Magnetic Susceptibility Analysis of Soil Affected by Hydrocarbon in Wonocolo Traditional Oil Field, Indonesia

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Abstract. Magnetic susceptibility of soil affected by hydrocarbon was studied through cored soil samples in two zones (Zone One and Zone Two) of an oil field in Wonocolo Village, East Java. We also collected soil samples as the background from a residential area near the oil field (Zone Three). The Zone One, consisted two cores near producing well; the Zone Two consisted two cores obtained from near a dry hole well and a discontinued well; and the Zone Three consisted two cores to validate the initial soil magnetic susceptibility value in this area. The hydrocarbon content measurement was also done for the upper part of each cores using distillation method to identify the correlation between magnetic susceptibility and hydrocarbon content. From magnetic susceptibility measurement in dual frequency, samples from the Zone One and Zone Two have magnetic susceptibility range from 6.1 x 10^{-8} m^3kg^{-1} - 160 x 10^{-8} m^3kg^{-1} and 15.7 x 10^{-8} m^3kg^{-1} - 417.9 x 10^{-8} m^3kg^{-1}, respectively. Whereas background samples from Zone Three have magnetic susceptibility range from 4.8 x 10^{-8} m^3kg^{-1} to 81.1 x 10^{-8} m^3kg^{-1}. We found low \( \chi_{fd} \) (%) in samples with high magnetic susceptibility values, shown that there was no indication of superparamagnetic minerals in the samples. The hydrocarbon content measurement shows the value range of 8\% - 14\% only exists in the upper part of all cores in Zone One and one core in Zone Two. From this analysis, we assume that other than the volume of the hydrocarbon content in soil, the period of petroleum hydrocarbon deposition in soil and the fossil fuel combustion generated in the study site could differently increase the soil magnetic susceptibility value in this area. Positive correlation between the two parameters hopefully could contribute to develop environmental magnetic methods for detecting oil spills in soil, especially to remediate former hydrocarbon exploration and production area.

1. Introduction
Magnetic methods have been used as one of hydrocarbon exploration surveys as several studies show the association of magnetic anomaly with the presence of hydrocarbon in subsurface [1]. In further research, many researchers use magnetic analysis on a smaller scale, such as on samples of sediment or even soil in certain size, known as rock magnetic method, to identify the magnetic characteristics of each sample. The study of rock magnetism for sediment affected by hydrocarbon confirms that there is a positive correlation between magnetic susceptibility anomaly with the presence of hydrocarbon from samples of sediments from core data in Barinas-Apure Basin, one of hydrocarbon exploitation area in Venezuela [2]. The magnetic susceptibility profile showed the positive correlation, that there were high magnetic susceptibility values measured in samples from the depth corresponding to the presence of reservoir from an oil-producing well.
Rock magnetic methods also contribute to detect and monitor contamination in soil or sediment from various contaminants, known as environmental magnetism [3]. The study of environmental magnetism in unconsolidated sediment affected by hydrocarbon was done in a former military site contaminated by petroleum hydrocarbon due to leak in oil storage tanks [4]. The results of this study show that there is also a positive correlation between high magnetic susceptibility value and the presence of hydrocarbon. Magnetic analysis of the samples indicates that hydrocarbon accumulation triggers geomicrobiological activity that forms magnetite in sediment with hydrocarbon fluctuation [4].

The purpose of this research is to determine the magnetic characteristic of soil in hydrocarbon exploitation area with petroleum hydrocarbon content due to oil exploitation and production activity. The magnetic characterization mainly focuses on magnetic susceptibility analysis. The result of the analysis is used to determine the type and grain size domination of magnetic minerals in samples and then used to analyze the cause of the presence of magnetic susceptibility anomaly value that measured on samples. For surface samples, the magnetic susceptibility values were then correlated with petroleum hydrocarbon concentration. The correlation found in this study would determine whether the use of magnetic parameters to detect hydrocarbon content in unconsolidated sediment is applicable for an early stage of soil remediation.

