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A Preliminary Study of the Magnetic Properties on Laterite Soils as Indicators of Pedogenic Processes

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Abstract. Mineral magnetic properties of soils can be strongly influenced by soil-forming factors. In this study, six laterite soil profiles from three different sites from Pomalaa, Southeast Sulawesi were studied for their pedogenic and magnetic characteristics. The magnetic minerals observed by X-ray diffraction analyses on extracted grains are magnetite, hematite and goethite. Morin transition of hematite was observed in all samples during low temperature magnetic susceptibility measurements. Verwey transition of magnetite, however, is greatly suppressed presumably due to intense oxidation. The values of low-frequency magnetic susceptibility and frequency-dependent susceptibility varies with depth but controlled by the soil horizons confirming that the changes in magnetic properties are related to pedogenic processes. Changes in magnetic parameters are mainly controlled by enhancement of superparamagnetic particles. Similarity in magnetic behavior in profiles from the same site suggests that the magnetic properties are also controlled by the local condition of the site, such as the type of source rock. This study indicates that magnetic parameters can be useful for pedogenic analysis including in the highly magnetic laterite soils.

Keywords: *Tropical soils, frequency-dependent susceptibility, Sulawesi, Indonesia*

Resumen. Las propiedades magnéticas de los minerales de los suelos pueden ser fuertemente influenciadas por los factores formadores de los suelos. En este trabajo se estudiaron las características pedogenéticas y magnéticas de seis perfiles de suelos lateríticos pertenecientes a diferentes sitios de Pomalaa, Sureste de Sulawesi. Los minerales magnéticos observados en granos extraídos empleando difracción de rayos-x son: magnetita, hematita y goethita. La transición de Morin de la hematita fue observada en todas las muestras durante las mediciones de susceptibilidad a bajas temperaturas. La transición de Verwey de la magnetita se encuentra en gran medida suprimida, presumiblemente debido a una intensa oxidación. Los valores de susceptibilidad de baja frecuencia y los dependientes de la frecuencia varían con la profundidad y están controlados por los horizontes de suelos, confirmando que tales cambios en las propiedades magnéticas están controlados por procesos pedogenéticos. Los cambios en los parámetros magnéticos están también controlados y resaltados principalmente por partículas super-paramagnéticas. De igual forma, el comportamiento magnético en perfiles de un mismo sitio, sugiere que las propiedades magnéticas son en gran medida dependientes de las condiciones locales del sitio, tales como el tipo particular de roca madre. Este estudio indica que los parámetros magnéticos pueden ser herramientas útiles en el análisis pedogenético, incluyendo los suelos lateríticos altamente magnéticoss.

Palabras Clave: *Suelos tropicales, susceptibilidad dependiente de frecuencia, Sulawesi, Indonesia*

1 Introduction

In recent years, magnetic methods have been increasingly applied in soil studies ranging from the studies of contamination or pollution in soils (Kapička *et al.*, 2001; Petrovský *et al.*, 2001; Hanesch and Scholger, 2002; Jordanova *et al.*, 2003; Sharma and Tripathi, 2008; Bijaksana and Huliselan, 2010) to estimating proxies for climate changes in loess and paleosol sequences (Heller and Evans, 1995; Maher *et al.*, 2003). The most common magnetic parameter used in soil studies is magnetic susceptibility as its reliable, simple, rapid, inexpensive and non destructive technique that can be used to characterize soils and sediments (Thompson and Oldfield, 1986; Dearing *et al*., 1997; Dekkers, 1997). In some studies, soil-forming processes and profile development were characterized by changes in magnetic susceptibility (Singer *et al*., 1996; Torrent *et al.*, 2007; Lu *et al*., 2008; Van Dam *et al*., 2008). Magnetic susceptibility was also used to identify the lithology of parent materials, to measure the quantity of magnetic minerals in soils, as well as to serve as a tool in soil taxonomy (Maher *et al*., 2003; Torrent *et al*., 2007; Lu *et al.*, 2008; Lu, 2000).

Magnetic properties in soils depend not only on minerals inherited from parent materials (known as lithogenic factors), but also minerals developed during pedogenic processes. Following Evans and Heller (2003), there are four interactive pedogenic processes that produce minerals responsible for vertical differentiation of magnetic properties in soil profiles, *i.e*., hydrolysis, oxidation, hydration, and dissolution. Other studies (Liu *et al*., 1992; Maher and Thompson, 1992; Jeleńska *et al*., 2008) show that pedogenic processes produce fine grained magnetite (Fe_3O_4) and maghemite (γ-Fe_2O_3).

Laterite is the result of intensive weathering processes of parent rocks containing iron and aluminum hydroxides under humid tropical conditions (Banerjee, 1998; Mitchell and Soga, 2005). Like in other types of soil, processes in laterite formation might affect its magnetic properties. For instance, chemical weathering might affect magnetic mineralogy while physical weathering might affect the granulometry as well as the overall quantity of magnetic minerals. The primary objective of this preliminary study is to seek out any pattern of relationship between magnetic properties of laterite soil and its pedogenesis. Moreover, it is also expected to demonstrate the role of pedogenesis in magnetic enhancement and in the transformation of magnetic minerals in soils.

