Original Article

Determination of Magnetic susceptibility of hydrocarbon contaminated soils in Port Harcourt and Bonny Island, Rivers State, Nigeria.

P. Adie[1], M.M. Orosun[2], S.A Oniku[1], N.B. Salawu[3], D.M. Akinnagbe[2].*

[1]Department of Physics, Modibbo Adama University of Technology, Yola, Nigeria.
[2]Department of Physics, University of Ilorin, Ilorin, Nigeria
[3]BS Geophysical and Consultancy Limited, Nigeria.

Abstract

In this study, determination of magnetic susceptibility were carried out on 366 soil samples using MS2B magnetic susceptibility meter connected to a computer system using MULTISUS2 software. The soil samples were selected from six sites namely: Shell environment, Nigeria Liquefied Natural Gas environment, Port Harcourt Refining Company James Hart, New Jerusalem and Port Harcourt respectively. Three of the six sites; Shell, NLNG and Port-Harcourt Refining Company environments have their soils contaminated with hydrocarbon. One hundred and ninety two (192) soil samples were collected from these hydrocarbon contaminated sites and 174 from non-hydrocarbon contaminated soil (control samples). The magnetic susceptibility values obtained from Shell environment and for hydrocarbon samples showed higher (enhanced) magnetic susceptibility with average values of 117.54×10^{-8} m^3kg^{-1} and 2016.39×10^{-8} m^3kg^{-1} and a moderate magnetic susceptibility for with an average value of 20.83×10^{-8} m^3kg^{-1} in comparison to magnetic susceptibility values obtained from the control samples whose average values were 2.39×10^{-8} m^3kg^{-1}, 12.42×10^{-8} m^3kg^{-1} and 3.31×10^{-8} m^3kg^{-1} for James Hart, New Jerusalem and Port Harcourt respectively. This means that the hydrocarbon sites are highly magnetic which could be indication of pollution. The results of the percentage frequency dependent susceptibility ($\chi_{FD}\%$) obtained in the hydrocarbon samples showed about 16% of the samples had percentage frequency dependent susceptibility ($\chi_{FD}\%$) values between 0-2%, 53% had values of $\chi_{FD}\%$ between 2-10% and 31% had $\chi_{FD}\%$ between 10-12% and above while about 21% of the control samples had $\chi_{FD}\%$ values between 0-2%, 58% between 2-10% and 21% between 10-12% and above. The high magnetic susceptibility value in the hydrocarbon soil samples is an indication of pollution due to hydrocarbon deposit. The Government is therefore advised to monitor the location and activities of the oil companies and initiate quick mop up strategies should be put in place in the eventuality of oil spillage.

Key words: magnetic susceptibility, hydrocarbon, pollution, Port Harcourt and Bonny Island.

Corresponding Author[*]:
OROSUN, Muyiwa Michael
Environmental Physics Research Group,
Physics Department,
University of Ilorin,
Ilorin, Kwara State, Nigeria.
Tel: +2348039184957
E-mail: muyiwaorosun@yahoo.com

1. Introduction

Magnetic susceptibility is a measure of iron-bearing components in a material. It can be used to identify the type and amount of iron-bearing minerals found in a material on which the test is conducted. The determination of magnetic susceptibility can be a useful, sensitive and fast method which provides an important parameter used in mineralogy and granulometry. This method is widely adopted for its use in agriculture and also by environmental scientists in techniques that employ the magnetic properties of soil and has proven to be a remarkably successful determinant in pollution research (Brempong et al., 2016; Ivakhnenko, 2012; Thompson and Oldfield, 1986). Many anthropogenic emissions contain fine particles highly magnetic in nature that cause heavy metal contamination in the soil of industrially active regions (Orosun et al., 2016). Magnetic properties of different types of soil display different aspects of soil mineralogy. The minerals that are present in soil are either natural (through lithogenesis, pedogenesis) or of anthropogenic (human activities) origin. The magnetic mineral content of the soil can be expressed in very broad terms by its magnetic susceptibility (Orosun et al., 2020; Brempong et al., 2016 and Thompson and Oldfield, 1986).

