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Parameterization of Magnetic Viscosity and Its Application in Inferring Magnetic Grains in Natural Samples

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Abstract. Magnetic viscosity, also known as viscous magnetization, is one of the magnetic properties that rarely used in study of rock magnetism. The recent emergence of portable magnetic viscosity meter allows scientists to exploit that magnetic viscosity as the proxy parameters of processes recorded in natural materials. One of such instrument is MVM1, a new kind of magnetic viscosity meter which allow measurement of viscous magnetization to be conducted in 14 steps of time delay ranging from 10 to 100 µs. In this study, we have measured the changes of magnetic viscosity over the time delay and magnetic susceptibility in a suite of natural samples. The results show that viscous magnetization decays with time (in logarithmic scale or *log t*) which follows the trend of cubical-logarithmic decay. This is a unique response of fine magnetic grains, *i.e.* superparamagnetic grains, when that magnetization was measured in very short time delay. We then found the correlation between parameters of magnetic viscosity, *S* in specific range of time delay, and parameters derived from magnetic susceptibility measurements. This correlation enables the measurements of magnetic viscosity to be used in order to approximate fraction of specific size of fine magnetic grains in bulk samples.

Keywords: magnetic viscosity, natural samples.
PACS: 91.25.F-

INTRODUCTION

Magnetic viscosity is simply defined as the change of magnetization during the increasing of time [1-2]. In case of instantaneous magnetic field induction, the behavior of magnetic viscosity is commonly characterized by the decay of remanence magnetic. Previous studies of magnetic viscosity [3-4] reported that coefficient of magnetic viscosity S is defined as changes of magnetization (dM) over changes in time delay (in logarithmic scale or $d\log t$).

Magnetic viscosity is closely related to the presence of viscous magnetic grains, *i.e.*, grains whose sizes are between that of superparamagnetic (SP) and that of stable single domain (SSD). Recently, properties of the above grains have been studied widely ranging from soil pedogenesis [5-6] to paleoclimate [7-8] and to UXO (unexploded ordnance) detection [9]. So far, the main magnetic parameter commonly used to infer these grains is frequency-dependent susceptibility (χ_{FD}) which is carried out in a dual-frequency magnetic susceptibility meter. Compared to magnetic viscosity, χ_{FD} has limitation as it represents rather narrow range of viscous grains.

Recent introduction of MVM1, a new kind of magnetic viscosity meter (Pulsepower Developments, Oxford, UK), allows speedy determination of S as it measures changes of M over time. In this instrument, time-delay between removals of magnetic field is very short ranging 10 to 100 µs. According to Néel theory [10] such time-delays would affect grains that are between SP and SSD in size.

The relationship or parameterization between S and magnetic susceptibility is yet to be established. In this study, we measured magnetic susceptibility and determine the value of S in a suite of natural samples to seek out such parameterization that would enhance our understanding on how very fine magnetic grains affect the bulk magnetic properties.

EXPERIMENT

In this experiment, we used ten natural samples consisted of eight samples of lake sediments, termed as LS1 to LS8, and two samples of volcanic ashes,

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termed as VA1 and VA2. These samples were selected because they were thought to have wide distribution of magnetic grain size. Samples were then prepared in 10 cm^3 cylindrical holder before their magnetic properties were measured. The first measurement is magnetic viscosity over time delay of 10 to 100 µs using magnetic viscosity meter MVM1 with B sensor. In principle, this instrument measures the response of viscous magnetization at some later time after removal the 400 µT instantaneous magnetic induction. The interval between measurements on time delay of 10 to 50 µs is 5 µs whereas that of 50 to 100 µs is 10 µs. Magnetic viscosity coefficients S was then obtained from the slope of viscous magnetization versus time. The second measurement is magnetic susceptibility in dual frequencies (470 and 4700 Hz) using a Bartington susceptibility meter with MS2B sensor (manufactured by Bartington Instruments Ltd., Oxford, UK). The value of mass-normalized magnetic susceptibility in low frequency (470 Hz) termed as χ_{LF} while in high frequency (4700 Hz) termed as χ_{HF}. Frequency dependent susceptibility (χ_{FD}) as an indicator of the proportion of viscous magnetic grains in sample is expressed as $\chi_{FD} = 100\% \times (\chi_{LF} - \chi_{HF})/\chi_{LF}$. Finally, the isothermal remanent magnetization (IRM) was performed by imparting all samples on DC field of about 1 T and then back field magnetization of about 300 mT. Intensity of IRM was then measured by Minispin Magnetometer. The ratio intensity of IRM on back field magnetization 300 mT (IRM_{-300mT}) to IRM 1T (IRM_{1T}) was used to determine predominant magnetic mineralogy in samples.

