Thermal fluctuation fields in basalts

Adrian R. Muxworthy[1], David Heslop[2], and Daniel M. Michalk[3]

[1]*Department of Earth Sciences and Engineering, Imperial College London, South Kensington Campus, London, SW7 2AZ, UK*
[2]*Fachbereich Geowissenschaften, Universität Bremen, Klagenfurter Straße, 28359 Bremen, Germany*
[3]*GeoForschungsZentrum Potsdam, Section 3.3, Telegrafenberg, 14473 Potsdam, Germany*

The thermal fluctuation field (H_f) is central to thermoremanent acquisition models, which are key to our understanding of the reliability of palaeomagnetic data, however, H_f is poorly quantified for natural systems. We report H_f determinations for a range of basalts, made by measuring rate-dependent hysteresis. The results for the basalts were found to be generally consistent within the space of H_f versus the coercive force H_C, i.e., the "Barbier plot", which is characterized by the empirically derived relationship; $\log H_f \propto 1.3 \log H_C$ obtained from measurements on a wide range of different magnetic materials. Although the basalts appear to occupy the correct position within the space of the Barbier plot, the relationship within the sample set, $\log H_f \propto 0.54 \log H_C$, is different to the Barbier relationship. This difference is attributed to the original Barbier relationship being derived from a wide range of different synthetic magnetic materials, and not for variations within one material type, as well as differences in methodology in determining H_f. We consider the relationship between H_C and the activation volume, v_{act}, which was found to be $H_C \propto v_{act}^{-0.68}$ for our mineralogically homogeneous samples. This compares favourably with theoretical predictions, and with previous empirical estimates based on the Barbier plot, which defined the relationship as $H_C \propto v_{act}^{-0.73}$.
Key words: Basalt, thermoremanence, thermal fluctuations, rock magnetism.

1. Introduction

Néel (1950, 1951) introduced the concept of a thermal fluctuation (or viscosity) field to describe the influence of thermal fluctuations on a magnetic system. This abstract concept is very powerful, as it allows for a magnetic system's behaviour to be entirely described in terms of magnetic fields. Thermal fluctuations influence all thermally activated magnetic processes, i.e., for temperatures $T > 0$ K, becoming increasingly important for magnetisation processes at high or variable temperatures, such as thermoremanence (TRM) acquisition. As such the concept of thermal fluctuation fields are central to many theories of both single-domain (SD) and multidomain (MD) TRM acquisition, on which many palaeomagnetic concepts and methodologies are based, e.g., the Thellier and Thellier (1959) method and its modifications for palaeointensity determination.

In the literature there are several definitions for thermal fluctuation or viscosity fields. In this paper we use the definition for the thermal fluctuation field, H_f, described by Wohlfarth (1984), which has subsequently been used widely in the physics literature. Wohlfarth's description is based on the work of Néel (1950, 1951) and Street and co-workers (Street and Woolley, 1949, 1950; Street *et al.*, 1952; Street and Woolley, 1956), and relates H_f to the magnetic viscosity parameter S and to the irreversible suscepti-

bility χ_{irr} by the equation:

$$S = \chi_{irr} H_f \qquad (1)$$

This equation is valid because H_f is related to relaxation events due to irreversible barrier hopping.

In selected literature the H_f term has been previously referred to as S_V (e.g., Barbier, 1954; Bina and Prévot, 1994), but we follow the notation of Wohlfarth (1984) who emphasised that using S_V can be misleading because it is an effective field and has different units to S.

It is common to define H_f by relating it to the thermal activation energy, E, which reduces to (Street and Woolley, 1949; Street *et al.*, 1952):

$$E = v_{act}\,\mu_0\,M_S\,H_f = k_B T$$
$$\text{i.e.,} \quad H_f = \frac{k_B T}{v_{act}\,\mu_0\,M_S} \qquad (2)$$

where k_B is the Boltzmann's constant, v_{act} the activation volume, M_S the spontaneous magnetisation of a material and μ_0 the permeability of free space. It is often assumed that v_{act} is identical to the actual volume for isolated "ideal" single domain (SD) grains, and for multidomain (MD) grains the effective volume covered by a single jump between pinning sites for a domain wall or other such domain wall events (Wohlfarth, 1984; Gaunt, 1986). For SD grains thought to switch via coherent rotation, this conclusion appears to be correct in the case of magnetite and thus magnetic granulometry techniques can be based on the determination of v_{act} (Dunlop, 1976; Dunlop and Bina, 1977). Studies on interacting particles have shown

that the estimated v_{act}, is greater than the volume of individual magnetic particles (e.g., Bottoni, 2005; El-Hilo and Bsoul, 2007).