Pollution of soil sediments and ground water by organic contaminants is an important global environmental problem. In order to analyze hydrocarbon contamin$_{at}$ed sites and applied suitable remediation, rapid and cost effective assessment method are needed (Petrovsky and Ellwood, 1999). Guzman et al., (2011) and Aldana et al., (2003) studied fields from Venezuela and identified magnetite and iron-sulfides (e.g greigite) as the major contributor of magnetic susceptibility values in oil wells. Studies by Ivakhnenko, 2012 and Aldana et al., (2003) in oil reservoirs demonstrated that high resolution aeromagnetic survey can be applied for exploring oil fields, suggesting that magnetic susceptibility measurement in soils, sediments and drill cuttings may be a complementary or alternative method for exploration and assessment of HC reservoirs. In two recent field studies, Rijal et al. (2010) observed increased magnetic susceptibility values in

hydrocarbon contaminated soils. Hanesh and Scholger (2002) observed a correlation between magnetic susceptibility and polycyclic and aromatic hydrocarbons (PAHs) contents in near Donawitz, steel at leoben, Austria. After analyzing sediment cores from Taraba, Nigeria and Hamilton harbour, Canada, Kan et al., (2013) and Morris et al., (1994) concluded that magnetic susceptibility could be a reliable and less expensive empirical method for determining the extent of contamination of sediments by iron bearing minerals. Martins et al. (2007) verified a good correlation between the distribution of magnetic susceptibility and hydrocarbon in the Santos Estuary, Brazil, mainly by comparing magnetic susceptibility and PAHs. Liu et al. (2006) reported magnetic enhancement that was caused by hydrocarbon migration in the Mawagmiao Old Field, Jianghan Basin, China. The authors observed a dramatic increase of some magnetic parameters such as magnetic susceptibility and saturation magnetization of an oil-bearing formation and also observed the presence of secondary magnetite particles in association with the oil-bearing strata. Diaz et al., (2006) used magnetic susceptibility, electron paramagnetic resonance and extractable organic matters parameter in drilling fines

from near surface levels of producer and non-producer wells to examine a possible casual relationship between magnetic anomalies and underlying hydrocarbons. In a recent study Guzman et al., (2011) argued that magnetic susceptibility together with other non-magnetic parameters could be used for preliminary reservoir characterization. Aldana et al., (2011) show that magnetic mineralogy associated to hydrocarbon micro seepage in oil field of Western Venezuela is represented by magnetite. Magnetic properties changes were also recognized in the ground water table fluctuation zone of hydrocarbon contaminated sediment (Rijal et al., 2010). This research is aimed at determining the effect of hydrocarbon contamination on soil magnetic susceptibility in Port Harcourt and Bonny Island of Rivers State, Nigeria.

1.2 Location and General Geology of the Study Area

The study area, Rivers state is located between Latitude $4^0 55^1 N$ and $4.750^1 N$ of the equator and Longitude $6^0 55^1 E$ and $6^0 83^1 E$ (Fig. 1). Bonny Island falls within the Beach ridges on-shore geomorphic sub-environment of the Niger Delta. Geologically, these comprise Pleistocene and Recent sediments deposited by fluvial and shallow continental shelf

hydrodynamic processes. The area is characterized by strong wave and tidal action, which further compacts the sediments. Plant growth on beach ridges over the years has resulted in the formation of extensive primary tropical freshwater forest. Energy conditions decrease from shore face to outer edge. The litho faces include the delta tip, mainly evenly laminated fine to medium sand.

