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The Effectiveness of Magnetic Methods in Delineating Soil Horizons: A Case Study of Volcanic Soil from Lembang, West Java

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Abstract. Rock magnetic methods are used widely in many studies ranging from environmental studies to exploration geophysics. The main advantages of these methods are their simplicity and non-destructiveness as well as their low cost. In this study, we test the effectiveness of rock magnetic methods in delineating soil horizons in highly magnetic volcanic soil. A soil outcrop in Lembang, West Java is used as a test bed. Samples were taken in duplicate at an interval of about 10 cm from the 3 meters outcrop. At the site, soil horizons are clearly defined based on their colorations and textures. A series of magnetic methods, in the form of bulk magnetic and frequency-dependent susceptibility measurements as well as measurement of anhysteretic remanent magnetization, were conducted on all samples. The results show that magnetic properties, especially bulk magnetic susceptibility correlate well with soil horizons. The three visually distinct horizons possess distinctive magnetic properties. The magnetic properties could even infer pedogenic changes in the third horizon, which visually homogeneous.

Keywords: Magnetic methods, soil horizons, West Java.
PACS: 91.25.F-

INTRODUCTION

Since the last decade, a number of soil studies have used rock magnetic techniques either as main or complementary methods. These studies cover a wide range of topics from soil contamination, climate change recorded in soil to soil pedogenesis [1-6]. Compared to other methods in soil analyses, magnetic methods are relatively inexpensive, fast, simple, reliable and non-destructive [7-8]. Magnetic properties of soils were derived from magnetic minerals inherited from parent materials as well as minerals developed during pedogenic processes. In case of volcanic soils, the parent materials are not necessarily local source rocks, but they might be volcanic ash or debris. Earlier studies [9-11] have shown that pedogenic processes produce fine grained magnetite (Fe_3O_4) and maghemite (γ-Fe_2O_3).

In this study, we test the effectiveness of rock magnetic methods in delineating soil horizons in a highly magnetic volcanic soil. The objective of this study is to correlate known soil horizons to specific indicators such as magnetic mineralogy and magnetic granulometry as well as to general magnetic parameter, such as bulk magnetic susceptibility.

SITE DESCRIPTIONS AND SAMPLING METHOD

The site from which soil samples were obtained is located in Bukit Tunggul Cinchona Plantation (6° 50′ 5.1948″ S; 107° 43′ 42.1148″ E, elevation 1499 masl) about 25 km to the northeast of Bandung, the capital-city of West Java Province. The nearest district is Lembang, which is about 15 km to the east of the plantation and is about 12 km to the north of Bandung.

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The area around Lembang is well known as one of the agricultural centers in the province due to its suitable micro-climate and fertile volcanic soils. Lembang lies in the slope of Mt. Tangkubanperahu, an active volcano, with a long history of eruption.

The soil samples were obtained from a soil-outcrop about 3 m in height. In the field, the soil horizons are identified and recognized visually based on colors changes and textural analysis (Figure 1). In general, the outcrop represents three distinct horizons that are controlled by volcanic activities as opposed to pedogenesis. The topmost layer or Horizon 1 (approximately 80 cm in thickness) is dominated by reddish organic horizon while the middle layer, Horizon 2, (approximately 65 cm thick) is a blackish block and ash-flow deposit. The third layer or Horizon 3 is brownish to reddish consolidated soil. Within the outcrop, samples for magnetic analyses were taken at interval of 10 cm, except in horizon 2 where they were taken at shorter interval of 5 cm. Samples are housed in cylindrical plastic holders that are 2.5 cm in diameter and 2.2 cm in height. In total, 32 samples were used in this study.

MAGNETIC METHODS

First, all samples were subjected to magnetic susceptibility measurement using a Bartington MS2 system (Bartington Instruments Ltd., Oxon, UK) with an MS2B sensor that would allow measurements at two different frequencies of 470 and 4700 Hz. The measured values are given as mass-specific magnetic susceptibilities at low frequency (χ_{LF}) as well as mass-specific magnetic susceptibilities at high frequency (χ_{HF}). The term bulk-magnetic susceptibility normally refers to χ_{LF} and approximates to the total concentration of Fe-bearing minerals in the samples. A measure of frequency-dependent susceptibility (FDS) termed $\chi_{FD\%}$ that approximates to the proportion of superparamagnetic (SP) ferrimagnetic minerals is also used in this study and is defined as

$$\chi_{FD\%} = 100\% \times \frac{(\chi_{LF} - \chi_{HF})}{\chi_{LF}} \qquad (1).$$

Samples were also subjected to anhsyteretic remanent magnetization by exposing them to the presence of slowly decaying alternating magnetic field with peak field of 70 mT and a steady biasing field of 0.05 mT. The procedure was carried out in a Molspin AF Demagnetizer (Molspin Ltd., Newcastle upon Tyne, UK). The acquired intensity was simply termed *ARM* and measured in a Minispin magnetometer (Molspin Ltd., Newcastle upon Tyne, UK). The ratio between *ARM* and the steady biasing field intensity of 0.05 mT is termed ARM susceptibility or χ_{ARM}. Both *ARM* and χ_{ARM} approximate to the concentration of ferromagnetic of stable single-domain (SSD) size.

