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Comparison of the temperature dependence of irreversible and reversible magnetization of basalt samples

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ABSTRACT

Thermomagnetic curves are commonly used to characterize the magneto-mineralogy of basaltic rocks. It helps particularly for pre-selection of samples for paleointensity studies. However, the temperature dependence of the total magnetization is often different to the behavior of the remanence carriers. It is therefore of advantage to apply a new method to measure simultaneously the reversible and irreversible magnetization part. The method is based on a modified version of the Variable Field Translation Balance (VFTB). It is shown that the temperature dependence of the remanence carriers may be distinctly different to the total magnetization as seen in ordinary thermomagnetic curves.

1. Introduction

The natural magnetization of basalts carries important information for paleomagnetic studies, particularly concerning paleointensity studies. The magnetic properties of basaltic rocks are imparted mainly by Fe–Ti oxides, sulfides and chromites playing only a very minor role. Fe–Ti minerals occur as primary accessories which are precipitated in the magma at temperatures between 1200 and 1000 °C. Additional Fe–Ti oxides may be released on devitrification of residual glass and by oxidation of paramagnetic Fe^{2+} present in pyroxenes and olivines.

The composition of the primary Fe–Ti oxides in basalts at solidus temperature (∼ 1000 °C) is restricted to a narrow compositional range of the two solid solution series: magnetite (Fe_3O_4) ulvospinel (Fe_2TiO_4) series (titanomagnetites) and hematite (Fe_2O_3) ilmenite ($FeTiO_3$) series (Buddington and Lindsley, 1964; Carmichael and Nicholls, 1967) with corresponding primary Curie temperatures T_c of around 160 ° C for titanomagnetite and −120 ° C for hemoilmenite (the latter therefore not contributing to the sample magnetization at room temperature).

Although the primary basaltic magneto-mineralogy is relatively simple, the final magnetic assemblage may be complex, leading to problems in paleomagnetic interpretations. This complex magneto-mineralogy is well reflected in a wide distribution of Curie temperatures of basalts (Fig. 1). Carmichael and Nicholls (1967) were the first to point out that basalts with Curie temperatures higher than about 200 ° C offer evidence of subsequent change due to oxidation/exsolution of the primary Fe–Ti oxides.

2. Thermomagnetic curves

Measurement of thermomagnetic curves is a convenient method to assess the magnetic state of a basalt sample (see for example Ade-Hall et al., 1968). However, such analysis may be difficult to interpret when different magnetic phases sum up the measured signal, the paleomagnetically interesting phase being only one among several other phases which may then easily be overlooked. This is the case when the magnetically dominating phase is not the one carrying useful paleomagnetic information, while the carrier of stable remanence hardly shows up in the thermomagnetic curve.

Here we show that a modified system of the Variable Field Translation Balance (VFTB) offers the possibility to measure simultaneously, both the reversible and irreversible part of the total magnetization during a thermomagnetic run and may thus be useful in better distinguishing coexisting magnetic phases.

3. The modified VFTB

The original VFTB is a modification of the translation balance of Weiss and Foex (1911). As distinguished to the original Weiss and Foex balance, in the VFTB the magnetic gradient is not produced

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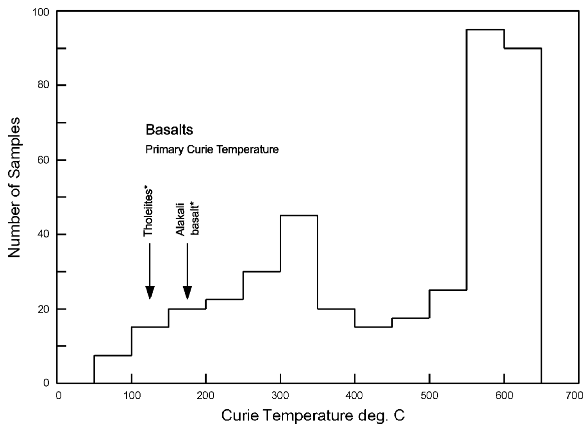

Fig. 1. Histogram of Curie temperatures of 400 basalt samples from different localities in Europe. (*) From Petersen (1976).