The hydrogeology of the area is highly influenced by the presence of ferruginous sandy formation due to high oxidation condition of the near surface aquifers and predominant saline water intrusion. The sand forms the major aquifer in the area while the clay forms the aquitards. The water table in the area varies with season. The area has a declining water table during the dry season. Generally, water table ranges between 0.1 (surface) - 3m depending on the season. Water table in the area is dynamic with reversal tidal influence. Generally, the Delta is characterized by three formations, namely: Akata (oldest), Agbada and Benin (youngest). These formations consist primarily of regressive Tertiary age sediments. The detailed geology of the Niger Delta formation is given by (Abam, 2016; Reyment, 1965 and Short and Stauble et al., 1967). It is bounded to the south by the Atlantic Ocean, to the North by Abia and Anambra states, to the East by Akwa Ibom state and to the West by Bayelsa and Delta states. Rivers state is home to many ethnic groups: Ikwere, Ijaw consisting of Ibani, Opobo, Okrika, Kalabari, Etche and Ogba and Ogoni.
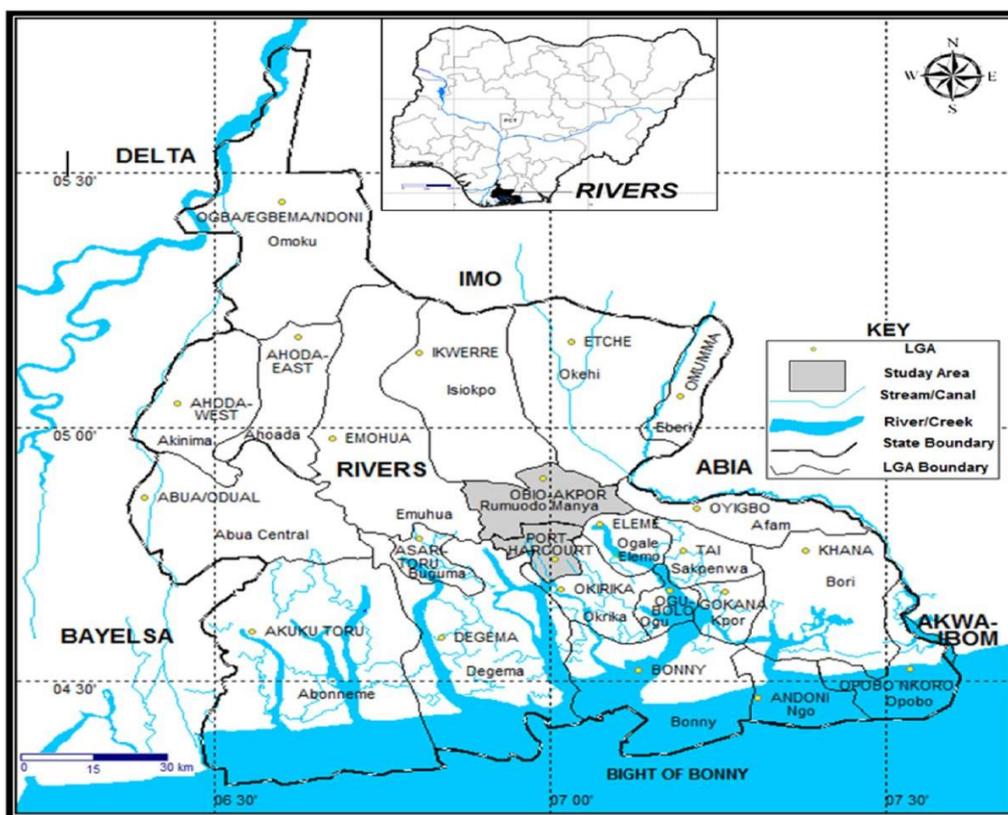
Figure 1: Geological Map of Nigeria Showing the Study Area, Bonny Island.

2. Materials and Methods

2.1. Materials

The materials used for this research work were as follows; Bartington instrument MS2B magnetic susceptibility system; Laptop; Desiccators; Micro oven; Ceramic crucible; Furnace; Digital electronic balance; Sieve; Soil auger and Plastic container.

2.2 Sample Collection, Preparation and Laboratory Analysis.

Soil samples were collected from eighteen different locations that have experienced hydrocarbon pollution in the past and eighteen different locations that are yet to experience hydrocarbon pollution (pure samples) in Rivers State at depths of 0 cm, 10 cm, 20 cm, 30 cm, 40 cm, 50 cm, 60 cm, 70 cm, 80 cm, 90 cm and 1 m respectively, in each location using soil auger and enveloped in a plastic container to avoid contamination. The soil auger was used to collect the soil samples at the aforementioned depths. The samples

enveloped in plastic containers were taken to the laboratory for further analysis. The samples were air dried at laboratory for some days to avoid chemical reactions. They were then sieved and stored in plastic containers for measurement. Magnetic susceptibility determinations were carried out on 366 soil samples selected from six sites (six different locations per site and average value for each depth per location taken) namely: Shell environment, Nigeria Liquefied Natural Gas environment (NLNG), Port Harcourt refining company limited (PHRC), James Hart, New Jerusalem and Port Harcourt respectively. Three of the six sites; Shell, NLNG and PHRC environments have their soils contaminated with hydrocarbon. To get a fair representation of the level of contamination, one hundred and ninety two (192) soil samples were collected from these hydrocarbon contaminated sites and one hundred and seventy four (174) from non-hydrocarbon contaminated sites (control samples).

Magnetic susceptibility measurement was carried on each sample using the Bartington MS2B meter linked to computer operated using Multisus2 software. All measurements were conducted at 1.0 sensitivity setting. Each sample was measured three times with; first air reading, sample reading and a second air reading before and after each series for drift correction. The MS2B sensor is a portable laboratory sensor which accepts $10cm^3$ samples in plastic containers. It has the ability of performing measurements at two different frequencies (470 Hz and 4700 Hz). The accuracy of the MS2B instrument is 1% when the $10 cm^3$ cylindrical plastic bottle is in use (Dearing, 1999). The Susceptibility Measurements was done at both low (0.47 kHz) and high (4.7 kHz) frequency susceptibilities which was further used to calculate the frequency dependent susceptibility (X_{FD}).

