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# Rock Magnetic Methods in Soil and Environmental Studies: Fundamentals and Case Studies

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**Abstract**

*Rock magnetic methods have increasingly been applied in many fields of study as they are relatively easy, fast, non-destructive and affordable. We present some examples of such applications in soil and environmental studies that had been conducted at InstitutTeknologi Bandung by its faculty members and graduate students. After a brief introduction on fundamentals of rock magnetism, we described our study on lateritic soil from Pomalaa, which show that magnetic properties correlate well with soil horizons suggesting that magnetic methods could be used as additional tools in pedogenic studies. We also described our study in leachate sludge samples from two sites near Bandung showing that leachate sludge samples are reasonably magnetic and that correlation between magnetic parameters and heavy metal content might exist. Supported by other analyses, such as SEM and XRD, we were also able to identify the sources of magnetic grains in leachate sludge.*

## 1. INTRODUCTION

In general, rock magnetism is defined as a study of the magnetic properties of natural substances such as rocks, sediments, soils, and (lately) dusts and other fine particulates in the air. It started in 1950s as scientists working in the field of paleomagnetism and geomagnetism need to justify that the recorded magnetic remanences were indeed stable and originated during the formation of the rocks and sediments. Rock magnetism relies heavily of the study of magnetic materials, especially fine grained magnetism, as fine magnetic grains are better recorder of the Earth's magnetic field.

While its techniques and methodologies were still being used intensively in the field of paleomagnetism and geomagnetism, in 1980s rock magnetism found other applications in soil and environmental studies. The methods are attractive as they are fast, easy, non-destructive, and relatively inexpensive. The term environmental magnetism was introduced widely in 1986 through the publication of book with that title by Thompson and Oldfield (1986). Since then, environmental magnetism has grown rapidly and is often regarded as a distinct field of study. In contrast, the term soil magnetism has never been regarded as a distinct field of study but rather as an extension of either rock magnetism or environmental magnetism.

In recent years, the number of published papers related to the applications of rock magnetic methods in soil and environmental studies has grown steadily. In the last five years, more than 500 papers containing the term


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environmental magnetism (in their titles, abstracts, or keywords) have been published according to Scopus search engine (www.scopus.com, visited at September 7, 2012). The number of is much less for soil magnetism (185).
In this paper, we reviewed the fundamentals of rock magnetism as it used in soil and environmental studies. The review is complemented by examples of such studies conducted at InstitutTeknologi Bandung.