RESULTS AND DISCUSSION

The Characteristic of Viscous Decay

Figure 1 illustrates the curves of magnetic viscosity response represented by MVM reading against time in logarithmic scale (*log t*). Each curve shows different responses as shown by different curvatures. Samples with low MVM reading (maximum reading of up to 31) are presented in Figure 1a whereas those with higher MWM reading are in Figure 1b. All samples, however, have similar characteristic which follow the trend of cubical-logarithmic decay. This differs from previous studies that generally show the decay curves to be either linear-logarithmic [2-4] or quadratic-logarithmic [11]. These the differences are possibly due to the response of ultrafine magnetic grains, *i.e.* SP grains, as consequence the use of very short time delay in the measurement of remanent magnetization. The SP grains have a very short relaxation time so that it has a unique pattern of decay compare to the coarse grains such as intermediate SSD grains.

The values of ratio of IRM_{-300mT} to IRM_{1T} for all samples are close to one (ranging from 0.97 to 0.99) which is indicating that properties of those samples strongly dominated by magnetite (Fe3O$_4$). It suggests that the difference response of MVM for these samples just depend on proportion of SP grains. Figures 1a and 1b also show that changes in magnetization, represented by changes in MVM reading, are greater in shorter time delay (low values of *log t*) compared to that in longer timey delay (high values of *log t*). Thus, viscous effect is greater in short time delay and weaker in long time delay.

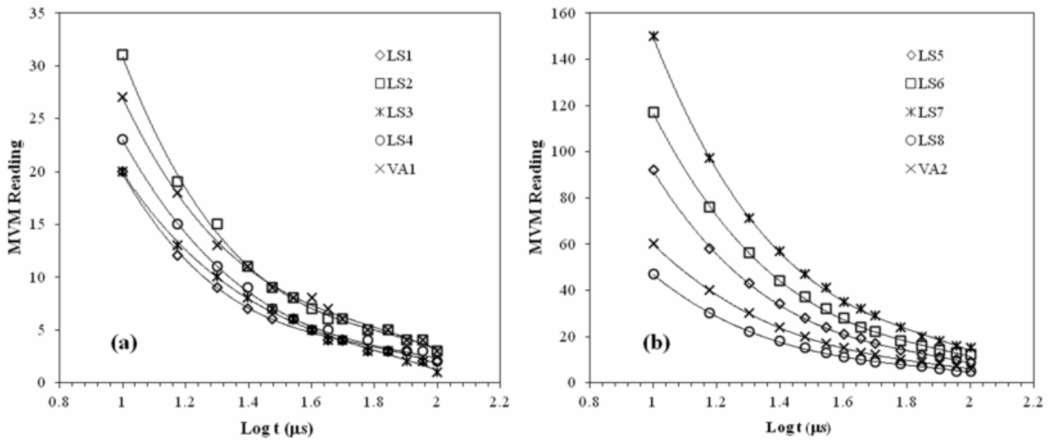

FIGURE 1. Viscous decay curves of the samples with low MVM response (a) and those with high MVM response (b).

The Relationship between Magnetic Viscosity Coefficient and Magnetic Susceptibility

According to Néel theory, the relationship of grain volume (V) and the measurement time (t) can be expressed as [10]:

$$V = \left(\frac{2kT}{\mu_0 H_k M_s} \right) \ln \left(\frac{t}{\tau_0} \right) \qquad (1)$$

where k is Boltzmann constant, T is temperature (in K), μ_0 is permeability of free space, H_k is anisotropic field, M_s is spontaneous magnetization, and τ_0 is a time constant. If particles are magnetite that are spherical in shape, then $H_k \approx 2.09\ H_c$ and $\mu_0 H_c \approx 20$ mT for SD magnetite particle [12], where H_c is a coercivity. By using room temperature $T = 298$K, $M_s = 470$ kAm^{-1} for magnetite as well as t of 10 µs and 100 µs (the minimum and maximum values of MVM1 time delay), then by equation (2) we obtain grain diameter of 19.5 and 20.9 nm respectively. These results are consistent with the estimated diameter of blocking volume of 19.5 and 20.2 nm based on calculation by Dearing *et al.* [13] which use dual frequency of 470 and 4700 Hz used commonly in Bartington magnetic susceptibility meter.

Table 1 shows the specific S values and values of magnetic susceptibility parameters of all samples. We define specific S values, *i.e.*, $S_{10\text{-}20}$ as change in MVM reading between t of 10 to 20 µs divided by the respective $\Delta(\log\ t)$. Similarly, we define $S_{50\text{-}100}$ as change in MVM reading between t of 50 to 100 µs divided by the respective $\Delta(\log\ t)$. The mass normalized of $S_{10\text{-}20}$ varies within -50.99 to -384.15 × 10^{-8} m^{3}kg^{-1} whereas $S_{50\text{-}100}$ from -8.70 to -67.67 × 10^{-8} m^{3}kg^{-1}. On the other hand, values of χ_{LF} varies from 90.2 to 766.7 × 10^{-8} m^{3}kg^{-1} whereas that of χ_{FD} varies from 3.12 to 21.66%. The square of correlation coefficient, R^2, equal to 0.064 indicating there is no correlation between χ_{LF} and χ_{FD}. This infers that χ_{LF} is influenced by a broad spectrum of grains size distribution.

