Geophysical Journal International

Geophys. J. Int. (2011) **187,** 118–127 doi: 10.1111/j.1365-246X.2011.05163.x

GJI Geomagnetism, rock magnetism and palaeomagnetism

Evaluation of the domain-state corrected multiple-specimen absolute palaeointensity protocol: a test of historical lavas from Iceland

Adrian R. Muxworthy and Samuel N. Taylor

Department of Earth Science and Engineering, Imperial College London, London, UK. E-mail: adrian.muxworthy@imperial.ac.uk

Accepted 2011 July 18. Received 2011 July 15; in original form 2011 January 17

SUMMARY

Palaeointensity estimates were made for a suite of five historical lava flows from Mt Askja, Iceland, with the purpose of testing the newly proposed domain-state corrections to the multispecimen parallel differential pTRM palaeointensity method (MSP), where pTRM stands for partial thermoremanent magnetization. Before beginning the experimental procedure, the chemical stability on heating to the determined pTRM induction temperature was assessed; some flows were found to be unaltered by heating, some displayed inconsistent repeatability, while one flow was severely affected by heating. To implement the domain-state corrections and interpret the data successfully, we had to implement two new approaches to the MSP method: (1) we used vector addition/subtraction in our calculations, and (2) we introduced a new selection/rejection criterion that improves the robustness of the estimates by preferentially removing outliers based on the error analyses of the linear regression. This rejection criterion typically rejected one or two points, and was found to significantly improve the estimates. With the exception of the one flow that displayed significant chemical alteration during the experiment, the palaeointensity estimates determined using the original MSP protocol yielded estimates within ±3 μT of the known field of 49.5 μT. The domain-state corrected MSP estimates were all within ±4 μT, with no clear relationship between the uncorrected and domain-state corrected palaeointensity estimates for this data set.

Key words: Palaeointensity; Palaeomagnetic secular variation; Rock and mineral magnetism.

1 INTRODUCTION

Quantifying the history of the Earth's magnetic field as recorded by rocks enables us to understand ancient geodynamic processes and constrain geodynamo models. The absolute geomagnetic field intensity (palaeointensity) recorded by rocks is critical to this process, however, recovering this information has been problematic since the first early attempts were made (Folgerhaiter 1899; Koenigsberger 1938a,b; Thellier 1941). The original methods assumed that the natural remanent magnetization (NRM) is a thermoremanent magnetization (TRM) in origin. By comparing the NRM of a rock with a laboratory induced TRM, the ancient field strength is estimated by simple scaling with the laboratory field. The main problem with this approach is that on heating and inducing the laboratory TRM, the magnetic minerals in the rocks often chemically alter, leading to incorrect palaeointensity estimates. To identify chemical alteration, Koenigsberger (1938a,b), Thellier (1941) and Thellier & Thellier (1959) developed multistep thermal heating protocols. The latter protocol was modified by Coe (1967) to include double demagnetization/remagnetization steps at increasing temperatures until a full TRM is induced. This 'Thellier-type' approach of Coe (1967) and its many subsequent modifications form the basis of most modern palaeointensity studies. In many cases it successfully identifies chemical alteration, and palaeointensity determinations can be made from the lower temperature measurements before chemical alteration occurs. However, because of the use of the multistep heating protocol, it is required that the samples obey the laws of partial TRM (pTRM) additivity, that is, a stepwise pTRM acquired over the temperature range T_1 and T_3 should be equal to the sum of two pTRMs acquired over the temperature range T_1–T_2 and T_2–T_3, respectively; pTRM independence, that is, a pTRM produced over one interval are independent of a pTRM acquired over another, and reciprocity, that is, blocking and unblocking temperatures are equal (Xu & Dunlop 2004). The laws of additivity and reciprocity are obeyed by small magnetically single domain (SD) grains, but larger multidomain (MD) grains violate the reciprocity law (Dunlop 1998) and the independence law (Yu & Dunlop 2006). The contribution of intergrain magnetostatic interactions has not been quantified rigorously, and it is still debated if interacting SD grains will obey these laws or not (Levi 1977; Shcherbakov & Sycheva 1997; Fabian 2001; Dunlop *et al.* 2005). These requirements present major problems for many rocks types, which contain a wide grain size spectrum of magnetic particles spanning the SD to MD states.

To reduce the effects of both chemical alteration and non-ideal SD behaviour, Dekkers & Böhnel (2006) proposed a new method, the 'multispecimen parallel differential pTRM method' (here referred to as MSP-DB). The basic idea behind the method is simple: to overprint an ancient NRM (assumed to be

Table 1. Localities of the samples and thermomagnetic properties.

