Geophysical Characterization of Surface Materials: Magnetic Susceptibility of Soil, Porosity, and Rock Densities

[1]Sahabo, Fatima Magaji [2]Audu, Jangura, [3]Dangari, Livinus Linus and [4]Shitu, Mohammed
[2,3]Department of Physics, Faculty of Physical Sciences Modibbo Adama University, Yola
[1,4]Department of Physics, School of Sciences Federal College of Education, Yola
Corresponding author's email: audujangura@gmail.com
DOI: 10.56201/ijgem.vol.11.no6.2025.pg86.94

Abstract
This research paper examines the magnetic susceptibility of agricultural topsoil and the determination of rock densities at Modibbo Adama University, Yola, utilizing a portable magnetic susceptibility meter alongside laboratory analysis. The findings indicate that the magnetic susceptibility values range from 5.0×10^{-6} to 1.54×10^{-3} SI, suggesting the soil is primarily composed of clayey sand with generally low magnetic susceptibility, which influences both the composition and fertility of the agricultural land. Additionally, the study measured the dry bulk density, saturated density, porosity, and particle density of the rock samples, with values ranging from 9.333 to 23 g/cm³, 10 to 23 g/cm³, 0.4 to 0.66 (40 to 66.6%), and 6.333 to 28 g/cm³, respectively. The mean porosity for the analyzed rock samples was also calculated. Consequently, this led us to recognize that magnetic susceptibility serves as a tool for detecting magnetic minerals, thereby indicating soil composition and fertility, as such minerals can influence nutrient availability in the soil. Measurements of rock densities and porosity assist in determining the type of rock present in the outcrop, which predominantly consists of sandstones characterized by fine to medium grains and a range of colors including brown, grey, and whitish-grey.

Keywords: *magnetic susceptibility, porosity, rock, saturation density, and bulk density*

Introduction

Magnetic susceptibility refers to the extent to which a substance can be magnetized within an external magnetic field (Dearing, 1994). For instance, rocks consist of various minerals, each exhibiting different degrees of magnetic intensity. In addition to attributes such as size, color, and chemical makeup, we can also characterize materials based on their magnetic characteristics (Dearing, 1994). All physical matter responds to magnetic fields, with the influence ranging from extremely minimal to potentially negative; nevertheless, this phenomenon can be readily measured. Moreover, soil plays a vital role in the ecosystem, facilitating the growth of crops and plants, while effective land management is essential for maintaining soil quality. Human activities, including mining and industrial processes, significantly impact soil nutrients, often causing them to be altered, disrupted, or eroded. The accumulation of excess heavy metals poses significant toxicity risks to humans and animals due to its impact on the food chain. These metals are, however, essential for the growth of various plants in agricultural, horticultural, and forestry contexts. Magnetic susceptibility is a useful method for detecting shallow soil characteristics resulting from human activities, such as construction, earthmoving, drainage ditches, and the delineation of agricultural fields. The magnetic minerals found in soils may originate from the underlying parent rocks (lithogenic source), develop during soil formation processes (pedogenic source), or arise from human-induced activities (secondary ferromagnetic materials). Hematite and magnetite are prevalent minerals, acting as both primary and secondary components in soils and solid waste; they serve as significant reservoirs for pollutants like heavy metals. Consequently, these minerals are recognized as major contributors to this environmental issue. The mineral composition of lithogenic minerals serves as an indicator of the characteristics of their source rock. Consequently, soils originating from sedimentary rock formations typically exhibit a significantly lower presence of magnetic minerals compared to those developed from volcanic or intrusive rock types (Jordanova 2017). Soil research holds significant importance in Nigeria, especially as the nation, which once thrived on agriculture prior to the oil boom, is making efforts to return to its agricultural roots. Globally, various soils display magnetic characteristics due to the presence of iron oxides in diverse forms and concentrations (Maher *et al.*, 2003). Several sources of magnetic minerals include; the parent material from which the soils are formed (orogenetic), in situ formation by pedogenetic processes, Aeolian deposition of dust, anthropogenic processes such as industrial fly ashes and flood deposition.