As thermal fluctuation fields were introduced by Néel (1950, 1951) as a "most pictorial concept" (Wohlfarth, 1984), the question arises as to how H_f can be quantified experimentally. There are basically four broad approaches to determining H_f; (1) by measuring the time dependency of remanent or induced magnetisation, e.g., viscous decay curves (Sholpo, 1967; Bina and Prévot, 1994; El-Hilo *et al.*, 2002), (2) by determining the time dependency of hysteresis, e.g., variable field-sweep-rate hysteresis (Bruno *et al.*, 1990), (3) by examining alternating field demagnetisation curves (Prévot, 1981; Bina and Prévot, 1994) and (4) by measuring magnetic behaviour as a function of temperature (Dunlop, 1976).

Each of these methods is based on certain assumptions and approximations and can yield different values for the same samples (e.g., Bina and Prévot, 1994). For some cases a method may only be appropriate for a particular domain state, for example, consider the last method; because H_f is temperature dependent for MD material (Barbier, 1954), this method is only appropriate for coherently switching SD particles.

Barbier (1951, 1954) showed a most surprising linear correlation between $\log H_f$ and $\log H_C$ for a range of soft and hard magnetic materials, yielding the empirical relationship,

$$\log H_f \approx m \log H_C - C \qquad (3)$$

where m is the gradient and C a constant. Barbier (1951, 1954) found empirical estimates for m and C of 1.3 and -3.3 respectively. This empirical relationship has been subsequently found to be consistent for other materials (Wohlfarth, 1984; Liu and Luo, 1990; Sun *et al.*, 1990; Liu and Luo, 1991; te Lintelo and Lodder, 1994). Using Eq. (2) this leads to the conclusion that $H_C \propto v_{act}^{-0.73}$ (Wohlfarth, 1984).

Theoretical models are in slight disagreement with this experimental relationship (e.g., Liu and Luo, 1990, 1991; Klik and Chang, 1992). These models for SD behaviour and various MD pinning mechanisms all predict via Eq. (2) a gradient of unity rather than the empirical value of 1.3, however, these results are based on simplified models for magnetic structure and do not incorporate the more complex micromagnetic structures predicted by numerical models (Williams and Dunlop, 1989) and observed using electron-holography (Mankos *et al.*, 1996), i.e., primarily non-uniform magnetic structures such as vortex-like structures.

As thermal fluctuation fields are central to our theories of natural magnetic remanence (NRM) in igneous and metamorphic rocks, a thorough understanding and knowledge of their effects in natural magnetic systems is important if we are to be confident of the robustness of palaeomagnetic results and predictions.

There have been numerous studies, which have investigated and quantified H_f and v_{act} in synthetic powders including magnetite and other minerals of geophysical interest (e.g., Shimizu, 1960; Sholpo, 1967; Sholpo *et al.*, 1972; Dunlop, 1976; Dunlop and Bina, 1977), however, there

have been far fewer reports for actual rocks, such as the basalts which are commonly used in palaeomagnetic studies and for palaeointensity determinations (Sholpo *et al.*, 1972; Prévot, 1981; Bina and Prévot, 1994). Sholpo *et al.* (1972) determined H_f and v_{act} for a range of rock types, with values for H_f in the range $\sim$1000–2200 A/m for basalts and up to $\sim$6400 A/m for sandstones. Prévot (1981) and Bina and Prévot (1994) determined H_f for two subaerial basalts and two ocean basalt samples containing maghematized MD titanomagnetite. Using a variety of different methods to determine H_f, yielded a scatter of values (subaerial basalts: 7–12 A/m, submarine basalts: 1.8–27 A/m), much lower than those reported by Sholpo *et al.* (1972) for their basalts. This difference may simply be due to different coercivities of the samples employed in the two studies. The MD submarine samples of Bina and Prévot (1994) had coercive fields of just $\sim$2500 A/m. Sholpo *et al.* (1972) did not report H_C for their samples, but using Eq. (3) to estimate H_C gives values of $\sim$34000–75000 A/m for their basalt samples. These are a little higher than is usually observed but possible for highly stressed SD material. The high value may also be related to the method employed (Sholpo, 1967), which is based on viscous decay curves alone, which can yield estimates for H_f an order of magnitude greater than those derived by other methods for the same samples (pers. comm. M. Prévot, 2007).

Prévot (1981) and Bina and Prévot (1994) found a strong dependence of H_f on temperature for their MD material in agreement with Barbier (1954).

Thermal fluctuation fields are central to thermoremanent acquisition theories and our understanding of viscosity, yet they are poorly quantified for natural systems, with only a few samples studied to date. In this paper we report a detailed study whose aim is to determine H_f for natural magnetic systems, in particular basalts, and to examine whether the empirical relationship originally derived by Barbier (1951, 1954) is valid for basalts and thus could be potentially applied to rock magnetic theories.