We then plot the values of $S_{10\text{-}20}$ and $S_{50\text{-}100}$ versus parameter $\chi_{LF}\ \chi_{FD}$ in Figure 2. These specific S values of all ten samples were found to strongly correlated with $\chi_{LF}\ \chi_{FD}$ ($r^2 = 0.9710$ for $S_{10\text{-}20}$ and $= 0.9674$ for $S_{50\text{-}100}$). This finding proves that the viscous effect is strongly depended on relative quantity of grain whose sizes are between that of SP and that of SSD. Samples with higher quantity of grains in this range would have higher viscous effect and vice versa. The relation of $S_{10\text{-}20}$ and $S_{50\text{-}100}$ respect to $\chi_{LF}\ \chi_{FD}$ found:

$$S_{10-20} = 7.9827 - 5.8047\,(\chi_{LF}\ \chi_{FD}) \qquad (2)$$

and

$$S_{50-100} = 0.2950 - 0.9467\,(\chi_{LF}\ \chi_{FD}) \qquad (3)$$

These relationships are very useful since the magnetic viscosity coefficient S can substitute and compliment the role of parameters derived from magnetic susceptibility measurements especially in estimating the relative quantity of fine magnetic grains.

TABLE 1. Mass normalized of specific value of S and magnetic susceptibilities of all samples (Initial LS refer to lake sediment samples while VA is volcanic ash samples).

Samples Code	$S_{10\text{-}20}$ (10^{-8}m^3/kg)	$S_{50\text{-}100}$ (10^{-8}m^3/kg)	χ_{LF} (10^{-8}m^3/kg)	χ_{FD} (%)
LS1	-73.34	-12.27	166.0	6.81
LS2	-83.93	-13.96	193.6	7.08
LS3	-42.46	-11.37	187.2	4.70
LS4	-56.03	-8.52	285.3	3.12
LS5	-223.96	-34.96	548.5	7.60
LS6	-295.16	-46.97	657.1	7.56
LS7	-384.15	-67.67	766.7	7.58
LS8	-121.44	-20.83	274.3	7.76
VA1	-50.99	-8.70	371.1	4.74
VA2	-88.64	-16.89	90.2	21.66

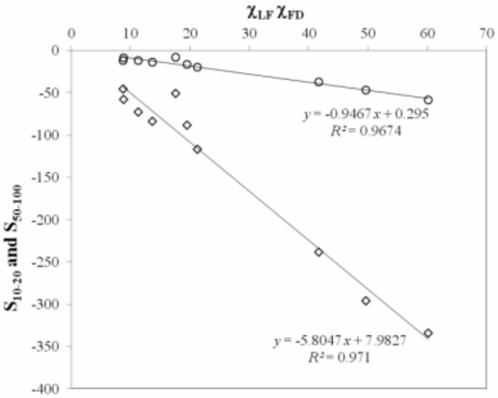

FIGURE 2. Correlation between coefficients of specific magnetic viscosity $S_{10\text{-}20}$ and $S_{50\text{-}100}$ and parameters derived from magnetic susceptibility measurements (diamonds are for $S_{10\text{-}20}$, while circles are for $S_{50\text{-}100}$).

One potential application equation (2) and/or (3) is in the estimation of fraction of magnetite fine grains in sample. For instance, fraction of SP grains (f_{SP}) can be expressed as [14]:

$$f_{SP} = \frac{\chi_{LF}\,\chi_{FD}}{\chi_{SP}\,\chi_{FD\max}} \tag{4}$$

where χ_{SP} is superparamagnetic susceptibility defined as

$$\chi_{SP} = \frac{\mu_0 V M_S^2}{3\,k\,T} \tag{5}$$

and χ_{FDmax} is maximum value of frequency-dependent susceptibility obtainable from models such as in [12].

Thus, if the fraction of interest is, let say, about 19.5 to 20.0 nm and 20.5 to 20.9 nm respectively, then the value of $\chi_{LF}\ \ \chi_{FD}$ in equation (4) can be replaced by that in equation (2) and (3) so than equation (4) could be expressed as:

$$f_{SP(d\approx 19.5-20nm)} = -\frac{S_{10-20} - 7.9827}{5.8047\,\chi_{SP}\,\chi_{FD\max}} \tag{6}$$

and

$$f_{SP(d\approx 20.5-20.9nm)} = -\frac{S_{50-100} - 0.295}{0.9467\,\chi_{SP}\,\chi_{FD\max}} \tag{7}$$

CONCLUSIONS

The following are the conclusions of this study. First, magnetic viscosity of natural samples in very short of time delay shows cubical logarithmic decay. This phenomenon is due to the response of very fine ferrimagnetic grains in the samples. Second, experimentally, we have found the relationship between magnetic viscosity parameters and parameters derived from magnetic susceptibility measurements. Specific magnetic viscosity values S_{10-20} and S_{50-100} correlate strongly with product of low frequency magnetic susceptibility and frequency dependent susceptibility ($\chi_{LF}\ \ \chi_{FD}$). Such correlation allows magnetic viscosity measurement to be used in estimating the presence and quantity of very fine magnetic grains in bulk samples.

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