Lastly, samples were also subject to isothermal remanent magnetization or IRM by exposing them to direct magnetic fields of 300 mT and 1 T, respectively. The acquired intensity at 300 mT was termed IRM_{300} while that at 1 T was termed saturation IRM or *SIRM*. Both were measured in a Minispin magnetometer. The ratio between IRM_{300} and *SIRM* is termed the *S-ratio*. If *S-ratio* approaches unity, then the predominant magnetic minerals in the samples are low-coercivity minerals, such as magnetite or maghemite. In contrast, if *S-ratio* is close to zero, then high-coercivity mineral such is hematite (α-Fe_2O_3) is the predominant magnetic mineral in the samples.

RESULTS AND DISCUSSION

Figure 1 show the soil profile along the profiles of magnetic parameters, χ_{LF}, *S-ratio*, $\chi_{FD\%}$, and the ratio of ARM/χ_{LF}. It shows that χ_{LF} values correspond to soil profiles. Horizon 2 is represented by relatively low values of χ_{LF} compared to that of Horizons 1 and 3. Within Horizon 3, χ_{LF} values increase with depth, but the trend reversed at the depth of 225 cm. The values of *S-ratio* in all samples are very close to unity indicating that magnetite is the predominant magnetic mineral. However, the reddish appearance of Horizons 1 and 3 infer that hematite and/or maghemite is also present in the samples. In all horizons, $\chi_{FD\%}$ varies rather irregularly. In some samples, the values of $\chi_{FD\%}$ are less than 2% indicating the absence of SP particles. For magnetite, SP particles are less than 30 nm in size. Representing the ratio of SSD over the total concentration of Fe-bearing minerals, values of ARM/χ_{LF} also vary in all horizons. Consistently low values of ARM/χ_{LF} at the depth of 210-250 cm in Horizon 3 infer that the presence of sub-horizon with distinct magnetic properties.

Since the predominant magnetic mineral in all samples is magnetite, plot similar to that of King *et al.* [12] could be reconstructed from data of χ_{LF} and χ_{ARM}. Such plot, inferring magnetic grain size distribution, is shown in Figure 2. It shows that in most samples, magnetite grain size varies between 0.2 to 1 μm, while that in remaining samples varies between 1 to 5 μm. Grain size does not vary greatly in samples of Horizons 1 and 2, but it varies considerably in Horizon 3. This supports the notion that there is a sub-horizon within Horizon 3.

Figure 3 is a scatter diagram of χ_{LF} versus $\chi_{FD\%}$ in similar fashion to that of Dearing [13]. Such diagram can be used to infer grain size, domain state as well as the possible source of minerals. Most samples fall in the non-specific area. As shown also by their $\chi_{FD\%}$ values in Figure 1, some samples have small amount of SP particles, while some others have sizable SP particles although their concentration is much less than that of enhanced soil or product of burning.

The volcanic soil of Lembang is as magnetic as the soils in other part of West Java reported earlier [5] but it is much weaker that the lateritic soil of Southeast Sulawesi [6]. The soil of Lembang, in general, also has relatively low value of $\chi_{FD\%}$ suggesting it is still in the early stage of pedogenesis. Later stage of pedogenesis is often accompanied by enhancement of SP grains in the soil.

Based on their magnetic properties, the three soil horizons shown in Figure 1 are assumed to have distinct source and forming mechanism. Within Horizon 1, profile of χ_{LF} that shows high value toward the upper part and low value in the lower part is very similar to the same profile observed in lateritic soil [6]. To certain extent, this represent magnetic enhancement as more Fe-bearing minerals were formed in the near surface. However, episodic changes of $\chi_{FD\%}$ suggest that this horizon were formed due to episodic translocation where soil forming materials were transported from areas of higher elevation. Horizon 2 represents zone of low magnetic concentration but sizable variation in SP content. As this horizon represents volcanic deposit, there is a possibility that it was formed in sequences of deposition instead of in one single deposition. In Horizon 3, variation in χ_{LF} value is not only due to variation in the concentration of magnetic minerals but is also affected but variation grain size. This horizon is clearly originated from weathering process of source rocks. The presence of nodules as well as the high concentration of multidomain (MD) grains infer that Horizon 3 is a mature or paleo-soil. Moreover, the presence of finer magnetic grains in Horizon 3 is indicative of weathering processes. Larger MD grains might weathered into smaller SD grains and then into finer SP grains. Nevertheless, SD grains are still predominant in this horizon. At depth of 245-255 cm, there is an indication of leaching process shown by decrease in SD and SP content. This might represent time of intense rain-fall. At depth of 244-275 cm, the weathering intensified and leaching continued as SD grains were reduced into SP grains.