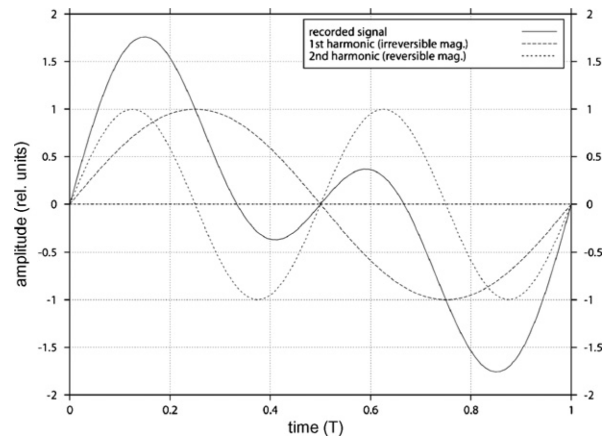

Fig. 3. Example of recorded sample movement (straight line). Basalt sample from Vogelsberg (Germany). $T = (1/f)$ with f the frequency of the gradient field.

by the special shape of the pole pieces of an electromagnet, but by a set of separate gradient coils (Krasa et al., 2007). The generated gradient field is not kept constant, but is oscillating with a certain frequency f. The VFTB can thus be considered a one-dimensional harmonic oscillator with damping, operated in forced oscillation mode. The oscillating part of the instrument is a pendulum with bifilar suspension, with the sample fixed to it. The motion of the sample is actuated by a periodic force of frequency f, generated by the gradient coils (Fig. 2 a). The amplitude of sample motion (Fig. 2b) is a measure of the sample magnetization in a certain magnetic field.

The modified VFTB makes use of the fact that the reversible part of a sample's magnetization oscillates with double frequency $2f$ (Fig. 2c). The signal is thus the superposition of irreversible magnetization (in the applied magnetic field) and reversible magnetization (following the weak gradient field). The latter one is equivalent to the weak field susceptibility of the sample.

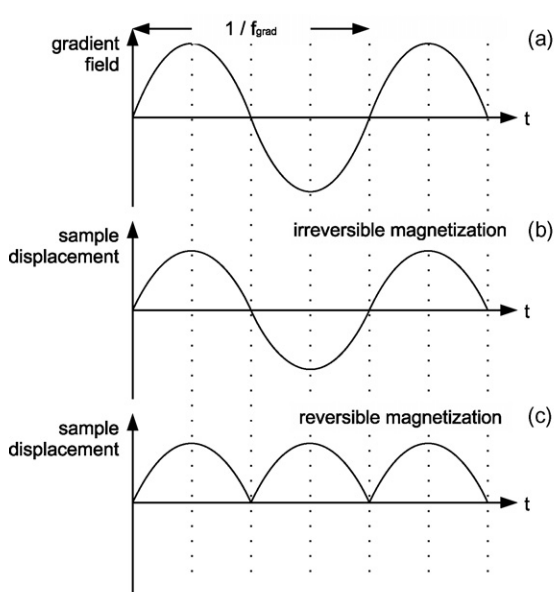

Fig. 2. Principle of the modified Variable Field Translation Balance (VFTB). (a) Gradient field oscillating with frequency f. (b) Sample movement actuated by the oscillating gradient field: irreversible magnetization oscillates with frequency f. (c) Sample movement actuated by the oscillating gradient field: the reversible magnetization part causes sample to oscillate with $2f$.

The two magnetization parts can be obtained by analyzing the first and second harmonic of the signal (Fig. 3). As an example the hysteresis loop of a basalt sample (Vogelsberg, Germany) is shown in Fig. 4.