2 Site Descriptions and Sampling Method

Soil samples were obtained from an area near Pomalaa that is located in the southeast arm of the island of Sulawesi (see Fig.1). Geologically, the area is located in an ultramafic complex (Simandjuntak *et al.*,

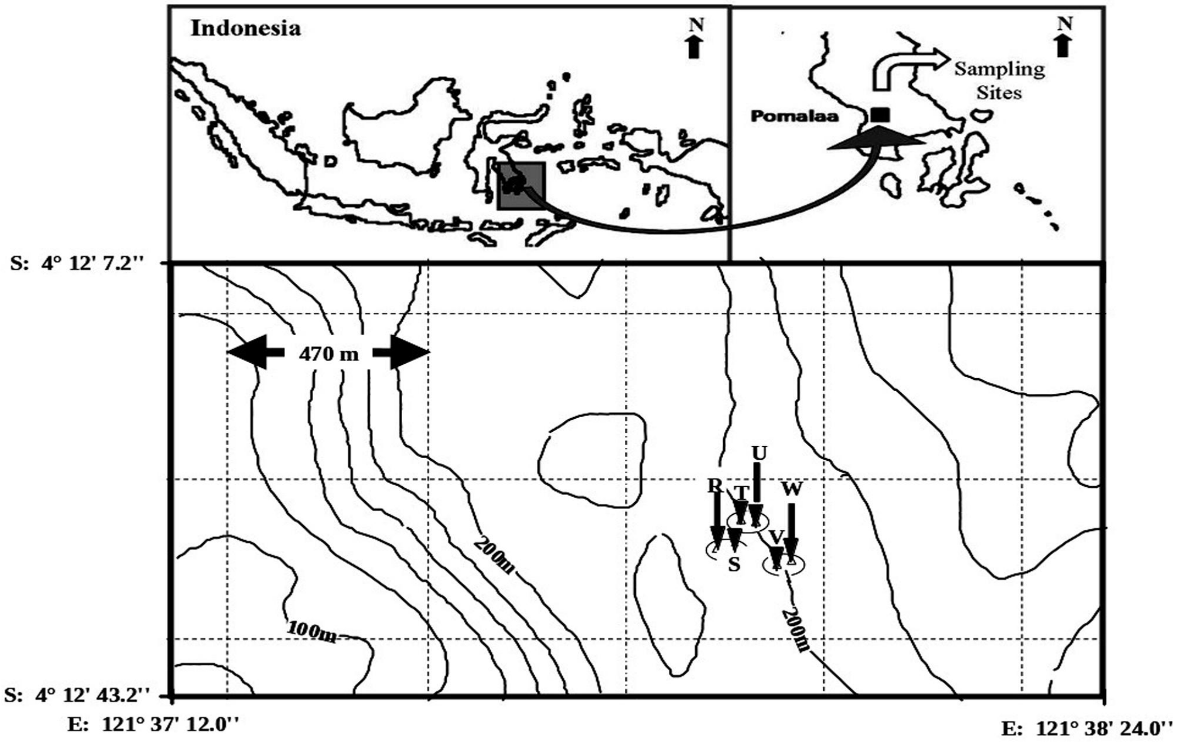


Figure 1. Map of the sampling site in Pomalaa, South Sulawesi, Indonesia.

1994) consisted of harzburgite, dunite, wherlite, serpentinite, gabbro, basalt, dolerite, metamafic, amphibolites, magnesise and in places rodingite (Simandjuntak *et al.*, 1994). Some rocks, such as harzburgite, dunite, and wherlite, are dominated by olivine, while some others, such as gabbro and dolerite are dominated by plagioclase (Simandjuntak *et al.*, 1994). To the north of the area there is the Pampangeo metamorphic complex. Laterite soils could be derived from both ultramafic and metamorphic rocks.

The samples were taken from six soil outcrops in three different sites (site I to site III). Two profiles separated about 50 m from each other, were taken from each site. Profiles R and S were obtained from site I, while the profiles T and U were obtained from site II. The last two profiles, V and W were obtained from site III. The sites were carefully selected based on the clear appearance of soils horizon as well as on their relative position and height. The sites are located in top of the hills (about 200 m above sea level) to minimize the influence of external factors such as erosion and precipitation that could affect soil formation or soil evolution. The geographic and the maximum depth of sampling for all profiles are listed in Table. 1

Site	Position	Profile ID	Maximum depth of sampling (cm)
I	S: 04 12′ 31.12″; E: 121 37′ 54.36″	R	193
	S: 04 12′ 30.82″; E: 121 37′ 55.52″	S	184
II	S: 04 12′ 29.08″; E: 121 37′ 56.04″	T	100
	S: 04 12′ 29.20″; E: 121 37′ 57.28″	U	96
III	S: 04 12′ 32.03″; E: 121 37′ 59.72″	V	90
	S: 04 12′ 32.34″; E: 121 37′ 58.92″	W	98