Akanbi and Adoyi (2008) investigated the magnetic susceptibility (χ) of soil samples from the Jos region in Nigeria, employing a Bartington susceptibility meter with an MS2 well sensor for their measurements. Their findings indicated that the magnetic susceptibility values for surface soils varied from (15.25-152.75) x 10^-5 SI for Aκ and from (0.0271-0.1175) x 10^-6 m³/kg for χ. At a depth of 15 cm, the measurements for Aκ ranged from (15.6-137.75) x 10^-5 SI, while χ fell between (0.0153-0.0984) x 10^-6 m³/kg. For soils at a depth of 30 cm, Aκ displayed values from (17.60-86.90) x 10^-5 SI, and χ ranged from (0.0133-0.0515) x 10^-6 m³/kg. The authors concluded that magnetic susceptibility demonstrates variability with depth, showing either an increase or decrease as depth changes. In their study, Akanbi and Uzomah (2008) measured the magnetic susceptibility of crushed rock samples from the Bukuru region of Nigeria using the Bartington MS-2 magnetic susceptibility system, specifically the MS-2G sensor. The findings revealed that the average magnetic susceptibility values for the 0.71 mm grain size ranged between 147.6x10^-5 and 591x10^-5 SI. For the 0.25 mm grain size, the values ranged from 5.44x10^-5 to $54.34\text{x}10^{-5}$ SI. Additionally, the mass-specific magnetic susceptibility values for the 0.71 mm grain size varied from $1.355\text{x}10^{-6}$ to $5.832\text{x}10^{-6}$ m^3/kg, while for the 0.25 mm grain size, the range was from $0.049\text{x}10^{-6}$ to $0.474\text{x}10^{-6}$ m^3/kg. The study concluded that there is a direct correlation between increasing grain size and rising magnetic susceptibility. In his 1977 work, Mullins outlined the various factors influencing the magnetic susceptibility (MS) of soil, concluding that it is determined by the size, shape, and concentration of minerals such as magnetite and maghemite, along with the techniques employed for measurement. He also noted that pedogenic maghemite could form even in soils with low magnetic susceptibility parent materials. Assessing magnetic susceptibility has diverse applications within soil science, including evaluations of soil drainage, magnetic granulometry leveraging the frequency dependence of MS, investigations into soil contamination, studies of soil erosion and land degradation, as well as reconstructions of paleoclimate scenarios (Jordanova, 2021).

This paper presents the necessary stages to successfully undertake the experimental setup of this technique to measure χ in solids and liquids. Special emphasis is given to the determination of the size and geometry of the samples.

Materials and Methods

Materials for Magnetic susceptibility and porosity, and density of rocks

Hand held magnetic susceptibility meter, GPS, measuring tape, wooden peg, Surfer software, five (5) rock samples, weighing balance, Measuring cylinder, Beaker, Water, and Oven

Methods

Magnetic Susceptibility

Magnetic susceptibility (k) of topsoil was measured randomly using a handheld magnetic susceptibility meter within the coordinate in an open field in Modibbo Adama University, Yola, and was recorded as in Table 2, surfer software was used to plot the magnetic susceptibility contour. The magnetic susceptibility measurement in situ was carried out under the following procedure;

- ✓ The magnetic susceptibility meter was set to low-frequency sensitivity mode
- ✓ The soil surface was cleaned and made flat and free from large debris
- ✓ The probe was gently pressed against the soil without any disturbance
- ✓ The meter readings were recorded accurately with the corresponding GPS locations

Rock Porosity and Density

The five rock samples collected from five different outcrops within Modibbo Adama University, Yola, and weighed as shown in the table 3, were heated in an oven at 100 ºC for about 12 hours under reduced pressure to remove all water content. Then they were weighed in air (W_d) and quickly in water (W_w) using a weighing balance. These samples were then saturated in water at reduced pressure for 24 hours and weighed in water (Ws) and air (W_t). From these masses, the dry density ρ_d, saturated density ρ_s particle or grain density ρ_g, and porosity σ were calculated using the following formulae (Akinyemi, *et al.,* 2012).