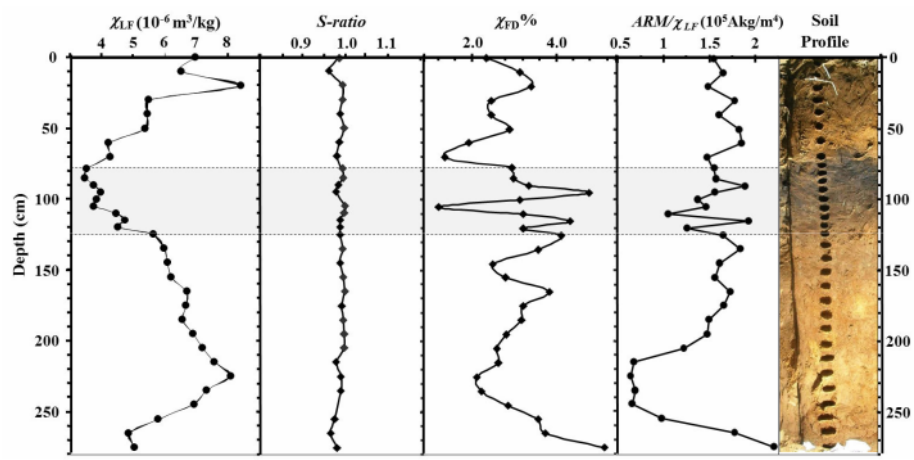

FIGURE 1. Soil profile from which samples were collected and profiles of selected magnetic parameters (χ_{LF}, *S-ratio*, $\chi_{FD\%}$, and the ratio of ARM/χ_{LF}. Values of χ_{LF} correlate well with soil horizons.

CONCLUSIONS

The following conclusions could be drawn from rock magnetic studies of volcanic soils from Lembang, West Java. First, rock magnetic methods have been shown to be effective in delineating soil horizons in a suite of volcanic soil. The bulk magnetic susceptibility, represented by χ_{LF} value, correlates well with the three soil horizons identified visually in the field. Second, the main magnetic mineral in the studied outcrop is magnetite of various sizes or domain states. Variation in grain sizes or in domain states (MD, SD, and SP), in turn, could be used to infer distinct sub-horizon(s), soil forming mechanism as well as the degree of pedogenesis.

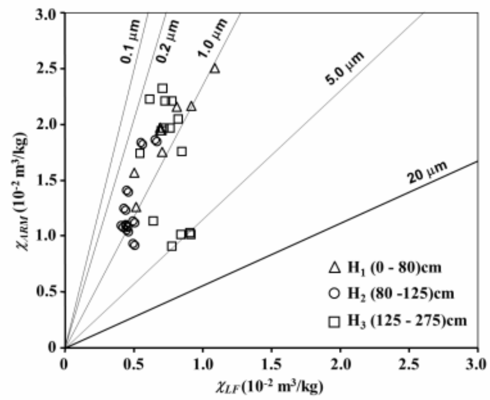

FIGURE 2. Plots of χ_{ARM} versus χ_{LF} for the three area in a profile of volcanic soil from Lembang. The guiding lines as prescribed by King *et al.* [12] for magnetite. Grain sizes in most samples vary from 0.2 to 1 μm.

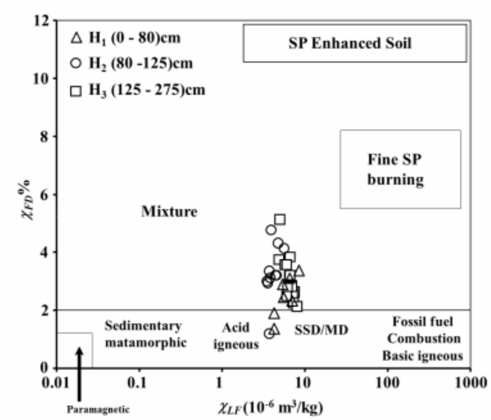

FIGURE 3. Plots of χ_{FD}% versus χ_{LF} and the guiding lines as prescribed by Dearing [13].

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