## 2. FUNDAMENTALS OF ROCK MAGNETISM

Magnetism in natural substances is associated with certain minerals that are often grouped into Fe-Ti oxides, iron sulfides, and iron-oxyhydroxides. These minerals occurs in almost every environment albeit their small quantities. The Fe-Ti oxides are often represented in ternary diagram with $TiO_2$, FeO, and $Fe_2O_3$ as end members (see Figure 1). The other minerals in this group are magnetite ($Fe_3O_4$), hematite ($\alpha$-$Fe_2O_3$), maghemite ($\gamma$-$Fe_2O_3$), and ilmenite ($FeTiO_3$). There are two solid solutions or intergrowths of different compositions of the end members, namely the titanomagnetite and the titanohematite series. Members of iron sulfides include pyrite ($FeS_2$), pyrrhotite ($Fe_7S_8$) and greigite ($Fe_3S_4$). The most common member of iron oxyhydroxides is goethite ($\alpha$-FeOOH). The presence and abundance of particular magnetic mineral represent particular condition or environment.
Each of the natural magnetic minerals has distinct magnetic properties, such as saturation remanence and coercivity. Magnetic minerals could also be identified by their temperature-dependence properties. For instance, magnetite, the strongest natural magnetic mineral with saturation remanence$J_s$ of 90-92 $Am^2$/kg, would lose its magnetic properties at 580°C but hematite, with $J_s$ of only 0.4 $Am^2$/kg s would lose its magnetic properties at 680°C. Such transition is termed Curie temperature. Magnetite would also experience changes in its magnetic properties at low temperature (known as Verwey transition at ~125K) as its structure undergoes phase transition from cubic to distorted-cubic spinel (see Maher, 2007). Hematite also has its own transition termed Morin transition at 242K as their spin orientation change from perpendicular to parallel to the *c* axis (see for instance Martín-Hernández and Ferré, 2007).
For each magnetic mineral, its magnetic behaviors are also controlled by the grain sizes and shapes. Grain sizes determine the configuration of magnetic domain; larger grains are multidomain (MD) while smaller grains are either single domain (SD) or pseudo-single domain (PSD). Finer grains, in contrast, tend to be superparamagnetic (SP). For mineral with high $J_s$, grain shapes could also affect its overall magnetic properties. In extreme cases, grains that are spherical in shape would have different magnetic properties compared to those that are elongated. This produces what is called magnetic anisotropy.
At sample level, the one parameter that is often used to represent bulk magnetic property of natural samples is the magnetic susceptibility. This parameter is easy to measure using various types of AC magnetic susceptibility meter. This parameter is also often measured in multi-frequencies leading to a new parameter termed FDS or frequency-dependent susceptibility. FDS is sensitive to detect the presence of SP grains.
In practice, rocks or sediments have magnetic minerals that are vary in mineralogy, concentration, grain sizes, and grains shape. Thus, identifications of concentration, mineralogy and granulometry (grain size and shape) are the main interest in rock magnetic studies. Apart from magnetic instrumentations, rock magnetists also use other instrumentations such as Mössbauer spectroscopy, scanning electron microscopy (SEM), and X-ray diffraction (XRD) to complement their studies.

## 3. CHANGES IN MAGNETIC PROPERTIES AND SOIL PEDOGENESIS

Rock magnetic methods have been used in soil studies for various purposes ranging from climate change to pollution studies. Driven by some studies that use magnetic parameters (mainly magnetic susceptibility) in identifying parent materials of soil as well as in soil taxonomy, the authors initiated a study to use magnetic properties as indicators of pedogenic process. Such magnetic properties are both lithogenic (*i.e.*, depend on magnetic minerals inherited from parent materials) as well as pedogenic (*i.e.*, depend on magnetic minerals developed during pedogenesis) in origin. Some studies show that pedogenesis produces fine grained magnetite and maghemite detectable by FDS.
One of the studies on soil magnetism conducted at InstitutTeknologi Bandung dealt with seeking any pattern of relationship between magnetic properties of laterite soil and its pedogenesis (Safiuddin*et al.*, 2011). The aforementioned study was also expected to demonstrate the role of pedogenesis in magnetic enhancement and in the transformation of magnetic minerals in lateritic soils. Laterite, a product of intensive weathering processes of parent rocks containing iron and aluminum hydroxides under humid tropical conditions (Banerjee, 1998; Mitchell and Soga, 2005), are common in some areas of Indonesia.
Supported by a mining company operating in Southeast Sulawesi (PT Aneka Tambang Tbk), the aforementioned study (Safiuddin*et al.*, 2011) took samples from six soil profiles (termed *R*, *S*, *T*, *U*, *V*, and *W*) in Pomalaa, Southeast

Sulawesi. To minimize the effects of factors, such as erosion and precipitation, the profiles, 1-2 m in length, were obtained from the top of the hills.

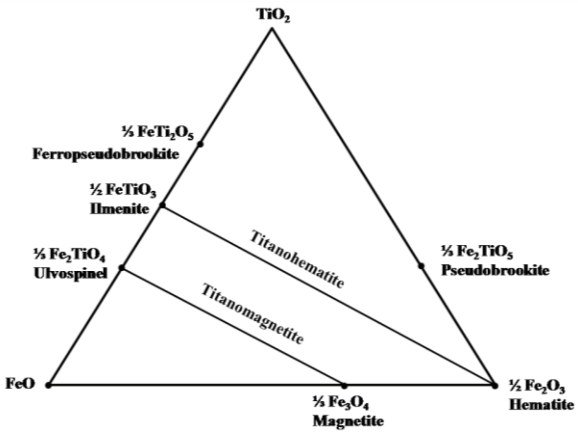


Figure 1.The ternary diagram for the Fe-Ti oxides.