Location code	Flow name	Locality	Date of eruption (A.D.)	Rock type	ARM thermomagnetic curve repeatability
AA	–	65.0684N, 16.7668W	1961	Basalt	Repeatable
AB	–	65.0699N, 16.7223W	1961	Basalt	Repeatable
AC	Suðurbotnahraun	65.0218N, 16.6943W	1922/1923	Basalt	Partially
AD	Kvíslahraun	65.0107N, 16.7032W	1922/1923	Basalt	Repeatable
AF	Mývetningahraun	65.0289N, 16.7942W	1922	Basalt	Not repeatable
AG	Bátshraun	65.0435N, 16.7228W	1921	Basalt	Partially

thermoremanent in origin) with a laboratory pTRM induced at a temperature T much less than the Curie temperature (T_C) in a laboratory field H_{lab} applied in the same direction as the NRM. It is then assumed, that if the final remanence is smaller than the original NRM, $H_{lab} <$ ancient field H_{anc}, and if larger $H_{lab} > H_{anc}$. The advantage of this method over the Thellier-type methods is that the samples are only subjected to moderate heating and that the number of pTRMs induced in the samples is significantly smaller, that is, the combined effect of repeatedly breaking pTRM additivity and reciprocity rules through multiple heating is reduced.

Dekkers & Böhnel (2006) originally claimed that the method was independent of domain state, however, Michalk *et al.* (2008) provided evidence to suggest that this was incorrect. Using the phenomenological model of Fabian (2000, 2001), Fabian & Leonhardt (2010) showed that the MSP-DB method will overestimate the palaeointensity for pseudo-SD (PSD) and MD grains. To account for domain state, they introduced a modified MSP-DB protocol, which they successfully tested using synthetic samples (covering SD, PSD and MD grain sizes). In this paper, we report a study whereby we test this new modified MSP-DB protocol of Fabian & Leonhardt (2010) using historical basalts collected at the Mt Askja volcano in central Iceland.

2 SAMPLES

We have collected historical basaltic lavas from five 20th century flows from Mt Askja in the central highlands in Iceland (Table 1): the Bátshraun lava flow (1921), the Mývetningahraun lava flow (1922), the Suðurbotnahraun lava flow (1922 or 1923), the Kvíslahraun lava flow (1922 or 1923) and the 1961 lava flow (Hjartardóttir *et al.* 2009). Mt Askja is a stratovolcano situated in the centre of Iceland in the 200-km-long Askja fissure swarm, and last erupted in 1961 A.D. Mt Askja is now dominated by a large caldera lake, which is the result of a Plinian eruption in 1875 A.D.

3 METHOD

Drill cores with a diameter of 10 mm (mini-cores) were collected and orientated in the field. In the laboratory, samples were cut into specimens of 9–10 mm length, which yielded 2–5 specimens for each drill core.

3.1 Rock magnetic analysis

In addition to the MSP-DB analysis, we conducted routine hysteresis measurements at the Institute for Rock Magnetism (IRM), University of Minnesota, USA. The hysteresis measurements including first-order reversal curves (FORCs) were made using a Princeton Measurements Corporation Vibrating Sample Magnetometers (VSM; Princeton Measurements Corporation, Princeton, NJ).

3.2 The MSP-DB method and its modifications

To conduct the MSP-DB measurements we used up to nine specimens per flow; there were insufficient specimens for flows AC and AD. For these two flows only six specimens were examined. The sample sets from the 1961 flow, that is, AA and AB (Table 1), were treated as one data set; the two localities were within 200 m of each other. Sister samples from neighbouring cores were intermixed with each other during the experiments. All the MSP-DB experiments and its modifications were made at Imperial College, London.

For the MSP-DB experiment, it is first necessary to check for the absence of secondary magnetizations in the sample, and then to select a temperature (T_i) for the pTRM acquisition that is below the point where chemical alteration is significant. To determine this temperature, the NRM of several samples from each flow were continuously thermally demagnetised using an Orion three-axis, low-field VSM. The thermal stability of the lavas' remanences on heating up to the temperature T_i was also tested, by first demagnetizing the samples using a tumbling alternating-field (AF) Molspin demagnetizer with a peak field of 100 mT. Then, an anhysteretic remanent magnetization (ARM) was then imparted using a DTECH AF demagnetizer with a peak field of 200 mT and a bias field of 0.1 mT. The thermal demagnetization behaviour of this ARM was then measured at temperature on cycling up to T_i and back to room temperature. This was repeated and the two curves compared for repeatability.

The MSP-DB experiments were conducted using a combination of an ASC TD-48 dual-chamber thermal specimen demagnetiser and an Agico JR5A spinner magnetometer. To induce the pTRM parallel to the NRM, we used a specially designed sample holder very similar to the one used by Michalk *et al.* (2008, 2010). The error in the orientation was $<5°$. The sample holder took only 10 mm cores. We applied successively increasing fields in 10 μT steps from 10 to 90 μT, using sister samples for each field. It is shown in Section 4.2 that the samples were essentially univectorial, therefore, no thermal pre-treatment was applied to the samples (Dekkers & Böhnel 2006).

We used the new protocol of Fabian & Leonhardt (2010), which includes additional steps to those proposed by Dekkers & Böhnel (2006) that allow for domain-state corrections and a chemical alteration test. The new protocol now includes five remanence measurements (m_0 is the original NRM) and four addition steps, as follows.

(1) m_1. In a constant external field H_{lab} aligned parallel to original NRM, the specimen is heated to T_i and then cooled to room

temperature. When combined with m_0, this is essentially the original protocol of Dekkers & Böhnel (2006) termed here MSP-DB.

(2) m_2. In a constant external field H_{lab} aligned anti-parallel to the original NRM, the specimen is heated to T_i and then cooled to room temperature.