2. Samples

Due to the nature of the relationship found by Barbier (1951, 1954), i.e., $\log H_f$ versus $\log H_C$, we required basalt samples with as wide a range of coercivities as possible. We considered two sets of samples, Pleistocene basalts from Mexico of Brunhes Chron ages ($<$780 ka), and historical samples from Iceland (1729–2000 AD). These basalt samples had a range of coercivities, varying from a minimum of 2.7 kA/m up to 36 kA/m (Table 1). Some further Mexican samples, characterized by highly wasp-waisted loops, were rejected from this study because they did not saturate during hysteresis (maximum available field = 1600 kA/m). It is thought that these rocks underwent alteration due to tropical weathering, which caused low temperature oxidation (maghemitization) of the magnetic carriers.

The Icelandic samples have magnetic hysteresis parameters typical of small PSD and SD behaviour (Fig. 1). Ore microscopy revealed that the Icelandic samples from Hekla generally consisted of homogeneous un-oxidised euhedral titanomagnetite grains between 5–20 μm in size (C1 oxidation state (Haggerty, 1991)), with large amounts of fine

Table 1. Curie temperature, H_C, H_f, and M_S predictions.

Sample name	Origin	Curie temperature (°C)	H_C (kA/m)	H_f (A/m)	estimated M_S (kA/m)
ab12	CSP (450 ka)	237	2.7	15	178
ad2	CSP (450 ka)	549	36	110	452
br6	VDB	533	9.7	48	436
bs02	VDB	561	22	38	465
bt09	VDB	328	9.5	51	251
bt11	VDB	332	9.7	48	253
bv03	VDB	552	14	26	455
h00h	Hekla (2000)	235	3.9	32	177
hc1	Hekla (1845)	120	14	72	92
hd1	Hekla (unknown)	90	22	49	71
hf2	Hekla (unknown)	320	31	110	244
hf5	Hekla (unknown)	320	28	110	244
ka1	Krafla (1981)	90	22	38	71
ka2	Krafla (1981)	90	38	28	71
ka3	Krafla (1981)	90	12	64	71
kb5	Krafla (1729)	110	9.8	64	85
kb9	Krafla (1729)	110	12	46	85

Ceboruco-San Pedro (CSP) and Valle de Bravo (VDB, undated but Brunhes Chron) are two monogenic volcanic fields within the Transmexican Volcanic Belt. Hekla and Krafla are two volcanoes in Iceland, with very recent eruptions. Hekla (unknown) lavas are from undated flows from Hekla, but Brunhes Chron. The Curie temperatures were determined from saturating thermomagnetic curves (heating in Argon). Only the primary or dominant Curie temperature is shown. H_C and H_f as depicted in Fig. 3 are tabulated. From the primary Curie temperature estimates, M_S was determined assuming that the variation in Curie temperature was due to titanium variation within titanomagnetite minerals (Hunt *et al.*, 1995). The Curie temperatures were determined using a variable field translation balance using an applied continuous field of 500 mT.
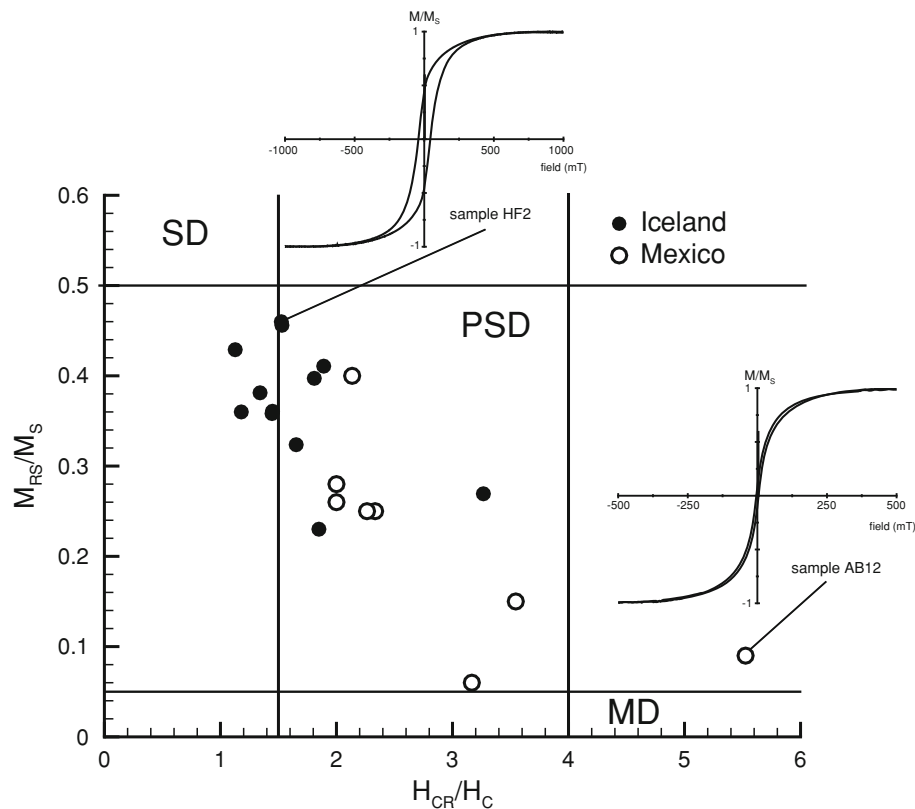