Table 1 Description of sampling sites

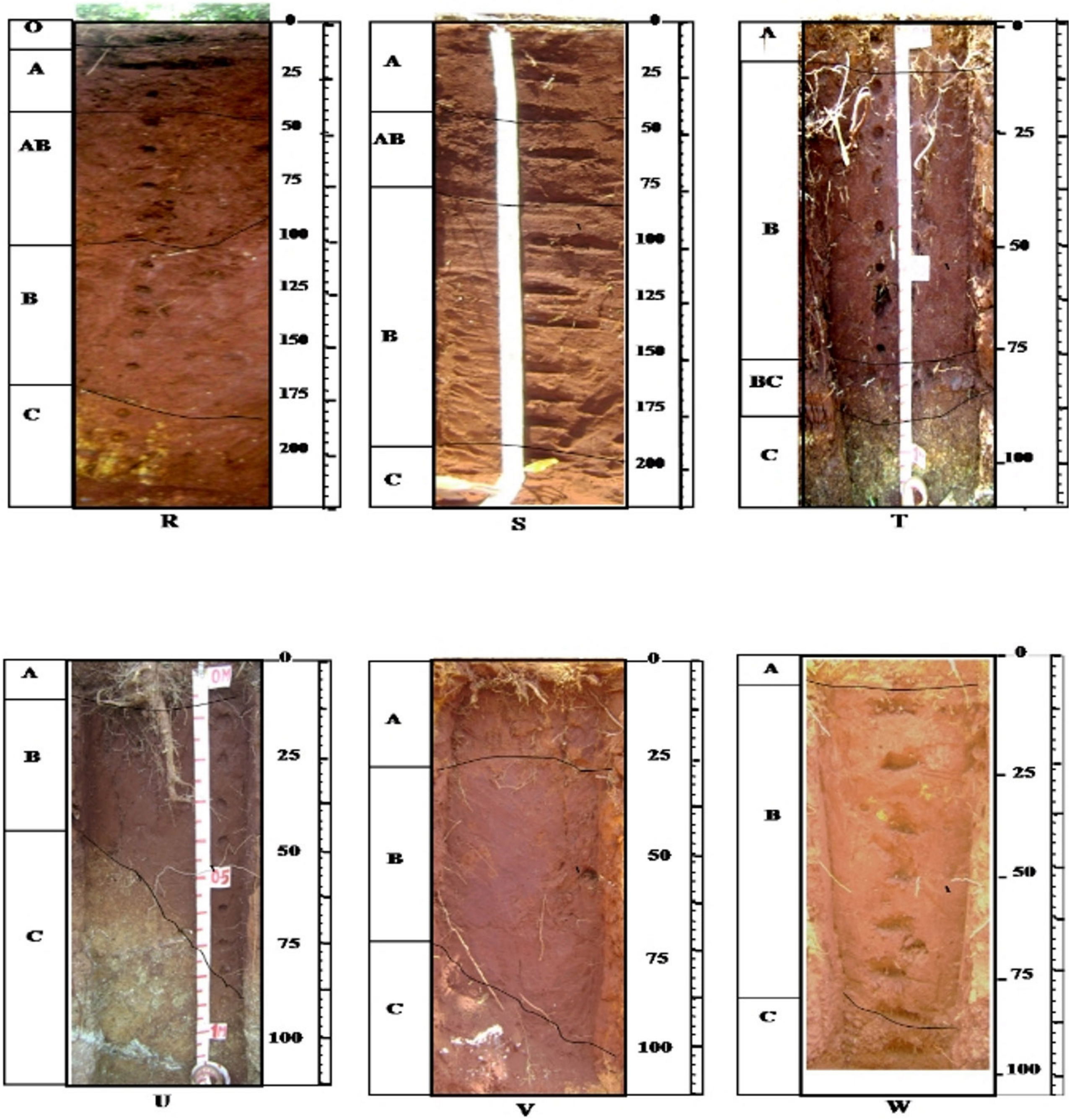


Figure 2. Six soil profiles of this study along with their depth and respective horizons based on system described by Mitchell and Soga (2005). Depth scales next to the profiles are in cm.

In the field, the soil horizons are identified and recognized visually based on colors changes and textural analysis (*i.e.*, consistency and the strength) from the soil surface to the parent material through the soil profile. The horizons were delineated based on the systems described by Mitchell and Soga (2005). Organic horizons (horizon O) are present in some but not all profiles (see Fig.2). Most profiles are dominated by the A and B horizons and in some profiles the C horizon is also observed. The A and B horizons are respectively the zones of eluviation and illuviation. The C horizon is the zone of altered materials from which A and B horizons are formed (Mitchell and Soga, 2005). Physically, the upper horizons in all profiles are observed to have fine granular structures. The structures change from slightly hard and friable at the top horizons to firm and sticky toward the bottom ones. The thickness as well as the variations of soil horizons suggests extensive weathering processes. Within a particular profile, samples for magnetic analyses were taken at interval of 10 to 15 cm. Samples were numbered top down, so for example, out of 14 samples from profile R, R-1 is the topmost sample and R-14 is the lowest sample in the profile. In total, 69 samples were obtained and analyzed in this study.

3 Methods

Several basic rock magnetic methods were employed in this study. The first method is measurement of mass-specific magnetic susceptibility (χ). All samples, place in standard cylindrical holders, were measured for χ at two different frequencies, 0.47 kHz for low frequency magnetic susceptibility (χ_{LF}) and 4.7 kHz for high frequency magnetic susceptibility (χ_{HF}) using a Bartington MS2 susceptibility meter with MS2B dual frequency sensor (Bartington Instrument Ltd., Oxford, United Kingdom). The measurements were conducted at the 1.0 range setting. Each sample was measured five times to get the average value, with an air reading before and after each series for correction of drift. The ratio, expressed as frequency-dependent susceptibility, is defined as $\chi_{FD}(\%) = 100\% \times (\chi_{LF} - \chi_{HF})/\chi_{LF}$.

The second method, measurement of ARM (anhysteretic remanent magnetization) was conducted on selected samples by exposing the samples under a peak alternating magnetic field of 80 mT with a constant field of 0.05 mT. ARM was given to the samples following demagnetization by AF (alternating field) demagnetizer in a Molspin AF Demagnetizer (Molspin Ltd., Newcastle upon Tyne, United Kingdom). After ARM was imparted, it was measured using a JR6A spinner magnetometer (AGICO, Brno, Czech Republic). The value of *ARM* in this study refers to the intensity of measured ARM.

The third method of this study is the measurement of magnetic hysteresis curve as well as the determination of the four hysteresis parameters (saturation magnetization, M_s, saturation remanence M_{rs}, coercive force H_c, and coercivity of remanence, H_{cr}). This method was conducted on all samples from the longest profile (profile R) and selected samples for the remaining profiles. The measurements were made using the 1.2H/CF/HT vibrating sample magnetometer (Oxford Instruments, Oxfordshire, United Kingdom).

The fourth method of this study is the measurement of temperature-dependent susceptibility by measuring the susceptibility of all samples at low temperatures. Small quantity of samples was air dried and then placed in a special container filled with liquid nitrogen. The container was placed inside an MS2W sensor connected to an MS2 susceptibility meter. Magnetic susceptibility was measured at certain time interval as the temperature of the sample increases from approximately 77 K to room temperature. Profiles of temperature as a function of temperatures would be useful in identifying magnetic minerals as well as distribution of grain sizes.

The above rock magnetic methods were also complemented by X-ray diffraction (XRD) analyses on magnetic grains extracted from several samples. Magnetic grains were extracted by mixing 3 to 4 gram of sample with 200 ml of ethanol. The mixture was stirred until it turned into slurry. Magnetic grains were then extracted using a strong neodymium magnet wrapped in a layer of thin plastic sheet. The extracted magnetic grains were then collected by removing the thin plastic sheet from the magnet and placed them into a Petri dish. The process was repeated until no more magnetic particles adhered to the magnet. The collected magnetic particles were then used in X-ray diffraction analysis performed on a Shimadzu XRD-7000 Maxima-X with CuKα target.