(3) m_3. The specimen is heated in zero field to T_i, and cooled in H_{lab} aligned parallel to the original NRM field.

(4) m_4. This is a repeat of m_1. This last step is a chemical alteration check.

Steps 2 and 3 were introduced by Fabian & Leonhardt (2010) to correct for domain-state effects. Using the pictorial representation of blocking and unblocking processes introduced by Fabian (2000), and used extensively by Fabian & Leonhardt (2010), step 2 corresponds to a correction for pTRM induced in the samples by MD material in area 1 (Fig. 1), and step 3, for the MD contribution to area 2 (Fig. 1). Using the new protocol adds two further estimates, that is, we now have three estimates for the palaeointensity depending on how many of the domain-state corrections are included. If none are included, that is, the protocol of Dekkers & Böhnel (2006), the original MSP-DB ratio Q_{DB} (nomenclature of Fabian & Leonhardt 2010) is given by

$$Q_{DB} = \frac{m_1 - m_0}{m_0}. \quad (1)$$

To determine the MSP-DB estimate, the Q_{DB} ratio is plotted versus pTRM inducing field for each sister sample, and where the fitted linear trend is equal to zero provides the field estimate. If the first domain-state correction is included, the so-called f-corrected MSP-DB ratio Q_{FC} is given by (Fabian & Leonhardt 2010)

$$Q_{FC} = 2\frac{m_1 - m_0}{2m_0 - m_1 - m_2}. \quad (2)$$

This does not account for all the domain-state effects. The final correction is the domain-state corrected ratio Q_{DSC} given by (Fabian & Leonhardt 2010)

$$Q_{DSC} = 2\frac{(1+\alpha)m_1 - m_0 - \alpha m_3}{2m_0 - m_1 - m_2}, \quad (3)$$

where α is an unknown parameter ≥0. Fabian & Leonhardt (2010) proposed a method of determining α when a sufficient number of measurements are available, the goodness of fit of the data to eq. (3) is highest for the optimal average choice of α. They suggest that α should be chosen by minimizing the mean quadratic deviation χ^2 (α) between the available site-specific data and the linear fit.

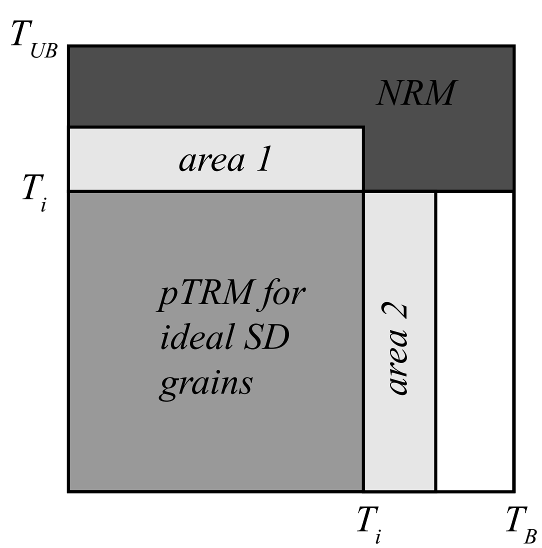

Figure 1. Schematic simplified blocking/unblocking spectrum diagram used to describe the remanent magnetizations for the domain-state corrected palaeointensity protocol of Fabian & Leonhardt (2010). Areas 1 and 2 correspond to the contributions MD remanence makes to the total remanence acquired on heating to T_i. For ideal SD grains the blocking and unblocking spectra are identical. Based on a drawing from Fabian & Leonhardt (2010).

4 RESULTS

4.1 Rock magnetic

The ratios of the magnetic hysteresis parameters, that is, the coercive force H_C, the remanent coercive force H_{CR}, the saturation magnetisation M_S and the remanent saturation magnetisation M_{RS} are shown for all the samples on a 'Day plot' (Day *et al.* 1977) in Fig. 2.

Generally the basaltic lava samples, notably those from the 1961 flow (AA and AB), plot towards the SD region. There are a few exceptions to this, that is, some samples from Kvíslahraun (AD) and Bátshraun (AG) plot in the middle of the PSD region, and some Suðurbotnahraun (AC) and Mývetningahraun (AF) samples lie in the area above the MD region on the right-hand side of the PSD region. This latter behaviour is often attributed to thermal relaxation, that is, superparamagnetism (Jackson *et al.* 1990). Specimens from flows AC and AF show a far wider variation in their magnetic properties than specimens from the other flows.

Two example FORC diagrams are shown in Fig. 3. Generally, samples displaying SD, PSD and MD characteristics, as indicated by their position on the Day plot (Fig. 2), display corresponding FORC diagrams (e.g. Roberts *et al.* 2000; Muxworthy & Roberts 2007). For example, the sample AA6, displays an SD-like FORC diagram (Fig. 3a), and plots near the SD region on Fig. 2. Samples from AC and AG, for example, AC2A (Fig. 3b), which fall outside the usual regions on Fig. 2, consist of a peak associated with a low-coercivity magnetisation, and a higher coercive-force-tail magnetisation that is likely to be a highly stable magnetic remanence carrier. Examination of the Day plot alone (Fig. 2) belies the potential of such samples.