Dry bulk density $\rho_d = \frac{W_d}{W_t - W_s}$

Saturated density $\rho_s = \frac{W_t}{W_t - W_s}$

Particle or grain density $\rho_g = \frac{W_d}{W_d - W_s}$

Porosity $\sigma = \frac{W_s - W_w}{W_d - W_w}$

Results and Discussion

Table 1: The coordinates of the magnetic susceptibility survey

Points	Latitude	Longitude	Elevation (ft)
1	09º 20.927	012˚ 29.778	756
2	09˚ 20.920	012˚ 29.724	751
3	09˚ 20.979	012˚ 29.767	767
4	09˚ 20.966	012˚ 29.715	753

Table 2: magnetic susceptibility values of topsoil

S/N	Latitude	Longitude	Elevation (ft)	Magnetic suscept. Values $(\times \mathbf{10^{-3}})$ (SI)
1	0920.971	01229.746	756	6.02×10^{-4}
2	0920.970	01229.754	759	9×10^{-5}
3	0920.976	01229.763	758	1.3×10^{-5}
4	0920.972	01229.767	758	9.1×10^{-5}
5	0920.974	01229.768	764	1.1×10^{-5}
6	0920.965	01229.764	759	1.08×10^{-4}
7	0920.962	01229.753	760	2.23×10^{-4}
8	0920.962	01229.752	757	6.34×10^{-4}
9	0920.762	01229.745	758	5×10^{-6}
10	0920.959	01229.737	761	3.4×10^{-5}
11	0920.963	01229.737	758	4.1×10^{-5}
12	0920.961	01229.722	758	1.67×10^{-4}
13	0920.966	01229.714	760	1.1×10^{-5}
14	0920.956	01229.717	759	3.4×10^{-5}
15	0920.952	01229.726	762	2.6×10^{-5}
16	0920.952	01229.741	756	3.1×10^{-5}
17	0920.949	01229.744	756	3.2×10^{-5}
18	0920.949	01229.744	757	9.4×10^{-5}
19	0920.953	01229.753	762	3.53×10^{-4}
20	0920.953	01229.754	761	1.54×10^{-3}
21	0920.953	01229.756	756	9.4×10^{-5}
22	0920.952	01229.762	748	3×10^{-6}
23	0920.955	01229.766	748	3.2×10^{-5}
24	0920.951	01229.772	743	4.04×10^{-4}
25	0920.946	01229.767	745	9×10^{-6}
26	0920.940	01229.765	765	4.86×10^{-4}
27	0920.942	01229.775	754	8.4×10^{-5}
28	0920.935	01229.771	757	2.09×10^{-4}
29	0920.937	01229.764	754	2.12×10^{-4}
30	0920.942	01229.757	751	2.6×10^{-5}
31	0920.944	01229.750	746	1.6×10^{-5}
32	0920.941	01229.742	745	2.92×10^{-4}
33	0920.947	01229.735	744	4.6×10^{-5}
34	0920.947	01229.728	745	1.24×10^{-4}
35	0920.945	01229.721	750	6.3×10^{-5}
36	0920.939	01229.732	753	1.9×10^{-4}
37	0920.932	01229.730	761	5.7×10^{-5}
38	0920.928	01229.726	748	6×10^{-6}
39	0920.927	01229.725	764	4×10^{-5}
40	0920.920	01229.724	752	3.66×10^{-4}
41	0920.922	01229.729	753	1.4×10^{-5}

42	0920.924	01229.733	750	1.95×10^{-4}
43	0920.923	01229.734	748	1.76×10^{-4}
44	0920.927	01229.741	749	1.09×10^{-4}
45	0920.926	01229.745	748	5.67×10^{-4}
46	0920.931	01229.746	748	2.03×10^{-4}
47	0920.936	01229.745	744	3.5×10^{-5}
48	0920.931	01229.754	753	1.97×10^{-4}
49	0920.927	01229.754	758	9×10^{-6}
50	0920.927	01229.761	755	1.96×10^{-4}
51	0920.932	01229.764	767	1.5×10^{-5}