4 Results and Discussion

Figure 3 show the diffractograms for extracted magnetic grains from three different samples (*i.e.*, sample R-3 representing profiles R and S, sample T-4 representing profile T and U, and sample W-4 representing profile V and W). All three diffractograms show the peaks for magnetite, hematite (α-Fe_2O_3), and goethite (FeOOH). Maghemite (γ-Fe_2O_3) might also occur in the extracted grains, but its peaks were not easily picked up in the rather noisy diffractograms. Peaks of maghemite are very close to those of magnetite (see Cui *et al.*, 1994). The presence of hematite and goethite in the samples explains why the soils are reddish to brown in color. The presence of hematite in our samples implies that the pedogenic processes in lateritic soils are not only marked by fine grain or oxidized magnetite. This also confirms the claim of Torrent *et al*. (2006) that magnetic enhancement in aerobic soils is marked by the presence of hematite. It also implies that the lateritic soil samples in this study had experienced advance pedogenic processes. However, due to their low values of magnetic susceptibility, the presence of hematite and goethite would not affect the bulk magnetic susceptibility of our samples.

Although the soil samples contain more than one kind of magnetic minerals, their overall magnetic

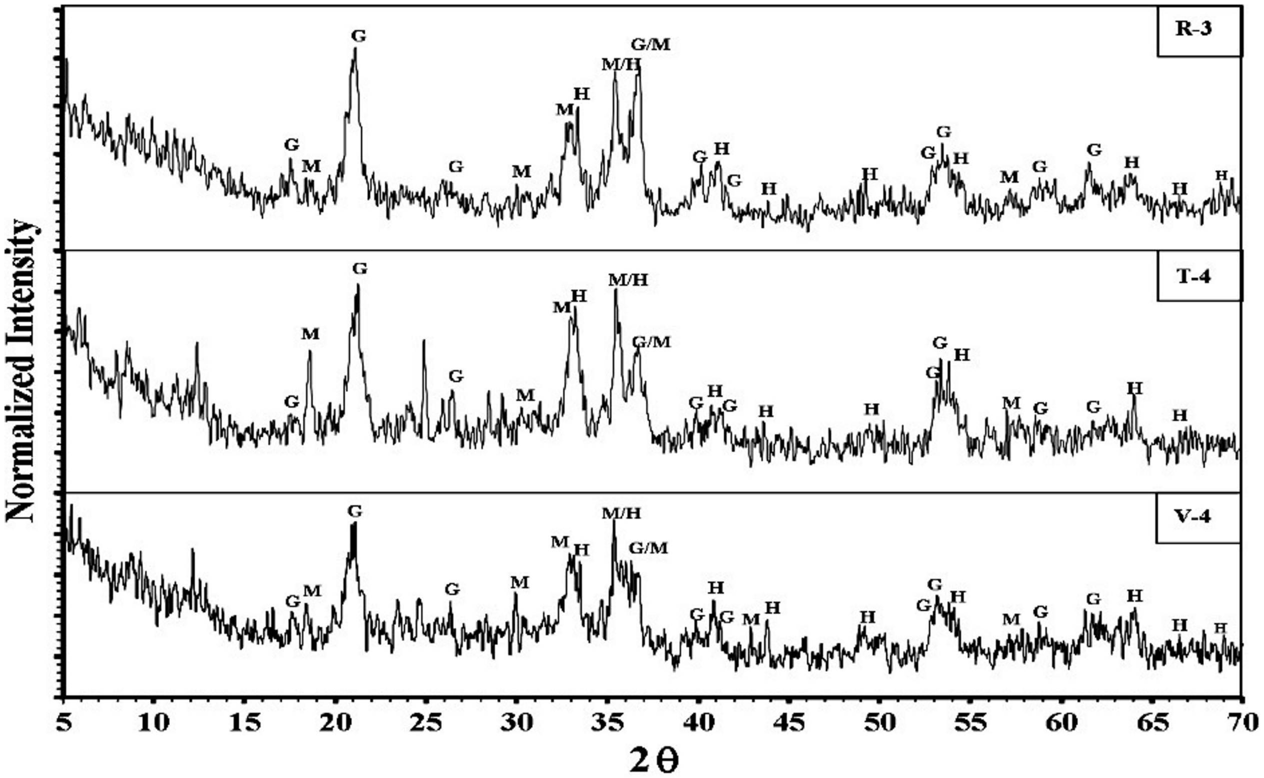


Figure 3. Diffractograms of selected samples (R-3, T-4, and V-4) showing the peaks of magnetite (M), hematite (H), and goethite (G)

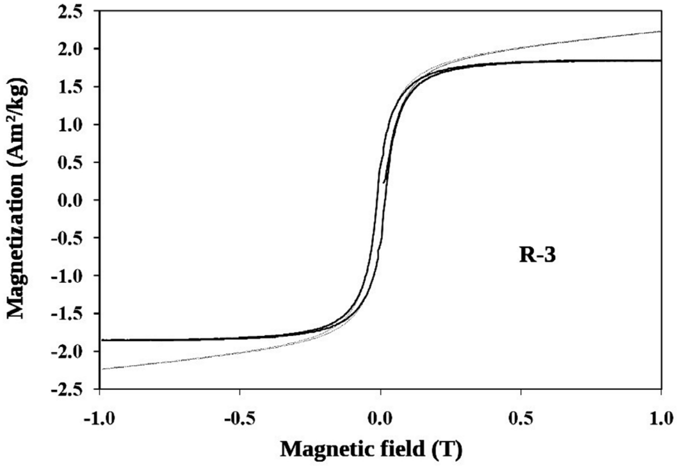
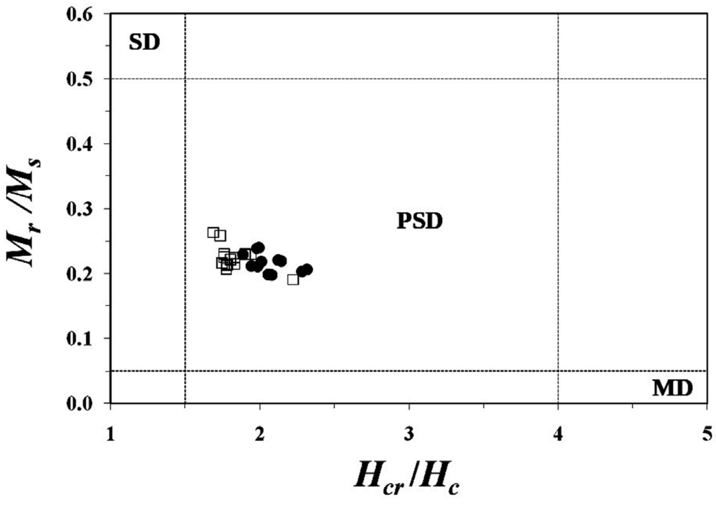