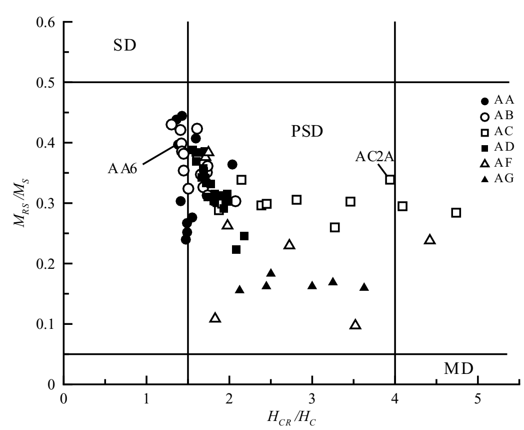

Figure 2. A 'Day plot' (Day *et al.* 1977) of the ratios of the hysteresis parameters M_{RS}/M_S versus H_{CR}/H_C for the five lava flows in this study. Two samples identified in this figure have their FORC diagrams displayed in Fig. 3. The regions commonly associated with SD, PSD and MD behaviour are labelled.

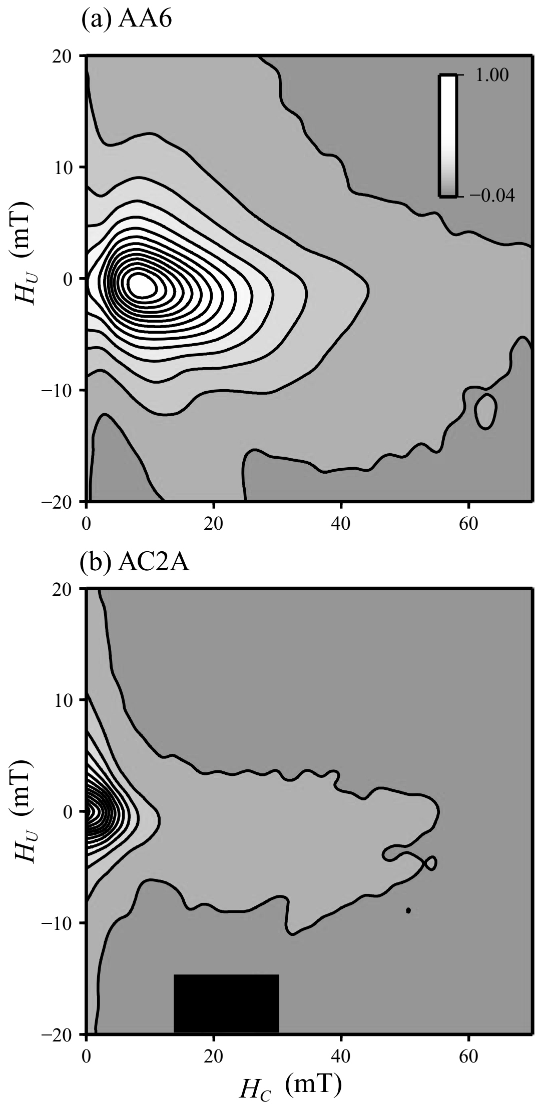

Figure 3. FORC diagrams for samples for sample (a) AA6 (1961 flow) and (b) AC2A (Suðurbotnahraun flow). The smoothing factor (SF) in all three diagrams is 2. The averaging time during the measurement was 100 ms. Note the identical scales for each diagram.

4.2 MSP palaeointensity results

To determine the pTRM inducement temperature and verify that the NRM was univectorial, the NRM of several samples was thermally demagnetised (Figs 4 and 5). To accommodate all the samples, a pTRM inducement temperature of 350 °C was chosen. This temperature may have been a little high for flow AG (Bátshraun). In all the test samples the NRM was found to be univectorial (Fig. 5). To further verify that the NRMs were univectorial, the NRM directions for all the samples in the palaeointensity study are considered; the first measurement of the palaeointensity protocol is of the NRM. The NRM directions are plotted on an equal area projection plot (Fig. 6). It is seen that the modern day field lies within the α_{95} confidence cone, that is, the lavas have recorded only the ambient field on formation. There is a degree of scatter amongst the modern data; however, it must be remembered that these specimens were sampled as 10 mm cores, which increases the directional error compared to

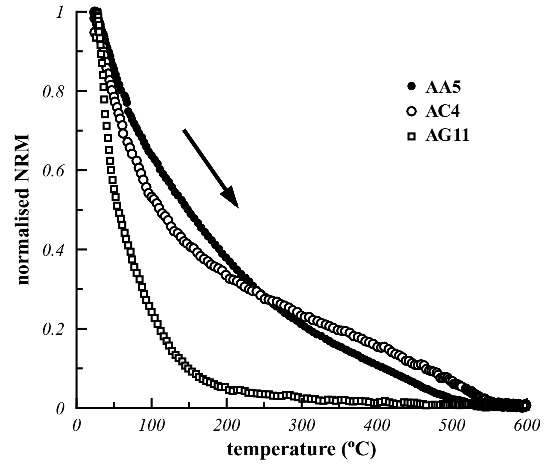

Figure 4. Continuous thermal demagnetisation curves of NRM in samples AA5, AC4 and AG11.

large core diameters, and we considered the NRM directions, that is, just one measurement, and not the characteristic direction.