Using XRD and a series of rock magnetic measurements, including measurement of temperature- dependent properties, Safiuddin*et al.* (2011) found that laterite contain magnetic minerals, such as magnetite, hematite, goethite and possibly maghemite. The presence of hematite and goethite was interpreted as an indication of advance pedogenic processes. The overall magnetic behavior, however, might be controlled by single and most magnetic mineral, i.e., magnetite. Safiuddin*et al.* (2011) also found that variation of magnetic parameters, notably the bulk low frequency magnetic susceptibility, $\chi_{LF}$ and the frequency-dependent susceptibility, $\chi_{FD}(\%)$, often correlate well with soil horizons.

Figure 2 below shows the variations of these two parameters with depth and soil horizons in profiles *R* and *S* (Safiuddin*et al.* (2011). The C horizon, which is zone of altered materials, has the lowest values of these two parameters. The values then increase considerably at the zone of illuviation (B horizon) and reach maximum at the zone of eluviation (A horizon). The values then decrease towards the organic horizon (O horizon). Based on these findings, Safiuddin*et al.* (2011) concluded that enrichment of SP grains is responsible for the variation of magnetic parameters in laterites.

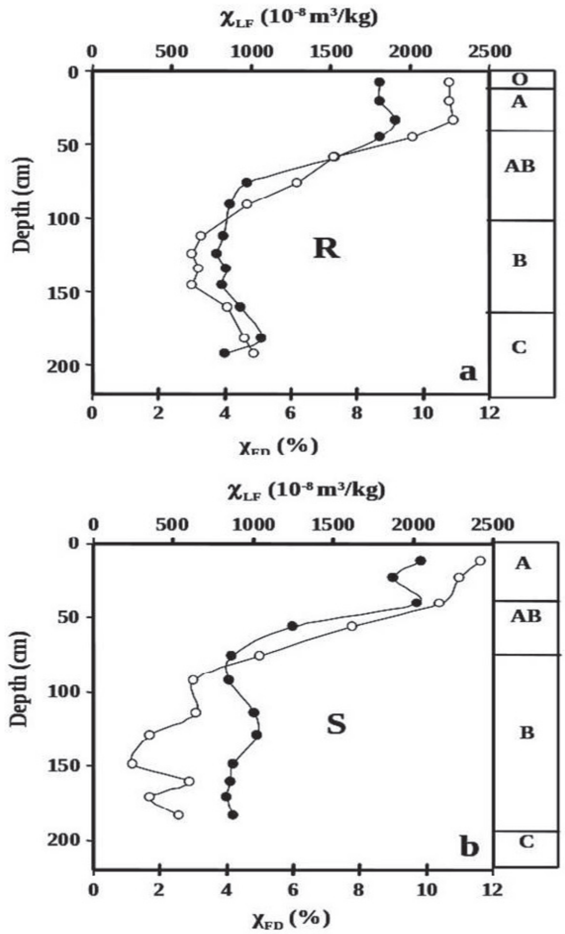


Figure 2.Variation of bulk low frequency magnetic susceptibility ($\chi_{LF}$) and the frequency-dependent susceptibility ($\chi_{FD}(\%)$) in selected profiles, *i.e.*, profile R (a) and S (b). (Modified from Safiuddin*et al.*, 2011).