3. Results and Discussion

3.1. Results

3.1.1 Results of magnetic susceptibility and percentage frequency dependence of susceptibility for hydrocarbon contaminated soil samples

The mean magnetic susceptibility values for the hydrocarbon contaminated soil samples are shown in Tables1, 2 and 3. For Shell environment shown in Table 1, the mean values for low frequency magnetic susceptibility ranges from $54.3x10^{-8}$ m^3kg^{-1}– $180x10^{-8}$ m^3kg^{-1} with an average value of

117.54 $\times 10^{-8}$ m^{3}kg^{-1}, the values of high frequency magnetic susceptibility ranges from 46.6 $\times 10^{-8}$ m^{3}kg^{-1} – 176.7 $\times 10^{-8}$ m^{3}kg^{-1} with average value of 107.54 $\times 10^{-8}$ m^{3}kg^{-1} and the mean frequency dependent magnetic susceptibility ranges from 0.65% – 14.18% with average value of 8.70%.

The mean magnetic susceptibility values for Nigeria Liquefied Natural Gas environment (NLNG) are shown in Table 2. The mean values for low frequency mass magnetic susceptibility ranges from 10.5x10^{-8} – 40.5x10^{-8} m^{3}kg^{-1} with an average value of 20.83x10^{-8} m^{3}kg^{-1}, the mean values of high frequency magnetic susceptibility ranges from 9.6x10^{-8} – 39.3x10^{-8} m^{3}kg^{-1} with average value of 19.97x10^{-8} m^{3}kg^{-1} and the mean frequency dependent magnetic susceptibility ranges from 0.00 – 11.93% with an average value of 4.41%.

The mean magnetic susceptibility values for PHRC are shown in Table 3. The mean values for low frequency magnetic susceptibility range from 706.5x10^{-8} – 4891.1x10^{-8} m^{3}kg^{-1} with an average value of 2016.39x10^{-8} m^{3}kg^{-1}, the mean values of high frequency magnetic susceptibility range from 680.4x10^{-8} – 4240.x10^{-8} m^{3}kg^{-1} with average value of 1822.15x10^{-8}m^3 kg^{-1} and the mean frequency dependent mass magnetic susceptibility range from 2.66 – 13.29% with an average value of 7.25%.

Table 1**:** Results of mean Magnetic Susceptibility and mean Percentage Frequency Dependent Magnetic Susceptibility Obtained from Shell Environment (SE), Bonny Island

Sample depth(cm)	χ_{LF} x10^{-8}(m^{3}kg^1)	χ_{HF} x10^{-8}(m^{3}kg^{-1})	χ_{FD} (%)
0.0	180.9	176.7	2.32
10.0	140.5	133.6	4.91
20.0	135.9	117.9	13.25
30.0	115.9	104.2	10.09
40.0	150.5	130.2	13.49
50.0	54.3	46.6	14.18
60.0	86.5	79.6	7.98
70.0	61.1	57.0	6.71
80.0	92.0	91.4	0.65
90.0	108.4	94.8	12.55
100.0	166.9	150.9	9.59

Table 2: Results of mean Magnetic Susceptibility and mean Percentage Frequency Magnetic Susceptibility Obtained from Nigeria Liquefied Natural Gas (NLNG), Bonny Island.

Depth (cm)		χ_{LF} x10^{-8}(m^{3}kg^1)	χ_{HF} x10^{-8}(m^{3}kg^1)	χ_{FD} (%)
0.0	40.5		39.3	2.96
10.0	24.2		22.6	6.61
20.0	24.7		24.5	0.81
30.0	20.6		20.6	0.00
40.0	20.3		19.1	5.91
50.0	10.9		9.6	11.93
60.0	10.5		10.4	0.93
70.0	10.8		10.3	4.63
80.0	17.4		17.3	0.57
90.0	18.6		17.3	7.20
100.0	30.6		28.7	6.99

Table 3: Results of mean Magnetic Susceptibility and mean Percentage Frequency Dependent Magnetic Susceptibility Values Obtained from PHCR, Port Harcourt

Depth (cm)	$\chi_{LF} \times 10^{-8}$ (m^3kg^1)	$\chi_{HF} \times 10^{-8}$ (m^3kg^1)	χ_{FD} (%)
10.0	1849.3	1800.2	2.66
20.0	706.5	680.4	3.64
30.0	2240.9	2106.1	6.02
40.0	1825.2	1680.6	7.91
50.0	2325.2	2110.4	9.29
60.0	2306.8	2000.4	13.28
70.0	4891.1	4240.2	13.13
80.0	1026.0	980.6	4.42
90.0	1660.8	1462.4	11.95
100.0	1338.1	1160.2	13.29