The thermal stability of the remanence carriers in the samples was then assessed to heating to 350 °C, by examining continuous thermal demagnetisation curves of ARM. The samples displayed a range of behaviour (Fig. 7). The samples from the 1961 flows (AA and AB) and the AC (Suðurbotnahraun) flow displayed mostly repeatable ARM demagnetisation curves. The Kvíslahraun (AD) and Bátshraun (AG) flows displayed a range of behaviours, that is, some samples from these flows displayed repeatable behaviour, whereas others did not (Table 1). Generally all the samples from the Mývetningahraun (AF) flow displayed evidence for chemical alteration during repeat thermal demagnetisation of ARM (Fig. 7).

Early analysis of the palaeointensity data revealed that rather than conducting a straight scalar subtraction of intensities in eqs (1)–(3), it was necessary to include a vector subtraction of the magnetisation (Table 2). This was necessary because of step 2 (eq. 2), which induces a pTRM in the opposite direction to the original NRM, that is, in some samples at step 2 the reversed pTRM combined with the remaining NRM was not aligned with the initial NRM. The MSP-DB data was least affected by the use of scalar subtraction (Table 2). Throughout the rest of the paper we present only the data derived from vector addition/subtraction of the measured magnetizations (Table 2).

In Fig. 8, we plot the estimates for Q_{DB}, Q_{FC} and Q_{DSC} ratios given, respectively by eqs (1)–(3), versus the pTRM inducing field for all five lava flows. Field estimates are presented in Table 2. To determine the error on each estimate, Fabian & Leonhardt (2010) propose a method based not on the quality of the linear fit, but on the measured degree of chemical alteration during the experiment, that is, by comparing the last measurement step m_4 with the second measurement m_1, plus the relative size of the domain-state corrections. They propose to use these errors as weights in the linear regression. We tried this approach, however, the weighting was often found to hinge on a particular point with a low error estimate. In addition, as Fabian & Leonhardt (2010) note, in their determination the error on each individual estimate is dependent on the inducing field. Given the problems with this suggested error analysis, we employed the approach of other earlier studies (Dekkers & Böhnel 2006; Michalk *et al.* 2008), by simply determining confidence intervals at 95 per cent (CI_{95}) to the linear fits (Table 2). We have excluded

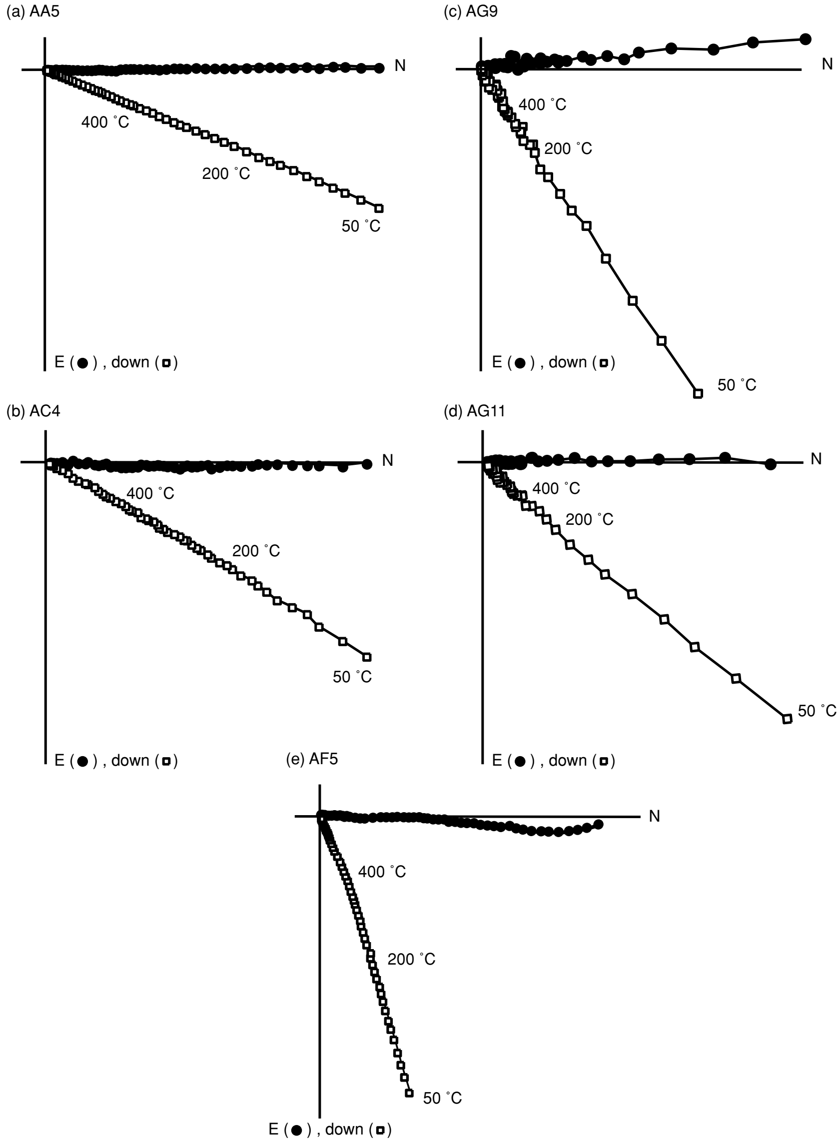

Figure 5. (a) Orthogonal-projection continuous thermal demagnetization plots for samples from cores: (a) AA5, (b) AC4, (c) AG9, (d) AG11 and (e) AF5. All the plots display univectorial magnetizations.

these confidence intervals from the plots for clarity. At 95 per cent confidence some confidence intervals were not defined (ND; Table 2), that is, the confidence limit does not cross the *x*-axis or is negative meaning that there is essentially no relationship at this confidence level.