Fig. 1. A "Day plot" (Day *et al.*, 1977) of M_{RS} / M_S versus H_{CR} / H_C for the Icelandic and Mexican samples considered in this study, where M_{RS} is the remanent saturation magnetisation and H_{CR} the remanent coercive force. The two insets show hysteresis loops for two of the end members. The Mexican sample AB12 is slightly wasp-waisted.

sub-micron titanomagnetite (C1) and ilmenite (R1) needles. The presence of needles is indicative of fast cooling. The samples from Krafla consisted of small skeletal titanomagnetites (C1) similar to those reported by Krása and Matzka (2007). Curie temperatures determined for the Icelandic samples ranged from 90 to 320°C (Table 1).

In contrast the Mexican samples' hysteretic properties were more indicative of PSD and small MD behaviour. Some of the hysteresis loops were slightly wasp-waisted (Fig. 1), suggesting possible oxidation. Ore microscopic

observations revealed a range of oxidation states and grain sizes. For example, sample AB consisted of a mixture of anhedral and euhedral titanomagnetite grains (C1 oxidation state, 10–50 μm in size), some larger grains displaying deuteric trellis textures (C3) and a few finer grains within the matrix. The "B" samples, i.e., BR, BS, BT and BV, displayed large grains with cracked rims probably due to maghemitization, with some evidence for high temperature oxyexsolution and fine-grained hematite. The samples also had a wide range of Curie temperatures, varying from 237°C to 561°C (Table 1).

3. Experimental Results

There are several approaches for determining H_f. We used the rate-dependent hysteresis method proposed by Bruno *et al.* (1990). This requires measuring the coercivity as a function of field rate, i.e., dH/dt, where H is the applied field and t the time. H_f is then given by (Bruno *et al.*, 1990; Basso *et al.*, 2000),

$$H_C = H_f \log(dH/dt) + C \qquad (4)$$

where C, according to theory, is constant for a given temperature (Bruno *et al.*, 1990). It might be argued that palaeomagnetists are more commonly interested in thermal activation of remanent magnetisation rather than during hysteresis, that is, it might be more appropriate to use viscous decay of remanence curves to determine H_f if the findings are to be applied to palaeomagnetic investigations. We chose to measure H_f using this in-field hysteresis approach, as it yields significantly improved signal-to-noise ratios compared to measurement of viscous decay of remanent magnetisation.

We measured H_f as a function of field rate using a Princeton Measurements alternating gradient magnetometer (AGM), with rates from $\sim$2 to $\sim$4000 A m^{-1} s^{-1}. The hysteresis loops were measured in an automated sequence requiring several hours to complete. A number of steps were taken to reduce and accommodate instrument drift, including off resonance-peak measurements and repeated intermediate measurements to allow drift correction. All measurements were made at room temperature and the instrument drift was assumed to be linear with respect to time. An example of H_f determination is shown in Fig. 2. As expected from Eq. (4), H_C is seen to increase in a linear manner with respect to $\log(dH/dt)$.

The values of H_f of the individual samples and their relationship with H_C were determined using a Monte Carlo procedure based on bootstrapping the measured hysteresis data (Efron and Tibshirani, 1993). Each iteration of the Monte Carlo procedure involved the following sequence of steps:

Step 1. The $\log(dH/dt)$ versus H_C data for each sample was bootstrapped (with replacement) to form an estimate of H_f for each sample.

Step 2. Based upon regression, the obtained values of H_f were used to make an estimate of the linear relationship between $\log H_C$ and $\log H_f$.

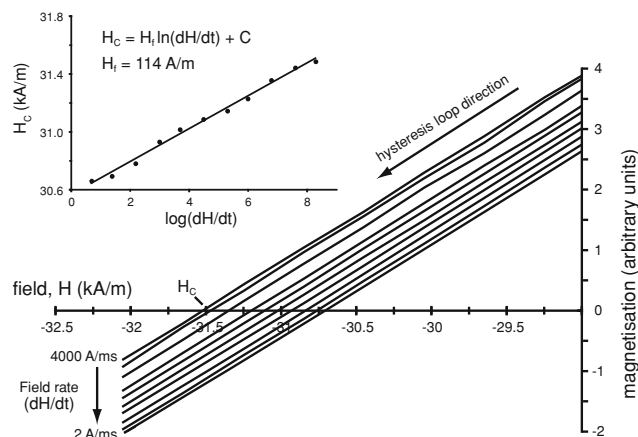The above procedure was repeated for 10^4 trials and the distribution of results for each step could be used to estimate

Fig. 2. A typical example of the measurement of field-rate dependent hysteresis, and the variation in coercive force H_C. The inset shows how H_f was determined from such hysteresis data. The sample is the Icelandic sample hf2.

the discussed parameters with associated confidence intervals. Step 1 of the procedure was used to estimate H_f within 90% confidence limits for each of the samples. The collection of regression equations determined in step 2 yielded an estimate for the linear relationship between $\log H_f$ and $\log H_C$ within a 90% region of confidence (Fig. 3(a)), where $\log H_C$ was defined using the fastest measuring rate in order to minimize the effects of thermal fluctuation (Fig. 2). It was found that as a first approximation the basalts can be fitted by the relationship $\log H_f \approx 0.54 \log H_C - 0.52$. H_C and H_f are tabulated in Table 1.

