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The Shaw paleointensity method: Can the ARM simulate the TRM alteration?

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ABSTRACT

The effectiveness of the ARM correction in Shaw's paleointensity method was investigated for four kinds of volcanic samples with different remanence characteristics from single domain to multidomain. Samples were heated in air and vacuum for successively longer times of 10, 20, 50, 100, 200, and 500 min and changes in the AF demagnetization curves of the ARM and TRM were observed. Drastic changes of the ARM and TRM were observed in three cases from two samples in which changes of the remanence magnitude were coherent between the ARM and TRM for a wide range of the AF demagnetization. However, the coherent change of the ARM and TRM due to alteration was not completely proportional, giving a moderate to large error in the ARM correction. This suggests that the double heating methodology should be practiced for the Shaw method to ascertain the effectiveness of the ARM correction. In two cases of andesite lava with a multidomain nature, the ARM-corrected Shaw plots with marginally linear data points were obtained from a heavily altered sample, indicating the insensibility of the coercivity spectra to changes in the blocking temperature. This fact suggests that strict linearity of the NRM to the corrected TRM should be posed in the analysis of Shaw plots.

1. Introduction

Absolute paleointensity from volcanic rocks is obtained by comparing the magnitude of the natural remanent magnetization (NRM) to that of the thermoremanent magnetization (TRM), which is artificially induced under a known magnetic field (Koenigsberger, 1938). In actual experiments, spectra of blocking temperatures (T_B) are compared to eliminate the effect of secondary remanence components (Wilson, 1961). To produce a TRM, it is necessary to heat a volcanic rock sample beyond the Curie temperature (T_C), which usually introduces a change of the rock magnetic properties of the sample due to its alteration. Hence, these methods are not considered to give a correct value. The Thellier method (Thellier and Thellier, 1959) avoids this problem by heating samples successively from low to high temperatures and only uses the T_B spectra under a critical temperature at which alteration begins. For this reason, the Thellier method is considered as the most reliable to determine the paleointensity from volcanic rocks, although there has been much debate about its occasional failure to give a correct value (e.g., Merrill, 1987; Valet, 2003).

An alternative method to obtain the paleointensity is to compare the spectra of the coercive force (H_C) obtained by alternating field (AF) demagnetization of the NRM and TRM (van Zijl et al., 1962). This method is also not reliable due to sample alteration by laboratory heating. Shaw (1974) introduced a new method which incorporates a procedure of filtering out the altered sample by comparing two anhysteretic remanent magnetizations (ARM) induced in the sample before and after heating. Detecting sample alteration by the change in the ARM was effective, but the experimental success rate by this method was low since few volcanic rocks are free from alteration by heating.

Kono (1978) introduced a method to correct the Shaw paleointensity result by the change of the ARM. The obtained paleointensity was corrected by the ratio ARM0/ARM1; where ARM0 and ARM1 are the ARMs induced before and after heating, respectively (the original notation by Kono was ARM1 and ARM2, but hereafter this scheme will be used). This correction method is based on the similarity of the H_C spectra in the TRM and ARM and based on the assumption that the change of the H_C spectra due to heating will also proceed similarly in the TRM and ARM. A further refined correction method was introduced by Rolph and Shaw (1985) who proposed to correct the ratio of the NRM to the TRM for each step of the AF demagnetization, NRM(H_C)/TRM(H_C), by the corresponding ratio of the two ARMs, ARM0(H_C)/ARM1(H_C); where H_C is a peak field of the AF demagnetization. Recent paleointensity studies using the Shaw method usually involve the Rolph and Shaw ARM correction.

In the community, the Shaw method is not used as widely as the Thellier method and one of the main reasons is the different grain size dependency of the remanence magnitude between the TRM and ARM. It has long been known that the magnitude of the remanence induced under a small direct current (DC) field is much different between the TRM and ARM, and the ratio, TRM/ARM,

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varies by a factor of 5–7 according to the grain size (e.g., Levi and Merrill, 1976; Sugiura, 1979). There seems to be a peak in the TRM/ARM ratio as high as 20 around 0.2 μm of grain size for magnetite (Dunlop and Argyle, 1997), which could be due to a different domain state between the ARM and TRM for this range of grain size (Yu et al., 2003). As sample alteration by heating usually involves a change in the grain size distribution, the ARM correction in the Shaw method would lead to an erroneous paleointensity.

As a matter of fact, in the original study by Rolph and Shaw (1985) it was suggested to apply the ARM correction only to the high coercivity portion of the data (over 100 mT), although this has not necessarily been routinely used in later studies. The reason Rolph and Shaw (1985) used only high H_C data was because the effect of the change in the grain size was considered to be small for the single domain (SD) range according to the TRM/ARM curve of Levi and Merrill (1976). However, as mentioned before, a recent summary of rock magnetic data by Dunlop and Argyle (1997) suggests a large grain size dependence on the TRM/ARM under 1 μm while the ratio is nearly flat over 1 μm. Kono (1987) studied the change of the H_C and T_B spectra for the TRM and ARM when a basalt sample is heated in air. One of the conclusions was that there is a limitation to the ARM correction due to different changes in the spectra between the TRM and ARM. Pan et al. (2002) studied the effectiveness of the ARM correction using laboratory heated basalt samples. The ARM correction was a powerful approach to correct the change of the TRM with weak alteration, but was sometimes invalidated for strong alteration.