4.2.1 Original MSP-DB determination

We have plotted the original MSP-DB calculation of Dekkers & Böhnel (2006), that is, Q_{DB} from eq. (1) in the left-hand column of Fig. 8. The palaeointensity estimates are tabulated in Table 2. The 1961 flow (AA and AB), returns an estimate of 51 μT but with a large CI_{95} level of 18–87 μT because of large levels of dispersion in the data. The expected value is 49.5 μT. Flow AC (Suðurbotnahraun) returns a value above the expected intensity at 64 μT, but CI_{95} is not defined and the estimate is rejected (Table 2). Samples from flow AD (Kvíslahraun) yield an overestimate (66 μT, CI_{95} is 38–126 μT), and flow AG (Bátshraun) a value of 53 μT, but with a wide confidence interval (CI_{95} is 28–93 μT). Samples from AF (Mývetningahraun) yield a negative intensity estimate, and CI_{95} is undefined (Table 2) and the estimate is rejected.

4.2.2 MSP-FC and MSP-DSC determinations

In Fig. 8 we consider the proposed domain-state correction ratios Q_{FC} and Q_{DSC} suggested by Fabian & Leonhardt (2010). The full MSP-DSC correction is dependent on a parameter α (eq. 3), which is found by minimizing χ^2 (α). For all our flows we found that χ^2 (α) was minimized at $\alpha = 0$. Fabian & Leonhardt (2010) suggest a default value of $\alpha = 0.5$. As Q_{FC} and Q_{DSC} are identical for $\alpha = 0$, we present the MSP-DSC terms for $\alpha = 0.5$, although it should be realized that for our data this is incorrect.

The MSP-FC and MSP-DSC estimates derived from the Q_{FC} and Q_{DSC} ratios, respectively, are rejected for the 1961, AC and AF flows, as their confidence limits were undefined (Table 2). Flow AD (Kvíslahraun) yielded an MSP-FC estimate of 66 μT (CI_{95} 42–123 μT), but the MSP-DSC estimate was rejected as CI_{95} is not defined. Flow AG (Bátshraun) returned an MSP-FC estimate of

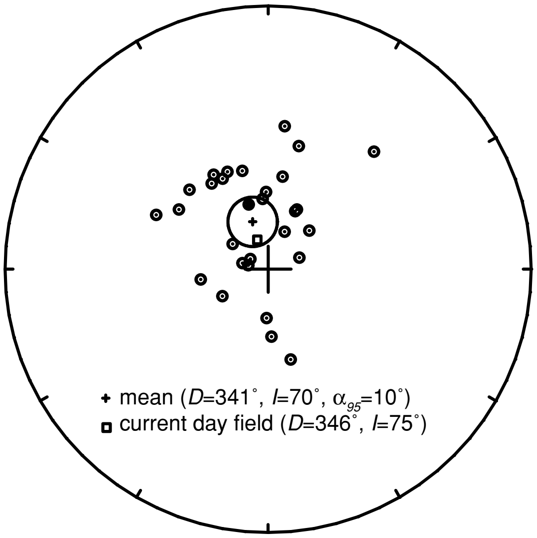

Figure 6. An equal area projection plot displaying the NRM directions for the samples used in the palaeointensity study. For cores where more than one sample was used, the core average direction was taken in the calculation of the mean declination (D), inclination (I) and α_{95}. The NRM data displays quite a high level of scatter, although it must be remembered that these cores were only 10 mm cores, which increases orientation error. The modern day field direction ($D = 346°$ and $I = 75°$) was determined using IGRF11. For comparison, the field in 1921 was $D = 331°$ and $I = 76°$.

53 μT (CI_{95} 29–81 μT), and an MSP-DSC estimate of 46 μT (CI_{95} 8–73 μT).

5 DISCUSSION

With the exception of flow AF (Mývetningahraun), the palaeointensity estimates all lay close to the expected field intensity of 49.5 μT (Table 2), however, all have very large confidence ranges. The net average effect of applying the MSP-FC and MSP-DSC protocols of Fabian & Leonhardt (2010) is to decrease the intensity estimate compared to the MSP-DB method of Dekkers & Böhnel (2006) (Table 2).

Unlike previous studies, we applied vector addition/subtraction in all our determinations. Given that the samples had essentially univectorial NRM direction (Fig. 5) and that some of the samples were found to be chemically unstable to relatively modest heating, it is suggested that the vector addition/subtraction was required because of the acquisition of chemical remanent magnetizations (CRMs). CRMs acquired in reverse field directions to the original NRM are likely to lead to more complex total remanences, than CRMs induced in the same direction as the original NRM. The use of the m_2 step has the potential to act as another alteration check.