Figure 4. Magnetic hysteresis loops for typical sample (R-3) before (dashed lines) and after (solid lines) correction for the paramagnetic contribution.

properties might be controlled by a single predominant mineral. Measurements of hysteresis curve show that magnetite is the predominant magnetic mineral in the soil samples. As shown in Figure 4, the magnetic remanence saturates in the ambient field of less than 0.3T indicating the predominant contribution of low coercivity ferromagnetic minerals, such as magnetite. Moreover, plots of M_{rs}/M_s versus H_{cr}/H_c in a way described by Day *et al.* (1977) suggest that the domain state of the magnetite is pseudo-single domain (PSD) (see Fig. 5).

The presence of hematite in our samples was also confirmed by the measurement of susceptibility as a function of temperature. Figure 6 show the curves of normalized susceptibility versus temperature for representative samples. In general, samples from the sites show almost similar curves. Sample R-5 represents samples in profiles R and S, while sample T-8 represents samples in profiles T and U. All three samples show a sharp change in normalized magnetic susceptibility at temperature of about 257K. Simple transition such as that in sample V-4 is similar to that of Morin transition (De Boer *et al*., 2001) inferring the presence of hematite. The transition in samples R-5 and T-8, however, is more complicated as the Morin transition is preceded by a decrease in normalized susceptibility. Although instrumental artifact could not be ruled out, such behavior might also arise from unknown transition or from the fact that Morin transition is sensitive to impurities (Kosterov, 2007). Despite the obvious presence of magnetite in the samples, its

Figure 5. Plots of Mr/Ms versus Hcr/Hc in a way described by Day et al. (1977) for all samples from profile R (hollow squares) and selected samples from the other five profiles (solid circles).



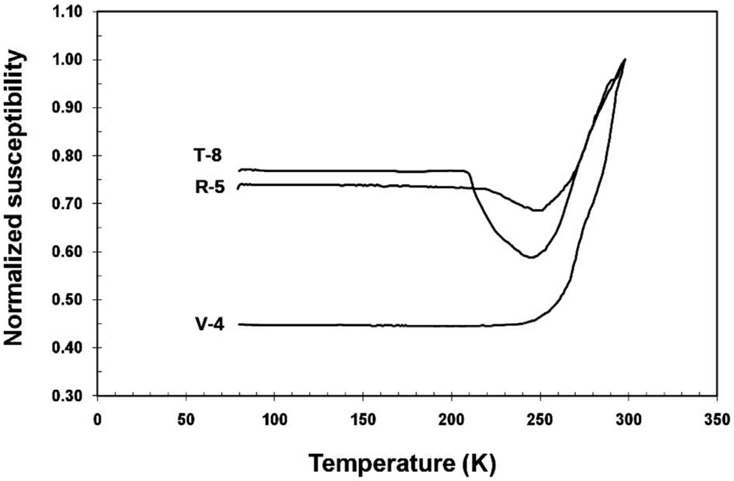


Figure 6. Curves of low temperature normalized magnetic susceptibility for selected samples (R-5, T-8, and V-4) showing transition of magnetic susceptibility.

Verwey transition is greatly suppressed. Such suppression of Verwey transition could be due to oxidation or maghemitization (see Özdemir *et al.*, 1993).

Figure 7 show the variations χ_{LF} and χ_{FD}(%) in the six soil profiles. The values of χ_{LF} of these soils varied greatly, ranging from the minimum value of 790.3×10^{-8} m^3/kg in profiles R to the maximum value of 8054×10^{-8} m^3/kg in profiles W. These values are greater than that of chernozem soil from Ukraine and Poland (Jeleńska *et al*., 2008) or that of basalt-derived soil from China (Lu *et al*., 2008). Compared to that of other profiles, profiles R and S have lower values of χ_{LF}. However, the value of χ_{FD}(%) varies greatly in profiles R and S, but such variation is much smaller in the other profiles. The bottom parts of profiles R and S show smaller values of χ_{FD}(%) indicating insignificant amount of SP (super paramagnetic) particles. The values of χ_{FD}(%) increase towards the upper part of the profiles implying greater contribution of SP particles. Increase in χ_{FD}(%) towards the upper part is also observed in profile U, but it was negligible in the remaining three profiles (T, V, and W). Along with the higher values of χ_{LF}, the higher values of χ_{FD}(%) in the upper parts of profiles R, S, and U represent magnetic enhancement that is likely due to the increase of SP particles. Such trend is also observed in soil samples of other studies (Jeleńska *et al*., 2008). Figure 8 shows the χ_{LF} and χ_{FD}(%) variations along the two longest profiles, i.e., profiles R and S. Graphs of Figures 8.a and 8.b are similar to graphs of Figures. 7.a and 7.b, except that the scale of χ_{LF} has been adjusted. As shown in Figure 8, there is correlation between the values of χ_{LF} and χ_{FD}(%) and the marked horizons. The A horizon is generally linked to high values of both χ_{LF} and χ_{FD}(%), while the B horizon is linked with lower values of χ_{LF} and χ_{FD}(%). The transition from high values χ_{LF} and χ_{FD}(%) to low values of χ_{LF} and χ_{FD}(%) occurs in the AB horizon and also at the B horizon in some sites.