2. Research Methodology

2.1. Study Area
The study area is a traditional petroleum hydrocarbon exploitation area in Wonocolo Oil Field, Bojonegoro, Indonesia. The geological map shown in Figure 1 was mapped from field observation and drawn using ArcGIS with basemap from ESRI Topographical Map. Petroleum hydrocarbon contaminated the site due to the exploration and exploitation activity since late 1800 where the locals exploit petroleum hydrocarbon mechanically with traditional equipments to lift up fossil fuels from the subsurface. The area consists of an upper layer of Quaternary sediments namely Wonocolo Formation, while the reservoir is composed of Miocene and Pliocene sandstones deposited in Ledok Formation with 18% maximum porosity [5].

We obtained cored soil samples from three zones, namely Zone One, Zone Two and Zone Three. Zone One and Zone Two are located at the oil exploitation activity area. We also collected cored soil samples from the residential area or Zone Three near the oil field to be considered as background samples. The location of the residential area is about one kilometer from the oil field, and there is apparently no oil spills in the soil of this area.

2.2. Field Sampling
Soil samples were collected by manual core using hand drilling with one-inch sample diameter. In Zone One we obtained two cores consists of Core W1A and W1B. Core W1A was taken near an active oil well and oil distillation point. The location of core W1B was surrounded by oil wells and far from oil distillation point. Zone Two consists of core W2A and W2B, where the location of Core W2A was near a dry hole well and distillation point and Core W2B was taken near an inactive oil well that has been discontinued since June 2015. Zone Three consists of core W3A and W3B. Core W3A and W3B is apparently not influenced by petroleum hydrocarbon and unaffected by contamination since there is no oil exploitation activity nearby. The location of each core is also shown in Figure 1. The depths of each core are in the range of 45 to 65 cm. All cores were divided into five centimeters interval for magnetic susceptibility measurement. The samples are then put into sample holders to prevent any change in magnetic properties. Totally we have 63 single samples. For samples from 0-5 cm depth, we also measured hydrocarbon content to identify the correlation between magnetic susceptibility value and the oil content of soil on the upper part of the cores.
2.3. Sample Characterization Methods

2.3.1. Magnetic Susceptibility. Magnetic susceptibility were measured using Bartington Magnetic Susceptibility meter with sensor B (MS2B) that operates on two frequencies, 470 Hz and 4700 Hz. This instrument measured the bulk magnetic susceptibility and the value was normalized with the mass to obtain mass-specific magnetic susceptibility (\(\chi\)). Magnetic susceptibility measured at 470 Hz is known as \(\chi_{lf}\). The relative differences of the magnetic susceptibility value in two frequencies were calculated to obtain \(\chi_{fd}(\%)\) to identify the existence of superparamagnetic minerals. This value, along with \(\chi_{lf}\) was then used to analyze the domination of grain size and domain of the magnetic minerals in samples.

2.3.2. Hydrocarbon Content. Homogenized samples were put into a ten mL steel container for hydrocarbon content measurement. Retort Kit measured the oil and water content with distillation principle.

3. Results and Discussions

3.1. Magnetic Susceptibility

From magnetic susceptibility measurement, the samples have \(\chi_{lf}\) in the range of \(4.8 \times 10^{-8} \text{ m}^3\text{kg}^{-1} - 417.9 \times 10^{-8} \text{ m}^3\text{kg}^{-1}\). There are 45 samples that have \(\chi_{lf}\) greater than \(10 \times 10^{-8} \text{ m}^3\text{kg}^{-1}\). Based on [6], samples with \(\chi_{lf}\) values greater than \(10 \times 10^{-8} \text{ m}^3\text{kg}^{-1}\) were dominated by ferrimagnetic minerals. The \(\chi_{fd}(\%)\) values are in the range of 0-11.1 %.