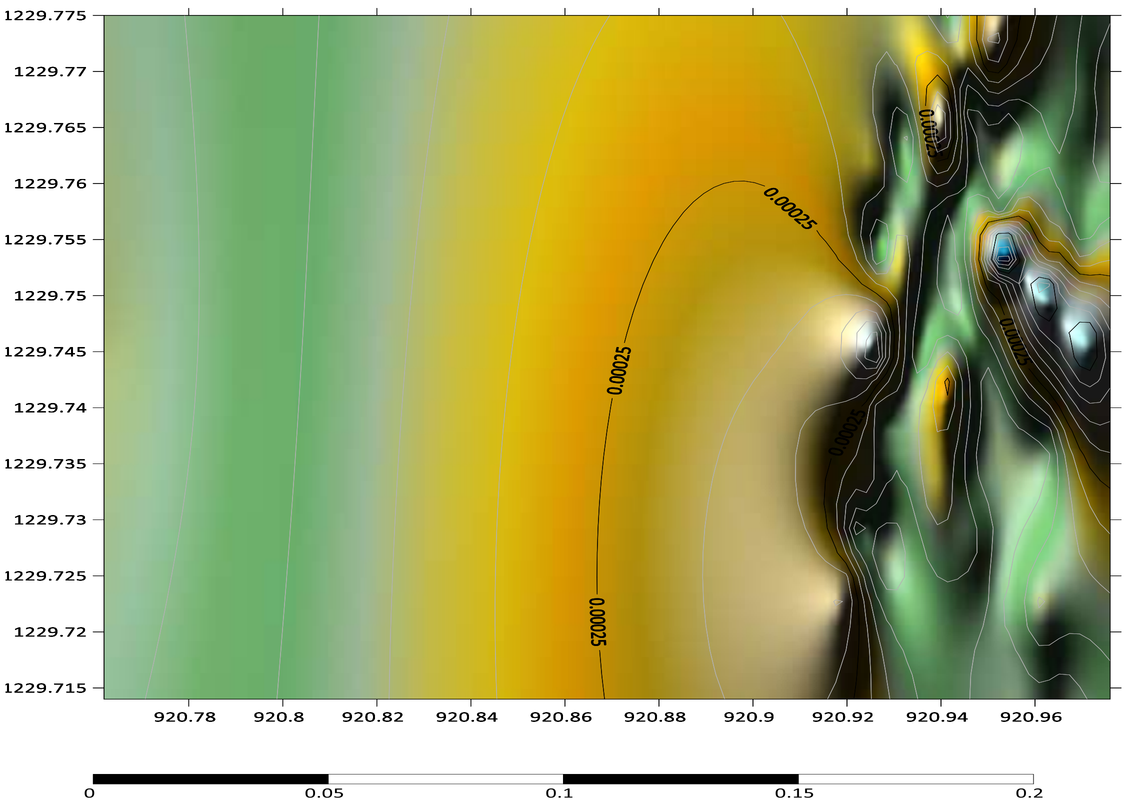
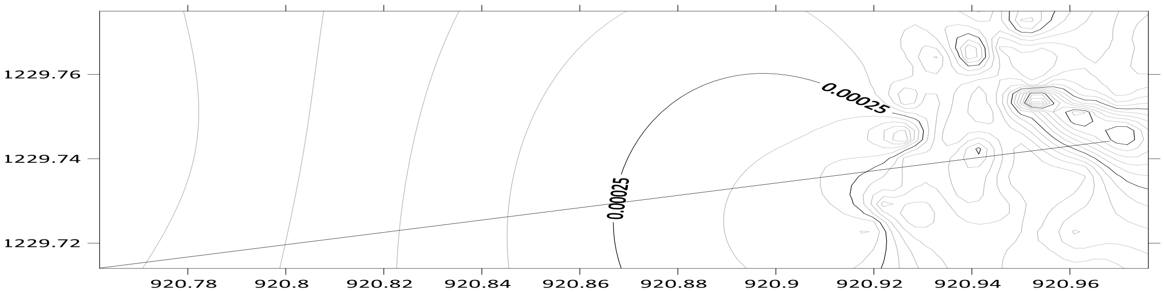


Figure 1: Magnetic Susceptibility of the Topsoil

The magnetic susceptibility of the Agricultural topsoil of the area ranges from 9.0×10^{-6} SI to 1.54×10^{-3}SI which shows consistent enhancement or even distribution of magnetic susceptibility in the farm land. The contours (1.0 to 2.53 ($\times10^{-4}$SI)) and (1.54×10^{-3}SI) respectively appears to have negligible paramagnetic/diamagnetic contribution (figure 1); here the higher values (1.54 $\times10^{-5}$ to 9.0×10^{-6} SI) represent lesser paramagnetic/diamagnetic contribution, (Meena *et al,* 2011; Brempong *et al,* 2016). The closed contours indicated isolated magnetic features, closely spaced contours indicated rapid changes in magnetic susceptibility and widely spaced contours suggested gradual changes, possibly indicating homogeneous rocks or sediments of the agricultural topsoil as in Meyer, 1976. Therefore the magnetic survey revealed that the field is composed of clayey sand composition with generally low magnetic susceptibility of 0.000005 to 0.00154 SI unit, such soils were formed from sedimentary rocks of low micronutrient availability which exhibits poor aeration and water retention, (Jordanova 2017).The profile shows how the magnetic susceptibility increases and decreases with elevation across the field with random distance that is high above 4×10^{-4} SI and decreases significantly to 9×10^{-6} SI (figure 2).