3.1.2 Magnetic Susceptibility and Frequency Dependence of Magnetic Susceptibility for non Hydrocarbon Contaminated Soil Samples

The mean magnetic susceptibility values for non hydrocarbon soil samples (Control samples) are shown in Tables 4, 5 and 6. Results show that in James Hart (JH), the mean values for low frequency specific magnetic susceptibility (χ_{LF}) ranges from 1.3×10^{-8} m^3kg^{-1} – 3.6×10^{-8} m^3 kg^{-1} with an average value of 2.39×10^{-8} m^3 kg^{-1}, the mean values for high frequency specific magnetic susceptibility (χ_{HF}) ranges from 1.2×10^{-8} m^3 kg^{-1} – 3.2 $\times 10^{-8}$ m^3 kg^{-1} with average value of 2.21×10^{-8} m^3 kg^{-1} and the mean percentage frequency dependent magnetic susceptibility ($\chi_{FD\%}$) ranges from 0.00% – 12.12% with average value of 6.86%.

Table 4: Results of mean Magnetic Susceptibility Values and mean Percentage Frequency Dependent Magnetic Susceptibility Values Obtained from James Hart (JH), Bonny Island

Depth(cm)	χ_{LF}x10^{-8}(m^3kg^1)	χ_{HF}x10^{-8}(m^3kg^1)	χ_{FD}(%)
0.0.	2.3	2.3	0.00
10.0	2.6	2.6	0.00
20.0	3.3	2.9	12.12
30.0	2.6	2.3	11.54
40.0	3.6	3.2	11.11
50.0	1.3	1.2	7.69
60.0	1.3	1.2	7.69
70.0	2.1	2.0	4.76

Table 5: Results of mean Magnetic Susceptibility and mean Percentage Frequency Dependent Magnetic Susceptibility Values Obtained from New Jerusalem (NJ), Bonny Island

Depth (cm)	χ_{LF}x10^{-8}(m^3kg^1)	χ_{HF}x10^{-8}(m^3kg^1)	χ_{FD}(%)
0.0.	19.7	17.4	11.22
10.0	17.3	15.6	9.83
20.0	6.7	5.9	11.83
30.0	14.0	12.2	12.86
40.0	17.9	16.1	10.06
50.0	13.4	11.6	13.43
60.0	11.4	10.03	11.40
70.0	8.5	7.4	12.94
80.0	6.5	5.6	13.85
90.0	11.1	10.3	7.21
100.0	10.2	9.2	9.80

Table 6: Result of mean Magnetic Susceptibility and mean Frequency Dependent Susceptibility Values Obtained from Port Harcourt (PH).

Sample depth (cm)	χ_{LF} x10^{-8}(m^{3}kg^1)	χ_{HF} x10^{-8}(m^{3}kg^1)	χ_{FD}(%)
0.0	3.5	3.4	2.86
10.0	5.2	5.1	1.92
20.0	3.0	2.7	10.00
30.0	2.2	2.0	9.09
40.0	4.0	3.6	10.00
50.0	3.0	3.0	0.00
60.0	3.5	3.1	11.43
70.0	3.0	2.9	3.33
80.0	3.3	3.1	6.06
90.0	2.4	2.2	8.33

In New Jerusalem (NJ), χ_{LF} results (Table 7) obtained varied between 6.5 to 19.6 x10^{-8} m^3 kg^{-1} with mean value of of 12.42x10^{-8} m^3 kg^{-1}, the values of χ_{HF} varied between 5.6 to 17.4 x10^{-8} m^{3}kg^{-1} with mean value of 11.04x10^{-8} m^3 kg^{-1} and the $\chi_{FD\%}$ varied from 7.21 to 13.85% with mean value of 11.32%.

In Port Harcourt (PH), χ_{LF} results (Table 8) obtained varied between 2.2 to 5.2 x10^{-8} m^{3}kg^{-1} with mean value of of 3.31x10^{-8} m^3 kg^{-1}, the values of χ_{HF} varied between 2.0 to 5.1 x10^{-8} m^3 kg^{-1} with mean value of 3.11x10^{-8} m^3 kg^{-1} and the $\chi_{FD\%}$ varied from 0.00 to 13.85% with mean value of 6.30%.