The values of χ_{LF} and χ_{FD}(%) could also be plotted differently as scattergram in Figure 9. The boxes and labels in the scattergram are obtained from Dearing (1999). The plots show that some samples from the bottom of profiles R and S are closer SSD/MD (stable single domain grain/multidomain grain) region. The plots show trend towards enrichment of SP particles to the area marked by Dearing (1999) as SP enhanced soil. Thus in term of grain sizes, during pedogenic process, there are grain size reduction of SSD/MD particles toward SP particles.

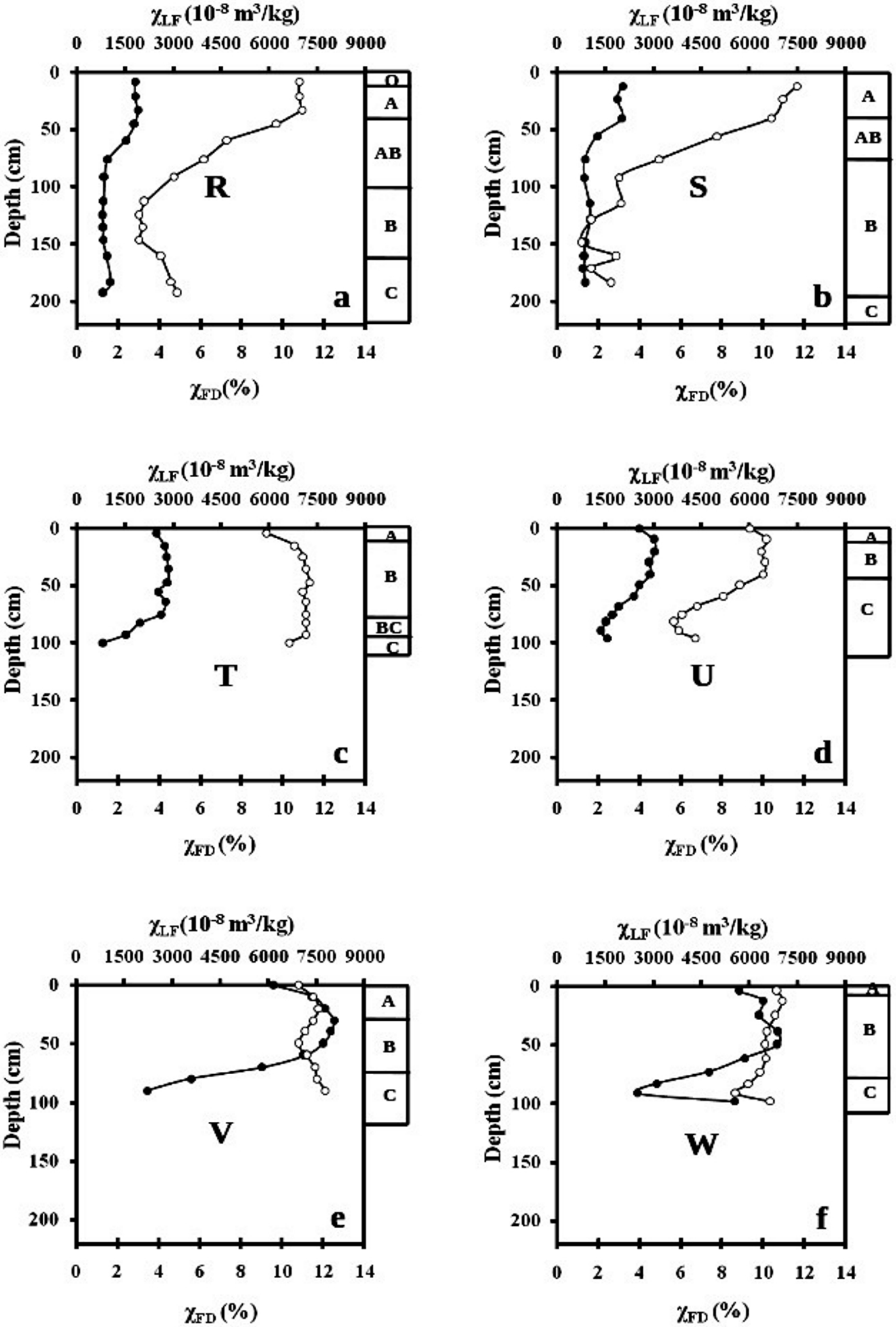


Figure 7. Variation of χLF (solid circles) and χFD(%) (hollow circles) in profiles R (a), S (b), T (c), U (d), V (e) and W (f).