Samples in Zone One have \(\chi_{lf}\) between \(8.4 \times 10^{-8} \text{ m}^3\text{kg}^{-1}\) and \(160 \times 10^{-8} \text{ m}^3\text{kg}^{-1}\) with \(\chi_{fd}(\%)\) ranges of 0% to 11.9%. Highest magnetic susceptibility value in this zone was found in upper part of core.
W1A. The fossil fuel combustion is thought to cause the high magnetic susceptibility value in this upper part of the core W1A. This process is defined as the contact between hydrocarbon and oxygen that could form multi-domain or pseudo single domain magnetic minerals [6]. The $\chi_{lf}$ values in W1A decreases over depth. Zone Two has magnetic susceptibility range of $15.7 \times 10^{-8}$ m$^3$kg$^{-1}$ to $417.9 \times 10^{-8}$ m$^3$kg$^{-1}$ and $\chi_{fd}$ (%) of 0% to 5.05%. Zone Three samples have range of magnetic susceptibility values from $4.8 \times 10^{-8}$ m$^3$kg$^{-1}$ to $81.1 \times 10^{-8}$ m$^3$kg$^{-1}$ with $\chi_{fd}$ (%) range from 1.59% to 10.13%. The magnetic susceptibility value differences of Zone Three and two other zones are thought to indicate that there are magnetic mineral differences between samples from those zones. Among all samples, the highest magnetic susceptibility value was found in core W2B at the depth of 25 to 30 cm.

![Figure 2. $\chi_{lf}$ from each core sample against depth](image)

We also measured the magnetic susceptibility of the petroleum hydrocarbon acquired from the study site. The magnetic susceptibility value of the petroleum hydrocarbon is $-0.4 \times 10^{-8}$ m$^3$kg$^{-1}$, indicates that it is diamagnetic. According to [7], the accumulation of the contaminant in soil triggers magnetic formation in soil, and the period of contaminant deposition could also affect the value of soil magnetic susceptibility. We assume that the difference of soil magnetic susceptibility values in W1A, W1B and W2B is because each site has different duration length of petroleum hydrocarbon deposition in soil.

The considerably high values of $\chi_{fd}$ (%) on samples were dominantly found in samples with low magnetic susceptibility value. According to [6] that condition can be described as weak samples because measurements of one sample in two frequencies show different value due to unstable state of magnetism in the sample. This finding indicates that all samples contained no magnetic minerals with the domination of superparamagnetic domain. It concludes that samples with high magnetic susceptibility values have the domination of either multi-domain or single domain magnetic grain size.

3.2 Hydrocarbon Content

The hydrocarbon content of six surface samples shows a wide variation. Core W1A contains the highest amount of hydrocarbon, reaching 14% of ten mL measured samples. Core W1B and W2B have hydrocarbon concentrations of 12% and 8%, respectively. Meanwhile core W2A has the hydrocarbon content of 0%, as well as core W3A and W3B.

There is a correlation between magnetic susceptibility and hydrocarbon content that concluded from values measured from surface core samples. Figure 3 shows the trend of $\chi_{lf}$ values and hydrocarbon concentration. Surface samples with hydrocarbon content such as from core W1A, W1B and W2B have higher $\chi_{lf}$ values than the $\chi_{lf}$ values of the background soils. Core W2A has high $\chi_{lf}$; however the hydrocarbon content is 0%. We assume that this anomaly was caused by fossil fuel combustion since the core was obtained near the oil distillation point.
4. Conclusions
From the result of magnetic susceptibility measurement with dual frequency, the $\chi_{lf}$ values of 45 samples out of 63 samples are categorized into ferrimagnetic because they have $\chi_{lf}$ values higher than $10 \times 10^{-8}$ m$^3$kg$^{-1}$. The samples acquired from Zone One and Zone Two, mainly samples from the upper parts of each core have higher magnetic susceptibility values than samples acquired from Zone Three that apparently show the initial soil magnetic susceptibility value of the study area. We found low $\chi_{fd}$ (%) in samples with high magnetic susceptibility values, shown that there was no indication of superparamagnetic minerals in the samples. We then conclude that samples with high magnetic susceptibility values have the domination of either multi-domain or single domain magnetic grain size. The hydrocarbon content measurement shows the value range of 8% - 14% only exists in the upper part of all cores in Zone One and one core in Zone Two. From this analysis, we assume that other than the volume of the hydrocarbon content in soil, the period of petroleum hydrocarbon deposition in soil and the fossil fuel combustion generated in the study site could differently increase the soil magnetic susceptibility value in this area. This correlation could be used to determine which treatment could be best to be applied for soil remediation in some former exploitation well site in this oil field.

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Figure 3. Measured $\chi_{lf}$ and oil concentration from surface samples