4. Discussion

When the basalt data from this study is plotted with the original "Barbier data" (which includes the data of Barbier (1951, 1954) and Wohlfarth (1961), Fig. 3(b)), it is seen that the basalt data lies on the overall trend of the Barbier data. When, however, the gradient of the basalt data is determined using Eq. (3) it is found to be substantially lower than that of the Barbier data set, i.e., 0.54 versus 1.3 respectively. There are a number of possible reasons for this; first—and we suggest the most important point—the original fit to the Barbier data essentially examines behavioural trends between a wide range of different materials, whereas, although the basalts examined have a variety of compositions, they are essentially the "same" material, i.e., titanomagnetites with varying degree of oxidation. In this way we are applying Eq. (3) in two different forms; for a range of materials in the case of the Barbier data and within a single material for the basalt samples. Second, the range for the Barbier data is much wider than for the basalt data set. Third, different methods have been employed to determine H_f; the method utilised in this paper determines H_f at higher fields than the viscous decay mechanisms; H_f is determined at different positions on the hysteresis curve, that is, one mechanism is examining the effect of thermal fluctuations on the remanence state the others on an in-field magnetisation. Fourth, the difference could be due to the slight waspwaisted nature observed in some of the oxidised Mexican basalts (Fig. 1). Wasp-waisted behaviour will decrease H_C,
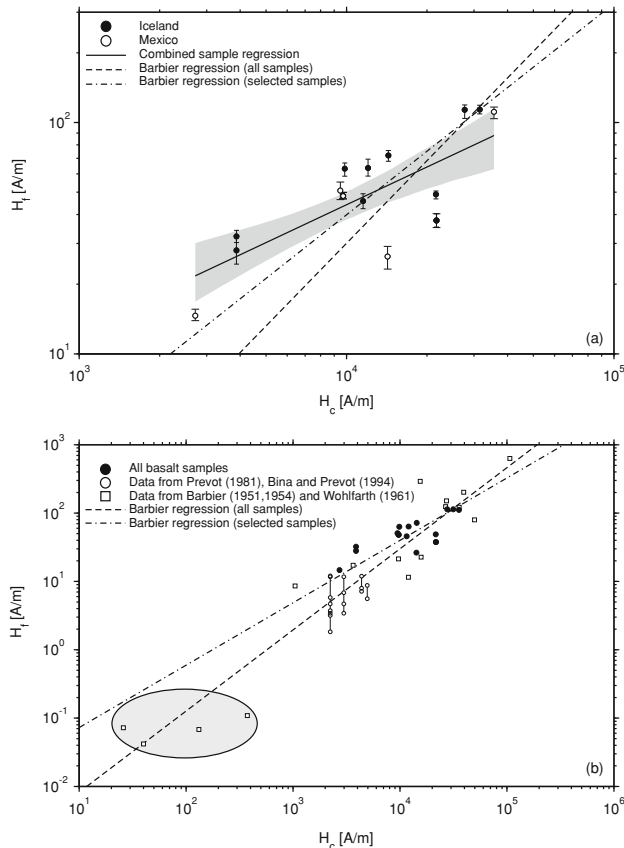
Fig. 3. (a) Plot of log H_f versus log H_C, i.e., a Barbier plot, for the Icelandic and Mexican samples considered in this study, the error bars on each point represent the 90% confidence interval obtained using the Monte Carlo procedure described in the text. The Monte Carlo procedure also yielded an estimate of the relationship (solid black line) between log H_f and log H_C and is shown with a 90% confidence region (shaded area). In addition we show two further regression lines, the first (dashed line) is based on the full "Barbier data set" (Barbier (1951, 1954 #21940) and Wohlfarth (1961)) and the second (dot-dashed line) is calculated from the same data with the low coercivity materials removed. (b) Plot of log H_f versus log H_C for the basalts measured in this study (filled circles), the "Barbier data" (open squares), plus trend lines for the Barbier and reduced Barbier data sets. As in panel (a) the former line is fitted to all the Barbier data, the latter to Barbier data minus the strongly biasing very low H_C samples, which are highlighted in the figure with a shaped ellipse. The data of Prévot (1981) and Bina and Prévot (1994) for four samples, are shown as a range of values (open circles with connecting lines) based on the variety of methods they employed to estimate H_f.

potentially leading to a lower gradient in Fig. 3. Fifth, the regression of the Barbier data set is heavily influenced by four data points at very low H_C values which exert a substantial leverage on the fit (highlighted in Fig. 3(b)). If these four data points are removed from the regression (Fig. 3), then the gradient is reduced and the new slope plots closer to the basalt data regression line. This alternative fit to the Barbier data, which is restricted to higher coercivity materials, passes through the centre of the basalt data and thus appears to be more appropriate to our sample set.