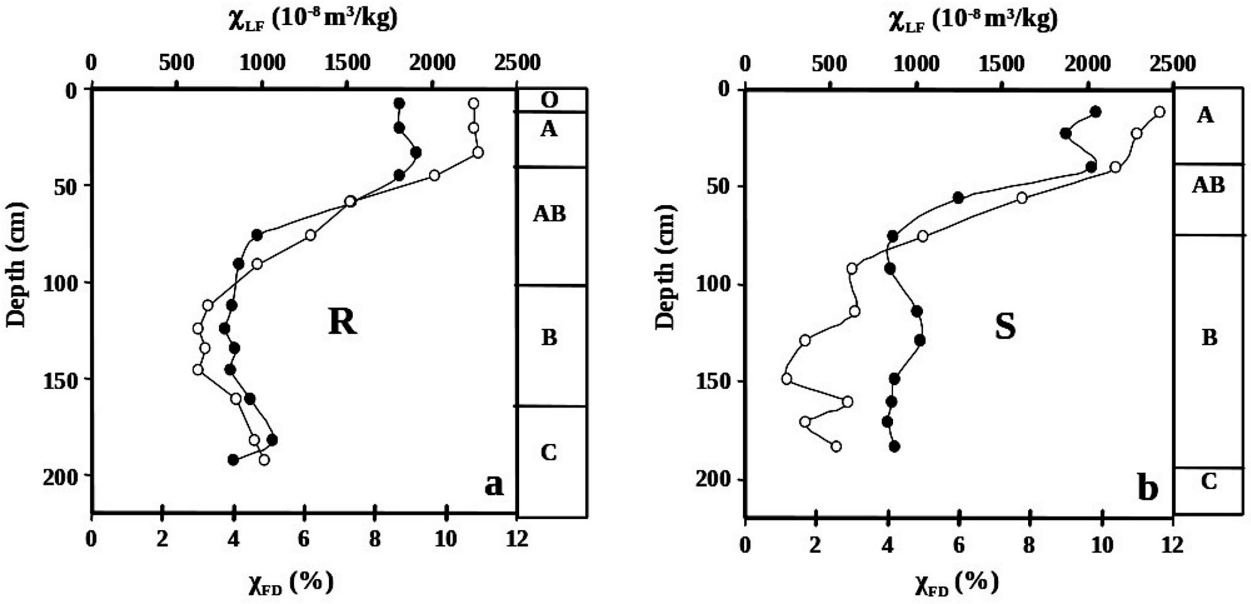


Figure 8. Variation of χLF (solid circles) and χFD(%) (hollow circles) in the longest profiles i.e. profile R (a) and S (b). The plots are similar to that in Fig. 7 except for the scale. Variation of χLF and χFD(%) correlate well with soil horizons.

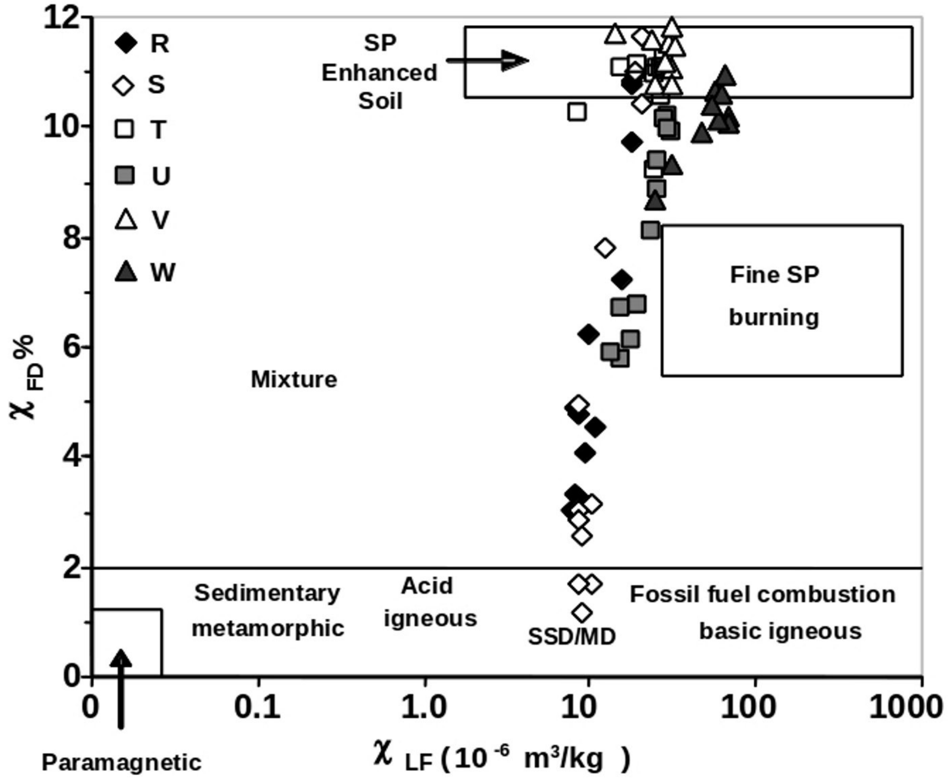


Figure 9. Scattergram of χFD versus χLF in the six soil profiles. The templates are from Dearing (1999).

Figure 10 shows the *ARM* and *ARM*/χ_{LF} (see Fig. 7). The value of *ARM* depends on the quantity of remanence-bearing fine-grained magnetite. In general, the values of *ARM* follow the same trend as that χ_{LF} and χ_{FD}(%) indicating that pedogenic process also alter the quantity of remanence-bearing fine-grained magnetite. Variation of *ARM* values in profile V is greater than that of other profiles. In longer profiles of R and S, the variation of ARM does not change beyond the depth of about 100 cm. As χ_{LF} is a concentration dependent parameter, the ratio of *ARM*/χ_{LF} indicates relative contribution of remanence-bearing fine-grained magnetite to the overall magnetic susceptibility. Good correlation between *ARM* and *ARM*/χ_{LF} observed in profiles R, S, T, and U implies that the increase in magnetic susceptibility is due mainly to fine grained magnetite.

Observing Figures 7 and 10, one finds that these three sites which are very close to each other show some differences in the magnetic parameters. For instance, the relatively low values of χ_{LF} observed in samples from profiles R and S (site I) imply that the source rock or some local conditions of site I might be different than that of soils in sites II and III. If the rocks of the studied area are indeed mafic and ultramafic rocks, as described in the geological map (Simandjuntak *et al* 1994), then there is possible to expect that soils derived from olivine dominated rocks (such as dunite) would exhibit higher values of χ than soils derived from plagioclase dominated rocks (such as gabbro). This would mean that in site I the source rock of soils is likely to be a mafic rock, while the source rock of soils in sites II and III is likely to be a more magnetic ultramafic rock. It is, however, unfortunate that we could not recover the source rocks of the soils in this study. Although almost all profiles contain the C, B, and A horizons, the variations in the χ_{LF}, χ_{FD}(%), *ARM* and *ARM*/χ_{LF} values might not solely be controlled by pedogenesis. Since the variations of the above parameters are similar for samples from the same site, it is likely that such variations could also depend on the type of source rock. Even other factors, such as topography and local climate might affect pedogenesis, they are very unlikely to cause such variations of magnetic parameters because the close proximity between the sites.