3.2 Discussion

The results of magnetic susceptibility measurements for hydrocarbon contaminated soil samples showed that the low frequency magnetic susceptibility values (χ_{LF}) for Shell environment (SE), Nigeria liquefy Natural Gas (NLNG) and Port Harcourt Refining Company (PHRC) varied between 54.3x10^{-8} - 180.9 x10^{-8} m^{3}kg^{-1}, 10.5 x10^{-8} - 40.5 x10^{-8} m^{3}kg^{-1} and 706.5 x10^{-8} - 4891.1 x10^{-8} m^{3}kg^{-1} with average values of 117.54 x10^{-8} m^{3}kg^{-1}, 20.83 x10^{-8} m^{3}kg^{-1} and 2016.39 x10^{-8} m^{3}kg^{-1} respectively. In comparison to the magnetic susceptibility value of 128 x10^{-8}m^{3}kg^{-1} obtained in Hanzhou, China (Lu, and Bai, 2008), the average values of χ_{LF} obtained were lower in SE and NLNG and higher in PHRC, this could be because the hydrocarbon concentration in PHRC was higher than that in SE and NLNG. Gautam et al., (2004) classified soils into three broad categories as follows: normal ($\chi_{LF} < 10$ x10^{-8}m^{3}kg^{-1}, moderately magnetic ($\chi_{LF} = 10 – 100$ x10^{-8}m^{3}kg^{-1}) and highly magnetic ($\chi_{LF} > 100$ x 10^{-8}m^{3}kg^{-1}) . From his classification, the samples in SE and PHRC were highly magnetic and NLNG were moderately magnetic. The results of the magnetic susceptibility measurements for non hydrocarbon soil samples also showed that the low frequency magnetic susceptibility values (χ_{LF}) for James Hart (JH), New Jerusalem (NJ) and Port Harcourt (PH) varied between 1.3x10^{-8}-3.6x10^{-8} m^3 kg^{-1}, 6.5 x10^{-8}-19.6 x10^{-8} m^3 kg^{-1} and 2.2 x10^{-8}-5.2 x10^{-8} m^3 kg^{-1} with average values of 2.39 x10^{-8} m^3 kg^{-1}, 12.42 x10^{-8} m^3 kg^{-1} and 3.31 x10^{-8} m^3 kg^{-1} respectively. In comparison to the magnetic susceptibility value of 2.8 x10^{-8}-10.2 x10^{-8}m^{3}kg^{-1} obtained in Jalingo Mechanic Village profile, Nigeria (Kanu et al, 2013), the average value of χ_{LF} obtained was a little lower in JH and PH and a little higher in NJ. Also, from Gautam et al, (2004) classification, the samples in JH and PH are all normal while the samples in NJ were moderately magnetic. The low magnetic susceptibility values indicate low magnetic particles coming from urban and industrial dust or as a result of remediation of soil samples. The moderate magnetic susceptibility value could be due to injection of anthropogenic magnetic particles.

The disparities in the values obtained for the hydrocarbon and non hydrocarbon samples could not be due to local geology because about 91% mass specific magnetic susceptibility of the hydrocarbon soil samples were higher than those of the non hydrocarbon soil. In fact about 50% of

hydrocarbon samples were highly magnetic and 50% were moderately magnetic while 28% were moderately magnetic and 72% were normal for non hydrocarbon samples.

The entire hydrocarbon contaminated soil sample showed enhancement in the magnetic susceptibility values indicating a high concentration of ferrimagnetic minerals in the samples. In most cases, magnetic susceptibility shows the concentration and type of magnetic minerals (Blundell et al., 2009). The high concentration of magnetic minerals in the hydrocarbon contaminated samples could be because of the hydrocarbon deposit in the soil (which results either from lithogenesis or pedogenesis) or anthropogenic sources originating from human impact on the natural environment.

The results of percentage frequency dependence susceptibility ($\chi_{FD\%}$) may be used to depict the relative concentration of ultrafine super-paramagnetic (SP) grains. Large grains [Coarse Multi-Domain (MD) grains] are practically non-sensitive to change in the percentage frequency dependence of the applied field used and hence contribute significantly to depression of high frequency susceptibility. Therefore,

the closer $\chi_{FD\%}$ is to zero, the more MD assemblages are expected to dominate the sample. Generally, for MD grains $\chi_{FD\%}$ is < 2%, whilefor SP grains $\chi_{FD\%}$ lies in the range 10-12% and $\chi_{FD}\%$ values between 2-10% indicates a mixture of MD and SP grains (Dearing et al., 1999). Based on Dearing's classification, the results of the percentage frequency dependence susceptibility obtained in the hydrocarbon contaminated soil showed about 16% of the samples had $\chi_{FD}\%$ values between 0-2%, inferring an assemblage of MD grains. This showed that SP particles from pedogenic process were completely out of play from these samples. Also, 53% had values of χ_{FD} between 2-10%, indicating a mixture of MD and SP magnetic grains. Thirty-one-percent(31%) of the hydrocarbon contaminated soil had values between 10-12% and above, while about 58% of the non-hydrocarbon samples(control samples) shown in Tables 5, 6 and 7 have values of $\chi_{FD}\%$ between 2-10% indicating a mixture of MD and SP magnetic grains. About 21% of the samples have $\chi_{FD}\%$ values between 0-2%, indicating an assemblage of MD grains. This showed that SP particles from pedogenic process were completely out of play from these samples. Finally, 21% samples had values between10-12% and above, meaning that the

dominant magnetic component on the samples were SP grains.