4. Comparison of the temperature dependence of irreversible and reversible magnetization of a basalt sample

For this measurement a basalt sample from the Vogelsberg, Germany (same sample as in Fig. 4) has been selected. Ore microscopic observation shows titanomagnetite with incipient signs of oxidation as the carrier of magnetization.

Prior to the thermomagnetic measurement the sample was given an isothermal remanent magnetization (IRM) in a field of 400 mT. Fig. 5 shows heating and cooling curves of irreversible (IRM) and reversible magnetization (weak field susceptibility). The maximum of the susceptibility curve at 130 °C can be interpreted as the Hopkinson peak of the original unoxidized titanomagnetite. The shape of the curve following the maximum indicates a spread of different titanomagnetite oxidation states. The IRM curve behaves differently. Unblocking of IRM takes place more or less uniformly over the whole temperature range between room temperature and 550 °C.

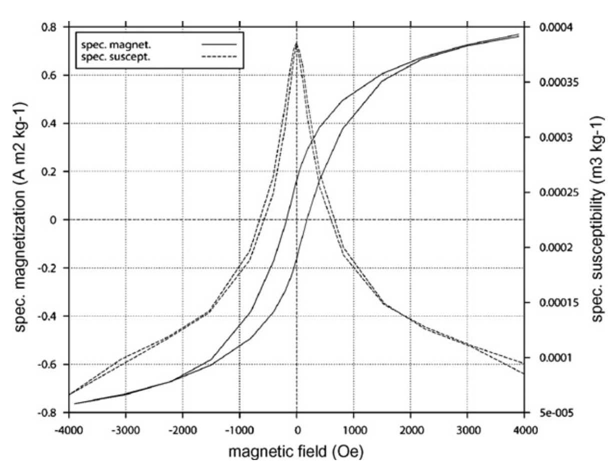

Fig. 4. Hysteresis loop of a basalt sample from Vogelsberg (Germany). Solid line: Normal hysteresis loop. Dashed line: Simultaneously recorded reversible magnetization part (weak field susceptibility).

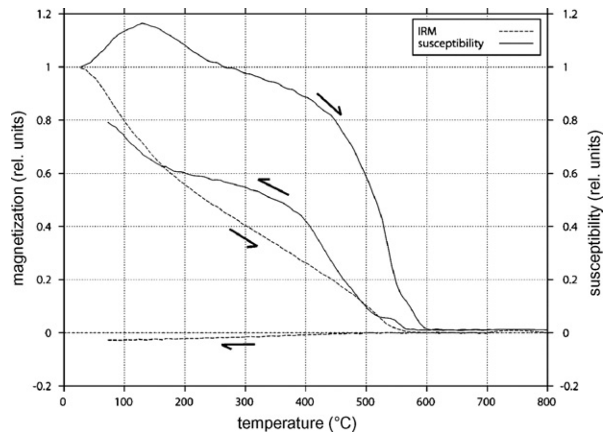

Fig. 5. Comparison of temperature dependence of reversible magnetization (weak field susceptibility, dashed line) and irreversible magnetization (IRM acquired in 400 mT, solid line). The measurement was taken in zero field. The cooling branches of the respective curves are also shown. The different susceptibility cooling curve indicates mineralogical changes due to the heating process in air. The IRM cooling curve remains zero as the sample cannot acquire a thermoremanent magnetization in zero field.

