5	10.40	10.04	3.46
C6	15.44	14.72	4.66
D1	6.08	5.80	4.61
D2	6.00	5.68	5.33
D3	5.36	5.04	5.97
D4	8.80	8.40	4.55
D5	6.92	6.56	5.20
D6	4.85	4.60	5.74
E1	8.84	8.36	5.43
E2	5.96	5.72	4.03
E3	5.84	5.52	5.48
E4	10.40	9.88	5.00
E5	7.80	7.24	7.18
E6	8.64	8.16	5.56

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F1	25.28	24.32	3.80
F2	36.96	35.60	3.68
F3	6.44	6.08	5.59
F4	31.44	29.68	5.60
F5	11.44	10.92	4.55
F6	43.88	42.20	3.83
F7	62.44	59.64	4.48
G1	17.92	17.24	3.79
G2	29.72	28.44	4.31
G3	13.56	13.12	3.24
G4	26.04	25.08	3.69
G5	18.52	17.68	4.54
G6	13.36	12.68	5.09
G7	11.96	11.44	4.35
G8	34.92	33.64	3.67
H1	15.24	14.56	4.46
H2	28.16	27.00	4.12
H3	30.20	29.12	3.58
H4	18.36	17.52	4.58
H5	20.28	19.36	4.54
H6	19.12	18.36	3.97
H7	17.36	16.68	3.92
H8	21.04	20.08	4.56
H9	29.60	28.32	4.32
H10	18.92	18.20	3.81

Table 3: Mass specific magnetic susceptibility

SAMPLE	Mass (x 10^{-3}kg)	Low Freq (lf) magnetic Susceptibility (x $10^{-8}m^3/kg$), Π_{lf}	High Freq. (hf) magnetic Susceptibility (x 10^{-8} m^3/kg), Π_{df}	Coeff. of Freq-Dependence (%) Π_{fd}
A1	18.40	24.70	22.90	7.29
A2	17.20	92.60	89.00	3.89
A3	18.30	54.70	53.10	2.93
A4	17.90	207.40	196.50	5.26
A5	18.50	53.10	51.40	3.20
A6	17.00	4.10	3.90	4.88
A7	16.70	34.90	33.00	5.44
A8	19.30	63.70	62.10	2.51
A9	19.30	138.80	135.20	2.59
B1	19.90	30.60	29.70	2.94
B2	19.00	11.30	10.80	4.42
B3	19.60	10.10	9.60	4.95
B4	19.30	13.70	13.20	3.65
B5	19.60	16.30	15.70	3.68
B6	18.90	9.80	9.40	4.08
B7	18.50	16.90	16.50	2.37
C1	18.50	8.40	7.90	5.95
C2	18.60	8.20	8.00	2.44
C3	18.30	9.40	9.00	4.26
C4	18.70	16.70	16.00	4.19
C5	18.90	17.70	17.20	2.82

C6	18.40	27.20	25.90	4.78
D1	18.90	10.40	10.00	3.85
D2	19.40	10.00	9.50	5.00
D3	18.60	9.40	8.80	6.38
D4	19.30	14.50	14.00	3.45
D5	20.80	10.40	9.90	4.81
D6	18.90	8.40	8.00	4.76
E1	19.20	14.90	14.10	5.37
E2	19.00	10.10	9.60	4.95
E3	19.00	9.80	9.40	4.08
E4	18.80	17.90	17.00	5.03
E5	19.00	13.20	12.40	6.06
E6	19.10	14.60	13.70	6.16
F1	19.10	42.70	41.00	3.98
F2	19.30	61.70	59.10	4.21
F3	19.70	10.40	9.90	4.81
F4	18.90	53.80	50.80	5.58
F5	19.60	18.80	18.00	4.26
F6	19.70	70.90	68.50	3.39
F7	19.20	104.50	99.30	4.98
G1	20.40	27.80	26.60	4.32
G2	20.50	45.70	43.90	3.94
G3	20.30	21.30	20.50	3.76
G4	19.70	42.80	40.30	5.84
G5	20.80	28.10	26.80	4.63
G6	20.30	20.90	19.70	5.74
G7	19.90	19.30	18.40	4.66
G8	19.00	60.00	56.60	5.67
H1	20.60	23.50	22.30	5.11
H2	20.70	42.90	41.10	4.20
H3	20.80	45.80	44.00	3.93
H4	20.20	28.90	27.50	4.84
H5	20.70	31.00	29.50	4.84
H6	20.50	29.50	28.30	4.07
H7	20.80	26.30	25.30	3.80
H8	20.00	33.60	32.00	4.76
H9	20.90	44.30	43.70	1.35
H10	20.70	28.90	27.80	3.81