On Fig. 3(b), the data of Prévot (1981) and Bina and Prévot (1994) are plotted. Prévot (1981) and Bina and Prévot (1994) used several different methods to determine H_f, producing a range of estimates. They did not use the rate-dependent hysteresis method that was employed in the

current study. It can be seen that for some of their samples, the variation in H_f for a given sample, is greater in log-space than the whole spectrum of variation in our data (Fig. 3(b)). This makes it difficult to draw detailed comparisons between the studies, however, it is clear that the low-coercivity Mexican samples in this study have higher H_f values than reported by Prévot (1981) and Bina and Prévot (1994). This difference maybe due to the different methods employed to determine H_f and/or the apparent bi-modal coercivity distributions of the Mexican samples.

4.1 Activation volumes

The basaltic samples have a wide range of domain states (Fig. 1), coercivities (varying from 2.7 kA/m up to 36 kA/m, Table 1), Curie temperatures (Table 1) and oxidation states, yet all the samples as a first approximation agree with a fit of Eq. (3). This implies that the mechanisms that control the coercivity in both SD and MD grains are affected by thermal fluctuations to the same extent. As stated previously, it is thought that in the smallest grains v_{act} corresponds to actual grain volume, whereas in the larger grains it is related to nucleation volumes and volumes associated with pinning movements. This implies that the same localities, which correspond to switching or reversal processes, are also the same sites that are activated thermally.

Using Eqs. (2) and (3) with the addition of one data point from Wohlfarth (1961) to the plot of Barbier (1954), Wohlfarth (1984) concluded that $H_C \propto v_{act}^{-x}$, with $x = 0.73$. This relationship has been cited many times (e.g., Liu and Luo, 1991; te Lintelo and Lodder, 1994), yet, it is unclear if Wohlfarth (1984) included the variation of M_S (Eq. (2)) in his determination; it is apparent that the description of the samples provided in the published work would be insufficient to do this. If the variation in M_S is ignored, using the data available to Wohlfarth (1984) yields $x = 0.74$; this small difference in x is likely to be within rounding errors. Theoretical estimates for x depend on reversal mechanisms, and range from $0.5 < x < 1$ (e.g., Néel, 1951; Hilzinger and Kronmüller, 1975; Liu and Luo, 1990, 1991). It is generally predicted that $x = 1$ for uniaxial SD particles, but there are several discrepancies between domain wall theories, for example, Liu and Luo (1991) predict $x = 1$ for all reversal mechanisms, in contrast to a lower value of 0.5 by Hilzinger and Kronmüller (1975).

Ignoring the variation M_S and apply Eq. (2) to our findings for all 17 samples in Fig. 3, yields $H_C \propto v_{act}^{-1.9}$. To estimate variations in M_S, we assumed that the variations in Curie temperature (Table 1) are due to titanium substitution. We could only make this assumption for the Icelandic samples, as the Mexico samples displayed visible alteration and oxidation under the microscope. We applied the relationships given by Hunt *et al.* (1995) to make predictions for M_S (Table 1). Our estimates of the Curie temperatures are "primary" i.e., the "main" peak of thermomagnetic curves. Two more steps were added to the previously discussed Monte Carlo procedure to evaluate v_{act} for our basalt samples and its relationship to log H_C:

Step 3. Given the values of H_f calculated in the first Monte Carlo step, estimates of v_{act} were made for each of the samples using Eq. (2).
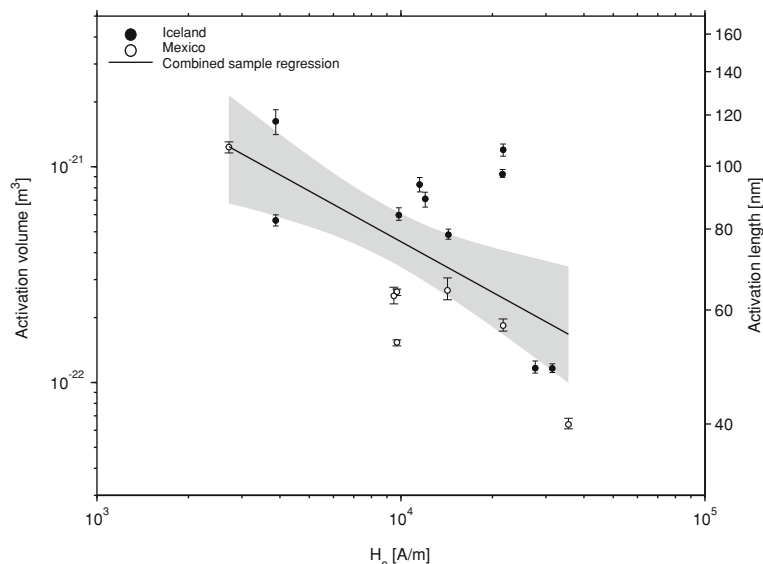
Fig. 4. Log v_{act} versus log H_C for the Icelandic samples. The activation volume was calculated from Eq. (2) using the Monte Carlo procedure described in the text and employing each sample's Curie temperature based M_S estimation. The error bars on each point represent the 90% confidence interval, (Table 1). The Monte Carlo procedure also yielded an estimate of the relationship (solid black line) between log v_{act} and log H_C which and is shown with the associated 90% confidence region (shaded area). The activation length, i.e., $v_{\text{act}}^{1/3}$, is depicted on the right vertical axis for reference.