It can be clearly seen from the results obtained that χ_{LF} had values higher than χ_{HF}. This is because at higher frequency, the relaxation time is shorter than the measurement time for super paramagnetic grains and their effect is insignificant. At lower frequency, the measurement time detects the susceptibility of all grains including those that have a short relaxation time. Also, the $\chi_{FD}\%$ for the non-hydrocarbon soil samples shown in Tables 4, 5 and 6 did not show any clear pattern with depth. While $\chi_{FD}\%$ for hydrocarbon contaminated soil shown in Table 1 showed an initial increase in $\chi_{FD}\%$ with depth up to 20 cm followed by a decrease and increase down. The values shown in Table 2 showed an increase in $\chi_{FD}\%$ up to 10 cm followed by a decrease and increase, also, the values in Table 3 for HCS showed an initial in $\chi_{FD}\%$ up to 70 cm followed by a rapid decrease and increase respectively.

In general, the percentage frequency dependence susceptibility ($\chi_{FD}\%$) of the hydrocarbon samples had 16% values between 0-2 % while the control samples had 21% of $\chi_{FD}\%$ values between 0-2%,

indicating more multi-domain grains in the control samples than in the hydrocarbon samples. Also, about 53% of the hydrocarbon soil sample (HCS) had $\chi_{FD}\%$ values between 2-10% while the control samples had 58% values between 2-10%, indicating more mixture of multi-domain (MD) and superfine paramagnetic (SP) grains in the control samples than in HCS. Finally, 31% of the hydrocarbon soil sample (HCS) had $\chi_{FD}\%$ values between 10-12 % and above while the control samples had 21% of $\chi_{FD}\%$ values between 10-12 and above, indicating more superfine paramagnetic (SP) grains in the hydrocarbon soil sample (HCS) than in the control samples.

4.0 Conclusion

In this research work, magnetic susceptibility of hydrocarbon and non hydrocarbon contaminated soil samples was carried out. Magnetic susceptibility and frequency dependent susceptibility were measured on 192 soil samples from hydrocarbon contaminated sites. Using simple percentage, the results show that about 91% of the magnetic susceptibility from hydrocarbon samples were higher than that the non hydrocarbon samples. Significant increase in magnetic

susceptibility values were observed in the hydrocarbon contaminated soil samples, indicating increased pollution in the hydrocarbon contaminated samples while most of the samples of the remediated soil were either normal or moderately magnetic.

So, based on the findings of this study, the Government is advised to monitor the location and activities of the oil companies and quick mop up strategies should be put in place in the eventuality of oil spillage.

5. References

Abam, T.K.S 2016. Engineering Geology of the Niger Delta. Journal of Earth Sciences and Geotechnical Engineering, vol.6, no. 3, 2016, 65-89

Aldana M., Costanzo-Alvarez V., Diaz M. 2003. Magnetic and mineralogical studies to characterize oil reservoirs in Venezuela. The Leading Edge. 22: 526-529.

Aldana, M., Costanzo-Alvarez, V., Gómez, L., González, C., Díaz, M., Silva, P., Rada, M. 2011. Identification of magnetic minerals related to hydrocarbon authigenesis in Venezuelan oil fields using an alternative decomposition of isothermal remanence curves. Stud. Geophys. Geod. 55: 343-358.

Blundell, A., Dearing, J.A., Boyle, J.F., Hannam, J.A. 2009. Controlling factors for the spatial variability of soil magnetic susceptibility across England and Wales. Earth-Science Reviews. 95: 158 – 188.

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. DOI: 10.5897/AJEST2015.2058

Dearing, J.A. 1999. Environmental Magnetic Susceptibility. Using theBartington MS2 System. Second edition, England: Chi Publishing. Pp 4-54.

Díaz M., Aldana M., Jiménez, S.M., Sequera, P., Costanzo-Alvarez, V. 2006. EPR and EOM studies in well samples from some Venezuelan oil fields: correlation with magnetic authigenesis. Física del Petróleo Revista Mexicana de Fisica. 52: 63-65.