5.1 A new selection criterion

It is clear by examination of Fig. 8 that the final fits are often strongly influenced by individual 'outliers'; the data generally display higher levels of dispersion than observed in most previous studies of this type (Michalk *et al.* 2008; Böhnel *et al.* 2009; Michalk *et al.* 2010). We propose a new selection/rejection approach, based on the observation that the outliers are generally associated with large differences between m_1 and m_4, that is, large changes in the magnetic mineralogies' recording capacity during the experiment. To apply

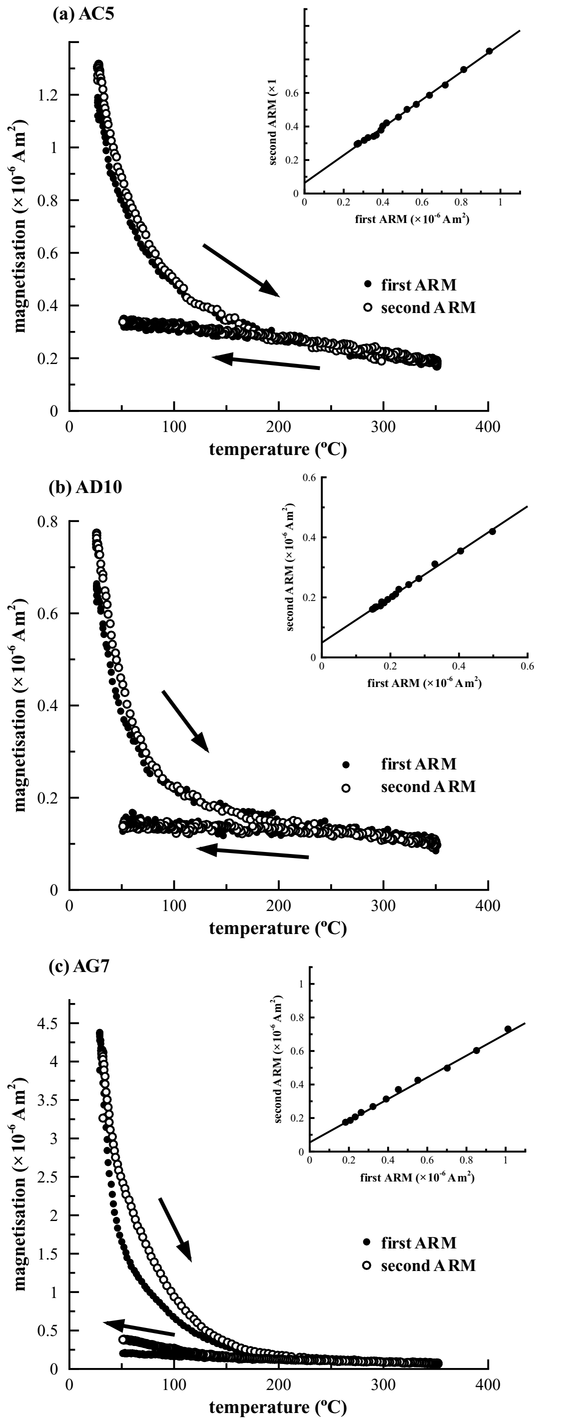

Figure 7. Continuous thermal demagnetisation curves for ARM induced twice, that is, first and second, in samples: (a) AC5, (b) AD10 and (c) AG11. Each plot contains an inset where the binned data for the first and second ARM curves are plotted against each other. A linear trend is fitted in the inset.

this new criterion, we first sort the data within each flow by $\varepsilon^*_{\text{alt}}$, where $\varepsilon^*_{\text{alt}}$ is similar to the ε_{alt} [$=|(m_1 - m_4)/m_1|$] parameter given by Fabian & Leonhardt (2010). $\varepsilon^*_{\text{alt}}$ is defined as

$$\varepsilon^*_{\text{alt}} = 1 - \left|\frac{m_1 - m_4}{m_1}\right|. \quad (4)$$

Table 2. Palaeointensity estimates for the basaltic lavas.

Location code	Geomagnetic field[a] (μT)	$\varepsilon_{\mathrm{alt}}$ range		MSP-DB		MSP-FC		MSP-DSC ($\alpha = 0.5$)	
				Estimate (μT)	CI_{95} (μT)	Estimate (μT)	CI_{95} (μT)	Estimate (μT)	CI_{95} (μT)
AA and AB	49.5		Scalar	46	19 − 67	14	ND–ND	25	ND–ND
		0.04–0.36	Vector	51	18 − 87	47	ND−59	41	ND−74
			E_i, reject 2[b]	49	35 − 75	45	13 − 71	41	ND−65
AC	49.5		Scalar	55	ND−ND	ND	ND−ND	ND	ND−ND
		0.03–0.90	Vector	64	ND−ND	74	ND−ND	68	ND−ND
			E_i, reject 1	49	35 − 62	50	36 − 62	45	30 − 56
AD	49.5		Scalar	52	43−ND	27	ND−ND	29	ND−ND
		0.01–0.30	Vector	67	40 − 126	66	42 − 123	49	ND−ND
			E_i, reject 2	52	40 − 77	54	38 − 91	40	ND−ND
AF	49.5		Scalar	ND	ND−ND	87	ND−ND	99	ND−ND
		0.01–0.60	Vector	ND	ND−ND	58	ND−ND	52	ND−44
			E_i, reject 3	35	ND−59	33	ND−ND	28	ND − ND
AG	49.5		Scalar	46	23 − 64	47	29 − 147	43	40 − 164
		0.01–0.26	Vector	53	27 − 93	53	29 − 80	46	8 − 73
			E_i, reject 0	53	27 − 93	53	29 − 80	46	8 − 73

Note: ND, not defined (this includes negative numbers).
[a]Deduced from the International Geomagnetic Reference Field (IGRF).
[b]Number of rejected points during E_i minimization, determined using vector calculations.