Step 4. A linear regression was performed between the estimated values of v_{act} and log H_C.

Estimates of v_{act} for each sample were made based on the results of step 3, again with 90% confidence intervals. Finally, the linear relationship between v_{act} and log H_C within a 90% confidence region was determined from the distribution of results from step 4 (Fig. 4). The Monte Carlo procedure yielded an estimate of $H_C \propto v_{\text{act}}^{-0.68}$. This is considerably closer to the value derived by Wohlfarth (1984), and falls within the range of theoretical predictions. Hilzinger and Kronmüller (1975) predicted $H_C \propto v_{\text{act}}^{-2/3}$ for strongly pinned domain walls, similarly the Kersten inclusion theory of domain-wall motion also predicts the same relationship (Wohlfarth, 1984).

5. Conclusions

This is the first time that the relationship found by Barbier (1951, 1954) has been measured and tested for natural magnetic systems. The basalt samples were found to agree with the general relationship found by Barbier when compared to other magnetic materials, but the relationship within the basalts themselves is slightly different. Linear regression for log H_f versus log H_C yields a gradient of 0.54 for the basalt samples, compared to the value of 1.3 found when many different materials are considered. This difference is attributed to the fact, that the original relationship by Barbier was derived for a wide range of different synthetic magnetic materials, and not for variations within one particular material type.

The relationship between activation volume and coercive force was examined. By considering variation of M_S estimated from measured Curie temperatures, we found for the homogeneous Icelandic basalts, that $H_C \propto v_{\text{act}}^{-0.68}$ (Fig. 4). This falls comfortably in the range of predicted values, i.e., $0.5 < x < 1$, and compares favourably with empirical find-

ing of Wohlfarth (1984) of $H_C \propto v_{\text{act}}^{-0.73}$ for a wide range of materials, however, it is unknown if Wohlfarth's empirical relationship included material variation in M_S.

This study provides experimental support for the use of Néel's (1950, 1951) thermal fluctuation field in models for TRM acquisition in natural systems. Such theories are key to our under understanding of the reliability of palaeomagnetic data, though the use of the relationship found by Barbier should be modified for more appropriate basalt-specific values.

References

Barbier, J. C., Le traînage irréversible dans les champs faibles, *J. Phys. Rad.*, **12**, 352–354, 1951.

Barbier, J. C., Le traînage magnétique de fluctuation, *Ann. Phys.*, **9**, 84–140, 1954.

Basso, V., C. Beatrice, M. LoBue, P. Tiberto, and G. Bertotti, Connection between hysteresis and thermal relaxation in magnetic materials, *Phys. Rev. B*, **61**, 1278–1285, 2000.

Bina, M.-M. and M. Prévot, Thermally activated magnetic viscosity in natural multidomain titanomagnetite, *Geophys. J. Int.*, **117**, 495–510, 1994.

Bottoni, G., Critical volume for the switching of the magnetization in recording media, *J. Magn. Magn. Mater.*, **272–276**, 2269–2270, 2005.

Bruno, P., G. Bayreuther, P. Beauvillain, C. Chappert, G. Lugert, D. Renard, J. P. Renard, and J. Seiden, Hysteresis properties of ultrathin ferromagnetic films, *J. Appl. Phys.*, **68**, 5759–5766, 1990.

Day, R., M. D. Fuller, and V. A. Schmidt, Hysteresis properties of titanomagnetites: grain-size and compositional dependence, *Phys. Earth Planet. Inter.*, **13**, 260–267, 1977.

Dunlop, D. J., Thermal fluctuation analysis: a new technique in rock mag-

netism, *J. Geophys. Res.*, **81**, 3511–3517, 1976.

Dunlop, D. J. and M.-M. Bina, The coercive force spectrum of magnetite at high temperatures: evidence for thermal activation below the blocking temperature, *Geophys. J. R. Astr. Soc.*, **51**, 121–147, 1977.

Efron, B. and R. J. Tibshirani, *An Introduction to the Bootstrap*, 456 pp., Chapman and Hall, New York, 1993.

El-Hilo, M. and I. Bsoul, Interaction effects on the coercivity and fluctuation field in granular powder magnetic systems, *Physica B*, **389**, 311–326, 2007.