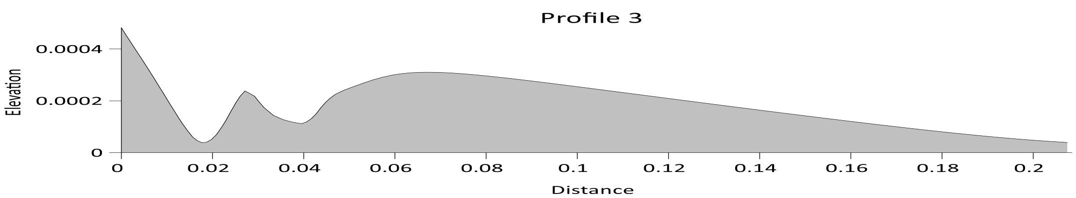


Figure 2: The profile of the magnetic susceptibility

Table 2: The Porosity and Densities of Rock

S/N	North	East	Elevation (ft)	MS (10^{-3})	ρ_d (gcm^{-3})	ρ_s (gcm^{-3})	ρ_g (gcm^{-3})	σ
S1	0920.879	01229.869	765	0.000009	10.667	11.333	16	0.5
S2	0920.829	01229.822	771	0.000213	9.333	10	28	0.666
S3	0920.671	01230.109	787	0.000002	23	23	23	0.666
S4	0920.958	01230.373	765	0.000002	9.333	10	28	0.5
S5	0920.958	01229.374	760	0.000005	19	17	6.333	0.4
Mean					**14.2666**	**14.2666**	**20.266**	**54.64**

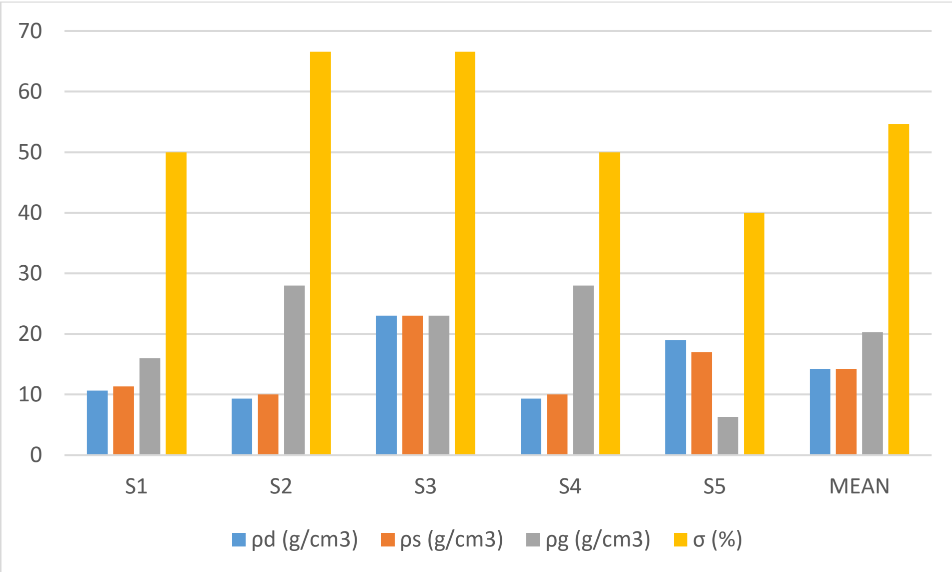


Figure 3: Densities and Porosity of the Rock Samples

Table 2 shows the summary of magnetic susceptibility, dry bulk density, saturated density, particle or grain density and porosity of the five rock samples

Dry Bulk Density

The five samples S1, S2, S3, S4, and S5 has dry bulk density of 10.667 g/cm^3, 9.33 g/cm^3 23.0 g/cm^3 9.333 g/cm^3 and 19 g/cm^3 respectively which shows that rock sample (S3) located N0920.671and E01230.109 with elevation of 787ft has the highest dry bulk density (23.0 g/cm^3) among the rock samples while S4 and S2 located at N0920.958, E01230.373 and N0920.829, E01229.822 respectively have the lowest dry bulk density (9.333 g/cm^3), the bulk densities of the rocks ranged from 9. 333 – 22 g/cm^3 with mean dry density of 14.2666 g/cm^3.