Gautam, P., Blaha, U., Apple, E. 2004. Integration of Magnetic Properties and Heavy Metal Chemistry to Quantify Environmental Pollution in Urban Soils, Kathmandu, Nepal. Extended Abstract: 19th

Himalaya-Karakoram-Tibet Workshop, Niseko, Japan. Pp 33-41.

Guzmán, O., Costanzo-Álvarez, V., Aldana, M., Díaz, M. 2011. Study of magnetic contrasts applied to hydrocarbon exploration in the Maturín Sub-Basin (eastern Venezuela). Stud. Geophys. Geod. 55: 359-376.

Hanesh, M., Scholger, R. 2002. Correlation between magnetic susceptibility and polycyclic and aromatic hydrocarbons. Environ. Geol. 42: 857-870.

Ivakhnenko, O.P. 2012. Magnetic Susceptibility of Petroleum Reservoir Crude Oils in Petroleum Engineering, Crude Oil Exploration in the World, Prof. Mohamed Younes (Ed.), ISBN: 978-953-51-0379-0, InTech, Available from: http://www.intechopen.com/books/crude-oil-exploration-in-the-world/magneticsusceptibility-of-petroleum-reservoir-crude-oils-in-petrole.

Kanu, M.O., Meludu, O.C., Oniku, S.A. 2013. A Preliminary Assessment of Soil Pollution in Some Parts of Jalingo Metropolis, Nigeria Using Magnetic Susceptibility Method, Jordan Journal of Earth and Environmental Sciences. 5(2): 53-61

Liu, Q.S., Liu, Q.S., Chan, L.S., Yang, T., Xia, X.H., Tongjin, C. 2006. Magnetic enhancement caused by hydrocarbon migration in the Mawangmiao Oil Field, Jianghan Basin, China. J. Pet. Sci. Eng. 53: 25-33.

Lu, S.G., Bai, S.Q. 2008. Magnetic Characterization and Magnetic Mineralogy of the Hangzhou Urban Soils and its Environmental Implications. Chinese Journal of Geophys. 51(3): 549-557.

Martins, C.C., Mahiques, M.M., Bícego, M.C., Fukumoto, M.M., Montone, R.C., 2007. Comparison between anthropogenic hydrocarbons and magnetic susceptibility in sediment cores from the Santos Estuary, Brazil. Mar. Pollut. Bull. 54: 240-246.

Morris, W.A., Versteeg, J.K., Marvin, C.H., Mccarry, B.E., Rukavina, N.A. 1994. Preliminary comparisons between magnetic susceptibility and polycyclic aromatic hydrocarbon content in sediments from Hamilton Harbour, Western Lake Ontario. Sci. Tot. Environ. 152: 153-160.

Orosun, M.M., Oniku, A.S., Adie, P., Orosun, O.R., Salawu, N.B., Louis, H. (2020).Magnetic susceptibility measurement and heavy metal pollution at an automobile station in Ilorin, North-Central Nigeria,

Environ. Res. Commun. 2(2020): 015001. https://doi.org/10.1088/2515-7620/b636a

Orosun, M.M., Tchokossa, P., Lawal, T.O., Bello, S.A., Ige, S.O., Nwankwo L.I. 2016. Assessment of heavy metal pollution in drinking water due to mining and smelting activities in Ajaokuta", Nigerian Journal of Technological Development. 13: 30-38. http://dx.doi.org/10.4314/njtd.v13i1.6

Petrosky, E., Ellwood, B.B. 1999. Magnetic monitoring of Air, Land and Water pollution. In: Maher, B. A. and Thompson, R. (eds.) Quaternary Climates, Environments and Magnetism. UK: Cambridge University Press. pp. 279-319.

Robertson, D.J., Taylor, K.G., Hon, S.R. 2003. Geochemical and mineralogical magnetic characterization of urban sediment particulates, Manchester, UK. Applied Geochemistry. 18: 269-282.

Rijal, M.L., Appel, E., Petrovský, E., Blaha, U. 2010. Change of magnetic properties due to fluctuations of hydrocarbon contaminated groundwater in unconsolidated sediments. Environ. Pollut. 158: 1756-1762.

Reyment, R.A. 1965. Aspects of Geology of Nigeria University of Ibadan Press: Ibadan, Nigeria 52 – 54.

Short, K.C., Stauble, A.J. 1967. Outline of the Geology of the Niger Delta. AAPG Bulletin. 51: 761– 769.

Thompson, R., Oldfield, F. 1986. Environmental Magnetism, George Allen and Unwin. London. P227-229