El-Hilo, M., K. O'Grady, and R. W. Chantrell, Fluctuation fields and reversal mechanisms in granular magnetic systems, *J. Magn. Magn. Mater.*, **248**, 360–373, 2002.

Gaunt, P., Magnetic viscosity and thermal activation energy, *J. Appl. Phys.*, **59**, 4129–4132, 1986.

Haggerty, S. E., Oxide Textures—A mini-altas, in Reviews in Mineralogy Volume 25—Oxide Minerals, in *Petrologic and magnetic significance*, edited by D. H. Lindsley, pp. 129–137, Mineralogical Society of America, Washington D.C., 1991.

Hilzinger, H. R. and H. Kronmüller, Statistical theory of the pinning of Bloch walls by randomly distributed defects, *J. Magn. Magn. Mater.*, **2**, 11–17, 1975.

Hunt, C. P., B. M. Moskowitz, and S. K. Banerjee, Magnetic properties of rocks and minerals, in *A Handbook of Physical Constants, vol. 3*, edited by T. J. Ahrens, pp. 189–204, American Geophysical Union, Washington, DC, 1995.

Klik, I. and C.-R. Chang, A discussion of the Barbier plot, *J. Magn. Magn. Mater.*, **114**, L235–L236, 1992.

Krása, D. and J. Matzka, Inversion of titanomaghemite in oceanic basalt during heating, *Phys. Earth Planet. Inter.*, **160**, 169–179, 2007.

Liu, J. F. and H. L. Luo, On the relationship between coercive force H_C and magnetic viscosity parameter S_v in magnetic materials, *J. Magn. Magn. Mater.*, **86**, 153–158, 1990.

Liu, J. F. and H. L. Luo, On the coercive force and effective activation volume in magnetic materials, *J. Magn. Magn. Mater.*, **94**, 43–48, 1991.

Mankos, M., M. R. Scheinfein, and J. M. Cowley, Quantitative micromagnetics: electron holography of magnetic thin films and multilayers, *IEEE Trans. Magn.*, **32**, 4150–4155, 1996.

Néel, L., Théorie du traînage magnétique des substances massives dans le domaine de Rayleigh, *J. Phys. Rad.*, **11**, 49–61, 1950.

Néel, L., Le traînage magnétique, *J. Phys. Rad.*, **12**, 339–351, 1951.

Prévot, M., Some aspects of magnetic viscosity in subaerial and submarine volcanic rocks, *Geophys. J. R. Astr. Soc.*, **66**, 169–192, 1981.

Shimizu, Y., Magnetic viscosity of magnetite, *J. Geomag. Geoelectr.*, **11**, 125–138, 1960.

Sholpo, L. Y., Regularities and methods of study of the magnetic viscosity of rocks, *Izv., Phys. Solid Earth*, **6**, 390–399, 1967.

Sholpo, L. Y., V. I. Belokon', and G. P. Sholpo, Thermally activated nature of the magnetic viscosity of rocks, *Izv., Phys. Solid Earth*, **1**, 42–46, 1972.

Street, R. and J. C. Woolley, A study of magnetic viscosity, *Proc. Phys. Soc. London (A)*, **62**, 562–572, 1949.

Street, R. and J. C. Woolley, Time decrease of magnetic permeability in Alnico, *Proc. Phys. Soc. London (B)*, **63**, 509–519, 1950.

Street, R. and J. C. Woolley, A comparison of magnetic viscosity in isotropic and anisotropic high coercivity alloys, *Proc. Phys. Soc. London (B)*, **69**, 1189–1199, 1956.

Street, R., J. C. Woolley, and P. B. Smith, Magnetic viscosity under discontinuously and continuously variable field conditions, *Proc. Phys. Soc. London (B)*, **65**, 679–696, 1952.

Sun, K., J.-F. Liu, and H.-L. Luo, Magnetic viscosity of magnetic recording media, *J. Phys. D: App. Phys.*, **23**, 439–442, 1990.

te Lintelo, J. G. T. and J. C. Lodder, On the relationship between magnetic viscosity and coercivity of perpendicular media, *J. Appl. Phys.*, **76**, 1741–1744, 1994.

Thellier, E. and O. Thellier, Sur l'intensité du champ magnétique terrestre dans le passé historique et géologique, *Ann. Géophys.*, **15**, 285–376, 1959.

Williams, W. and D. J. Dunlop, Three-dimensional micromagnetic modelling of ferromagnetic domain structure, *Nature*, **337**, 634–637, 1989.

Wohlfarth, E. P., Thermal Fluctuation Effects in Thin Magnetic Films, *J. Elect. Con.*, **10**, 33–37, 1961.

Wohlfarth, E. P., The coefficient of magnetic viscosity, *J. Phys. F: Met. Phys.*, **14**, L155–L159, 1984.

A. R. Muxworthy (e-mail: adrian.muxworthy@imperial.ac.uk), D. Heslop, and D. M. Michalk