Saturated Density

The saturated density results shows that rock sample S3 has the highest saturated density (23.0 g/cm^3) while S4 and S2 located at N0920.958, E01230.37 and N0920.829, E01229.822 respectively has the lowest (10 g/cm^3) saturated density.

Particle or grain Density the particle density results shows that rock sample S2 and S4 located at N0920.829, E01229.822 with elevation of 771ft and N0920.958, E01230.373 with elevation of 765 ft respectively, have the highest particle density (28.0 g/cm^3) while rock sample (S5) has the lowest (6.333 g/cm^3) particle density.

Porosity

The porosity of five samples of sedimentary rock from the rock outcrop of different locations within Modibbo Adama University ranges from 0.4 – 0.666 with mean porosity of 0.5464 (54.64 %). The five different rock samples from the rock outcrop are sedimentary rocks (sandstone) rock samples with porosities 0.5, 0.666, 0.666, 0.5, and 0.4 respectively. It is clearly seen that the rock sample (S5) have lowest (0.4) porosity compared to other rocks samples while S2 and S3 has the highest porosity of 66.6 %.

Conclusion

The magnetic susceptibility has been determined for topsoil within the coordinates randomly and it's varies with different points and elevation. This finding revealed that the field topsoil is composed of clayey sand composition with generally low magnetic susceptibility of 0.000005 to 0.00154 SI unit. This implies that magnetic susceptibility of the field is generally low indicating low micronutrient availability, poor soil structure that leads to poor aeration and water retention. The rock samples are generally sandstones, (S3) has the highest dry bulk density (22.0 g/cm^3) while rock sample (S4) has the lowest dry bulk density (9.333 g/cm^3). The mean porosity of all the rock samples is 0.7332 which shows that all the location does not have the same porosity when one location is compared with the other locations, making the rocks generally porous with about 73 % mean porosity. It was observed that significant relationship exists between the densities and the porosities of the rocks that is the lower the density the higher the porosity (figure 3).

References

Akanbi E. S. & Adoyi I. M. (2008). Determination of magnetic susceptibility of rock samples in Bukuru area, Nigeria: https://www.researchgate.net/publication/343888952

Akanbi, E. S. & Uzomah, K. (2008). Determination of magnetic susceptibility of rock samples in Bukuru Area, Nigeria.

Brempong F., Mariam Q. & Preko K. (2016). The use of magnetic susceptibility measurements to determine pollution of agricultural soils in road proximity. *African Journal of Environmental Science and Technology.* 10(9), 263-271

Dearing, J.A. (1994) Environmental magnetic susceptibility: using the Bartington MS2 system. In Akanbi E. S. & Adoyi I. M. (2008). Determination of magnetic susceptibility of rock samples in Bukuru area, Nigeria: https://www.researchgate.net/publication/343888952

Dearing, J.A. (1994) Environmental magnetic susceptibility*: using the Bartington MS2 system*. Kenilworth: *Chi Publishing*. 104.

Jordanova, D., & Jordanova, N. (2021). Updating the significance and paleoclimate implications of magnetic susceptibility of Holocene loessic soils. *Geoderma,* 391: 114982.

Jordanova, N. 2017. Soil magnetism. Applications in pedology, environmental science and agriculture. *Academic Press, Elsevier, Amsterdam*. 446

Maher, B.A., H. MengYu, H.M. Roberts, and A.G. Wintle, (2003). Holocene loess accumulation and soil development at the western edge of the Chinese Loess Plateau: implications for magnetic proxies of palaeorainfall. *Quaternary Science Reviews*; **22**:445-451.

Meena N.K., Sabyasachi M., & Ankush S. (2011) Discrimination between anthropogenic (pollution) and lithogenic magnetic fraction in urban soils (Delhi, India) using environmental magnetism. *Journal of Applied Geophysics;* 73, 121–129

Meyer A. A (1976). Interpretation of magnetic susceptibility contour maps. In Mullins C. E (2006). Magnetic susceptibility of the soil and its significance in soil science. *Journal of soil science;* 28(2):223-246.