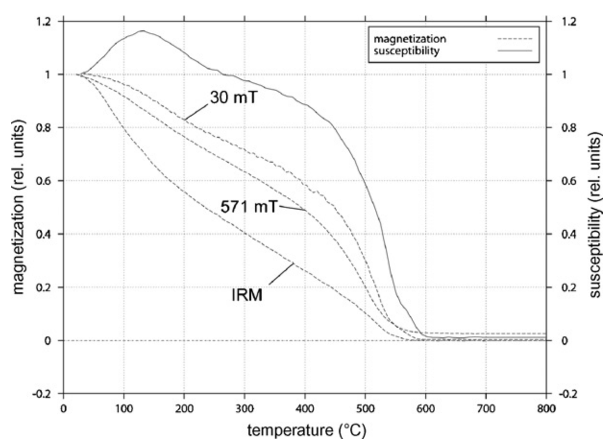

Fig. 6. Comparison of the temperature dependence of thermomagnetic curves measured in 30 and 571 mT respectively. Superimposed are the heating curves of Fig. 5, IRM and susceptibility. All curves are normalized to one at the starting temperature. The measured samples are taken from the same handpiece of the Vogelsberg basalt.

The different shape of the susceptibility cooling curve compared to the heating curve indicates irreversible mineralogical changes due to heating in air. The cooling curve of the irreversible magnetization remains zero as the experiment is carried out in zero field and the sample cannot acquire a thermoremanent magnetization.

5. Thermomagnetic measurements in different magnetic fields

Subsamples of the same handpiece from the Vogelsberg basalt have been measured in fields of 30 and 571 mT respectively (Fig. 6). Superimposed in the figure are the IRM and the susceptibility heating curves of Fig. 5, with all curves normalized to one at starting temperature.

It is interesting to note the characteristic differences between the curves: the stronger the applied magnetic field, the smoother the curves. The low T_c phase can only just be seen in the 571 mT curve where it is superseded by the paramagnetic contribution of the sample.

6. Conclusions

Comparison of thermomagnetic curves measured in different magnetic fields helps to distinguish coexisting magnetic phases present in samples with inhomogeneous magnetic constituents. Frequently the carrier of stable remanence is different to the bulk magnetically dominating phase and may easily be overlooked in ordinary thermomagnetic measurements in strong magnetic fields.

The same may be the case when measuring only weak field susceptibility where the signal usually comes mainly from MD or SP particles whereas the stable remanent magnetization resides in either SD particles (Evans et al., 1968; Hargraves and Young, 1969) or stress centers within larger particles (Verhhogen, 1959; Appel, 1987). The simultaneous registration of irreversible and reversible sample magnetization helps to solve this dilemma.

References

Ade-Hall, J.M., Khan, M.A., Dagley, P., Wilson, R.L., 1968. A detailed opaque petrological and magnetic investigation of a single tertiary lava flow from Skye, Scotland, I, II, III. Geophys. J. 16, 375–415.

Appel, E., 1987. Stress anisotropy in Ti-rich titanomagnetites. Phys. Earth Planet. Int. 46, 233–240.

Buddington, A.F., Lindsley, D.H., 1964. Iron-titanium oxide minerals and synthetic equivalents. J. Petrol. 5, 310–357.

Carmichael, C.M., Nicholls, J., 1967. Iron-titanium oxides and oxygen fugacities in volcanic rocks. J. Geophys. Res. 72, 4665–4687.

Evans, M.E., McElhinney, M.W., Gifford, A.C., 1968. Single domain magnetite and high coercivities in a gabbroic intrusion. EPSL 4, 142–146.

Hargraves, R.B., Young, W.M., 1969. Source of stable remanent magnetism in Lambertville diabase. Am. J. Sci. 267, 1161–1777.

Krasa, D., Petersen, K., Petersen, N., 2007. The variable field translation balance. In: Gubbins, D., Herrero-Bervera, E. (Eds.), Encyclopedia of Geomagnetism and Paleomagnetism. Springer, Netherlands.

Petersen, N., 1976. Notes on the variation of magnetization within basalt lava flows and dikes. Pageoph 114, 177–193.

Verhhogen, J., 1959. The origin of thermoremanent magnetization. J. Geophys. Res. 64, 2441–2449.

Weiss, P., Foex, G., 1911. Study of the magnetisation of ferrous bodies above the Curie point. J. Phys. 5 (1), 274–287.