How could we describe the magnetic enhancement and transformation of magnetic minerals in the lateritic soils? First, the source rocks begin to weather and produce altered materials such as fresh and predominantly multidomain grains of ferrimagnetic minerals (mostly magnetite) which are reduced in size by physical weathering. The soil is known as C horizon characterized by relatively low χ_{LF} and lower χ_{FD}(%) values. Second, as weathering and pedogenesis progress, the concentration of SP particles increases as indicated by an increase in χ_{LF} and higher values of χ_{FD}(%). At this time, some ferrimagnetic minerals are also oxidized and turned into maghemite or hematite and later into goethite. The presence of hematite and goethite could be clearly seen from the color of the soils. This transition from low values of χ_{LF} and lower χ_{FD}(%) values into higher values of χ_{LF} and lower χ_{FD}(%) is generally associated with the B or AB horizons. As pedogenic development proceeds, SP grains are enhanced, resulting in the continuous increase of χ_{LF} and χ_{FD}(%) until they reach maximum values associated with the A horizon. Depending on the presence of O horizon and its thickness, the values of χ_{LF} and χ_{FD}(%) might decrease slightly toward the top soil.

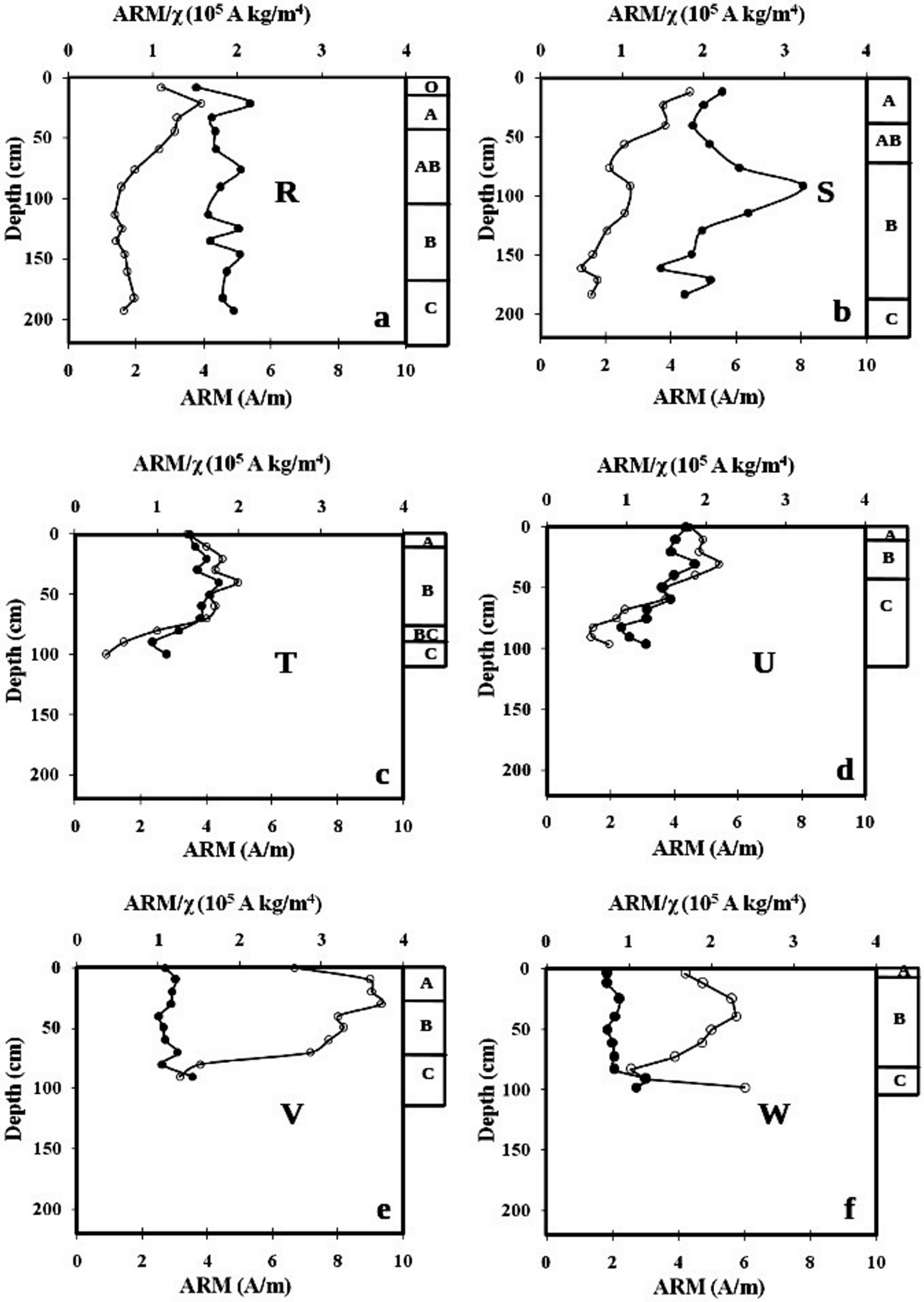


Figure 10. Variation of ARM (hollow circles) and ARM/χLF (solid circles) in the six soil profiles

5 Conclusion

The following conclusions could be drawn from rock magnetic studies of laterite soil samples from Pomalaa, Southeast Sulawesi:

1. The following magnetic minerals, *i.e.*, magnetite, hematite, goethite and possibly maghemite were identified in the lateritic soil samples of this study. Despite the visual appearance of hematite and goethite that affect the coloration of the soil, magnetite is the predominant magnetic mineral. The presence of hematite and goethite, nevertheless, indicate that the soils had experienced an advanced pedogenic processes. The presence of hematite is also confirmed by the low temperature magnetic susceptibility measurements that show Morin transition. However, Verwey transition of magnetite is greatly suppressed possibly due to intense oxidation of magnetite.
2. Variations of magnetic parameters often correlate well with soil horizons. The C horizon has the lowest values of these parameters. The values of χ_{LF}, $\chi_{FD}(\%)$, and *ARM* increase considerably at the B or the AB horizons. In most cases, these values reach their maximum at the A horizon. Finally, they slightly decrease toward the top soil at the O horizon. The changes of magnetic parameters are governed mainly by enrichment of SP particles.
3. The magnitudes as well as the variations of magnetic parameters are similar in profiles from the same site suggesting that some of the variations are site-dependent. Since all sites are from the same area, factors such as local climate and environmental conditions could not be the differentiating factors. This leave difference in the type of source rock in each site as the possible factor controlling the observed variation of magnetic parameters.

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