## 4. MAGNETIC PROPERTIES AND HEAVY METAL CONTENT IN LEACHATE SLUDGE

The correlation of magnetic parameters and heavy metal content has been studied quite intensively in many forms of substance, ranging from natural substances such as lake sediments, soil and dust (see Yang *et al.*, 2007; Petrovský*et al.*, 2001; Hanesch and Scholger, 2002; Chapparo*et al.*, 2007; Ng *et al.*, 2003) to anthropogenic substances such as automobile emission particulates and fly ashes (for instance Lu *et al.*, 2005, Sharma and Tripathi, 2007). Following these leads, the scientist and graduate students at InstitutTeknologi Bandung set up to study such correlation in leachate sludge. To do this, they had to characterize the magnetic properties of leachate sludge and measure the heavy metal content.

They collected leachate sludge from leachate ponds in two municipal solid waste disposal sites near the city of Bandung. One of the sites, Jelekong, was in operation from 1991 to 2006 while the other one, Sarimukti, was opened only in 2006. They also collected soils from areas around the disposal sites. The leachate sludge and soil samples were then subjected to a series of rock magnetic measurements as well as XRD and SEM analyses. The results have been published in two different publications.

In the first publication, Bijaksana and Huliselan (2010) reported that the leachate samples from the two sites are considerably magnetic although their bulk magnetic susceptibilities are still lower than that of soil samples. Leachate samples from Jelekong were found to be more magnetic than that from Sarimukti. These differences are important as significant correlations were found between magnetic parameters and heavy metal content (notably Al, Mn, Fe, Co, Ni, Cu, Zn, Cd, and Hg) in leachate samples from Jelekong but not in those Sarimukti. Bijaksana and

Huliselan (2010) suggested that magnetic susceptibility can be used as a measurement for heavy metal content in leachate provided that it exceeds certain threshold value.

In the second publication, Huliselan*et al.* (2011) examined the origin of magnetic minerals in leachate sludge especially to understand why the magnetic properties of leachate sludge from Jelekong differ from their counterpart from Sarimukti. Using XRD, SEM and a series of magnetic analyses, Huliselan*et al.* (2011) found that the magnetic grains in leachate sludge samples from Jelekong are lithogenic in origin, while the grains from Sarimukti are anthropogenic in origin. These differences are clearly demonstrated in their shapes as observed in SEM images. Magnetic grains from Jelekong are octahedral and angular with fractured edges and corners (Figure 3a). In contrast, some grains from Sarimukti are imperfect spheres (Figure 3b). Huliselan*et al.* (2011) argued that some of these anthropogenic artifacts were originated by the practice of solid waste burning.

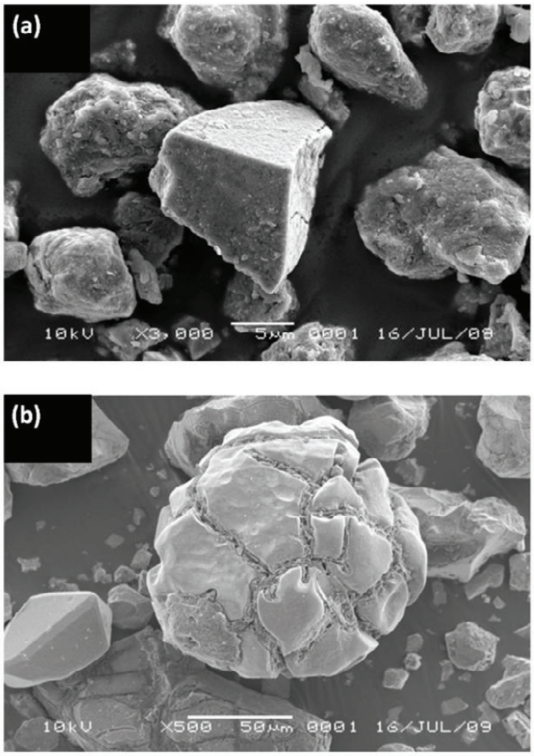


Figure 3. Typical SEM images of magnetic grains extracted from leachate sludge from Jelekong (a) and Sarimukti (b).(Modified from Huliselan*et al.*, 2010).

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