Tsunakawa and Shaw (1994) introduced a double heating methodology to ascertain the effectiveness of the ARM correction. This method relies on the ARM correction by Rolph and Shaw (1985), but includes an additional procedure of a second heating to induce the TRM2 under the same laboratory field followed by the ARM2 acquisition. If the TRM1/TRM2 ratio corrected by the ARM1/ARM2 ratio fails to give a unit slope within a certain error, the ARM correction was judged to be non-effective and the paleointensity obtained from the NRM/TRM1 ratio corrected by the ARM0/ARM1 ratio was discarded.

The double heating method is now further refined as the LTD-DHT (low temperature demagnetization-double heating technique) Shaw method. When this method was applied to the present-day or historical lavas, correct intensities were successfully obtained while the Thellier method sometimes gave erroneous values (Yamamoto et al., 2003; Mochizuki et al., 2004; Oishi et al., 2005; Yamamoto and Hoshi, 2008). Hence, in spite of the non-flat grain size dependent curve of TRM/ARM, it is considered that the ARM correction in the Shaw method must have practical merit if the experiment is carefully performed.

This study revisits the problem of the change in the TRM and ARM when volcanic rocks are heated in the laboratory and presents some case studies applied to natural volcanic rock samples.

2. Samples and experimental procedures

Four types of natural volcanic rock samples were used in the experiments: the glassy part of 500 Ka andesite lava (OT57), the massive part of 740 Ka andesite lava (OT58), an andesitic block in 2200 yrs B.P. pyroclastic flow (AS03), and a 1983 AD basalt lava (MY07). OT57 and OT58 are both from the Older Ontake Volcano, central Japan. The rock magnetic property of the former is close to those of SD grains, giving successful paleointensity results by the Thellier method (Tanaka et al., 2007), while the latter shows a multidomain (MD) nature with unstable remanence. AS03 is Kotaki Pyroclastic Flow from the Asama Volcano in central Japan. This sample has often been used as a standard sample for paleointensity experiments because it usually gives highly successful results from both the Thellier and Shaw methods with high intensities of ~ 80 μT. MY07 is from the Miyakejima Volcano, a basaltic volcanic island 180 km south of Tokyo. AS03 and MY07 both demonstrate a pseudo SD (PSD) nature.

Rock types of these samples range from an andesitic pyroclastic flow to basalt lava, and their rock magnetic nature vary from those of SD to MD. Hence, as a case study of the TRM alteration, the samples will represent a wide range of volcanic rocks. The rock magnetic properties of the samples, which were measured with a vibration sample magnetometer (VSM) (Princeton Micromag 3900), are summarized in Table 1. The magnetic hysteresis parameter is a mean of three measurements of sister tip samples and the Curie temperature (T_C) is a single measurement. These samples were taken from the same core that was used for the heating experiments.

Two specimens that are 25 mm in diameter and 22 mm in height were taken from each sample. One is treated in air and another in a vacuum of about 5 Pa. First, the AF decay curves of the NRM and ARM were measured before the heat treatment, where the ARM was induced with a maximum peak of the AF field of 180 mT under a DC field of 80 μT. Measurements and the AF demagnetization of remanences were made by an automatic spinner magnetometer-AF demagnetizer system, Natsuhara-Giken DSpin (Kono et al., 1981, 1997). The AF steps are every 5 mT for 0–50 mT and thereafter every 10 mT up to the maximum peak field of 180 mT. Next, the samples were kept at 610 °C for 10 min in each atmosphere and the TRM was induced under 40 μT. Four specimens were treated at the same time as a batch for each atmosphere of the furnace. Then the AF decay curves of the TRM and ARM were similarly measured. This procedure was repeated for successively longer heating times of 20, 50, 100, 200, and 500 min. The furnace reaches a plateau of 610 °C in 30 min for both air and vacuum atmospheres, but 40 and 75 min, respectively, are necessary to cool down to room temperature. As both heating and cooling of the furnace are fairly rapid, most of the sample alteration should depend on the heating time at the plateau.

Small tips of sister samples were included in the batch and magnetic hysteresis parameters were measured after each heat treatment.

3. Experimental results

3.1. Changes in the Shaw plot

Results from each of the experiments were drawn on the Shaw plot in which all remanences are adjusted by vectorial subtraction of the residuals at the maximum AF step of 180 mT. The NRM was

Table 1
Rock magnetic properties of the samples.

Sample	Rock type	M_S (Am^2/kg)	M_{RS} (Am^2/kg)	H_C (mT)	H_{CR} (mT)	M_{RS}/ M_S	H_{CR}/H_C	T_C (°C)
OT57-22	Andesite lava	0.81	0.35	15.8	21.6	0.43	1.37	172, 329
OT58-4	Andesite lava	1.32	0.10	7.7	23.2	0.08	3.01	386, 565
AS03-2B	Andesite block	0.70	0.13	14.1	52.7	0.19	3.74	544
MY07-1	Basalt lava	2.52	0.36	11.9	28.7	0.14	2.41	519

Note: OT57 is a glassy part of the lava flow. AS03 is a block in a pyroclastic flow. The hysteresis parameter is a mean of three measurements and T_C is a single measurements of a sister tip sample taken from the same core used for the heating experiments.