The range of $\varepsilon^*_{\mathrm{alt}}$ values for each flow are tabulated in Table 2. Second, we stepwise reject the data with the largest $\varepsilon^*_{\mathrm{alt}}$ values, determining the error estimate (E_i) of each linear regression ($y = a_i x + b_i$), where E_i is given by

$$E_i = \left[\left(\frac{\Delta a_i}{a_i}\right)^2 + \left(\frac{\Delta b_i}{b_i}\right)^2\right]^{\frac{1}{2}}, \tag{5}$$

and a_i and Δa_i are the gradient and its associated error, b_i the fitted constant and Δb_i its error and i the number of samples used to make the determination. We then take the minimum value of E_i as the most robust palaeointensity estimate. E_i is reduced by removing outliers and by increasing the number of points used in the linear fit, therefore E_i is minimized by removing only a few samples with large $\varepsilon^*_{\mathrm{alt}}$ values, that is, typically outliers.

We applied this approach to our data set, and the 'E_i minimized' palaeointensity estimates are tabulated in Table 2. Fig. 9 depicts a plot of E_i versus i for three flows, and in Fig. 8 the rejected data points are highlighted. It is readily seen that the removal of outliers both improves the quality of the palaeointensity estimate and significantly reduces the confidence interval ranges compared to the palaeointensity estimates made for all the samples. For example, for flow AD (Kvíslahraun) two points are removed, reducing the MSP-DB estimate from 65 to 52 μT and the 95 per cent confidence range from 38–126 μT to 40–77 μT. For flow AC (Suðurbotnahraun), the removal of just one point reduces the MSP-DB and MSP-FC estimates to 49 and 50 μT, respectively, but also allows for the definition of confidence limits that are relatively narrow, that is, 35–62 μT and 36–62 μT, respectively (Table 2). The most unreliable flow AF (Mývetningahraun), now produces more realistic palaeointensity estimates, for example, the MSP-DB estimate is 35 μT rather than being negative, however, we still reject all the estimates for this flow as the confidence limits cannot be defined (Table 2). For flow AG (Bátshraun), which had no obvious outliers, E_i was minimized when all the data points were included, that is, the proposed selection criteria palaeointensity estimate and the original estimate are identical.

5.2 How well do the domain-state corrections work?

Given the significant improvement to the palaeointensity estimates after the new selection criteria introduced in Section 5.1, we consider only the E_i minimized MSP-DB, MSP-FC and MSP-DSC estimates (Table 2). As stated earlier for our data set, we found that χ^2 (α) is minimised for $\alpha = 0.0$ for which MSP-FC ≡ MSP-DSC; in our estimations in Table 2, we have used $\alpha = 0.5$, albeit incorrectly, as suggested as the default value by Fabian & Leonhardt (2010). It is clear from Table 2 that for our data set, MSP-FC provides better estimates than MSP-DSC ($\alpha = 0.5$), that is, in four out of five case MSP-FC produces an estimate that is closer to the expected value than the MSP-DSC ($\alpha = 0.5$) estimate (Table 2). In the other case, that is, for the AG flow (Bátshraun), the MSP-FC estimate is 3.5 μT over the actual field, the MSP-DSC ($\alpha = 0.5$) estimate 3.5 μT under. This demonstrates the importance of determining α for individual data sets.

The MSP-DB and the MSP-FC [≡MSP-DSC ($\alpha = 0.0$)] estimates are generally similar, although there is no consistent trend. For example, for flow AC the MSP-DB estimate is 49 μT and the MSP-FC estimate is 50 μT with similar confidence ranges (Table 2), and for the 1961 flow, the MSP-DB estimate is 48 μT and the MSP-FC estimate is 45 μT with similar confidence ranges (Table 2). The flow with the most MD-like characteristics, that is, AG, displayed the largest difference between the MSP-DB and MSP-FC estimates, although the latter estimate was only marginally better (Table 2). Therefore, from this data set it is not clear whether the application of the domain-state corrections improves the palaeointensity, however, given the limitations of this data set, that is, five lava flows from the same volcano, it is probably worth pursuing the protocol of Fabian & Leonhardt (2010) in future studies. The data supports the first-order symmetry model of Biggin & Podrais (2006).

6 CONCLUSIONS

We have determined palaeointensity estimates from a suite of historical lavas from Mt Askja, with the purpose of testing the domain-state corrections proposed by Fabian & Leonhardt (2010) to the original MSP-DB method of Dekkers & Böhnel (2006). We have

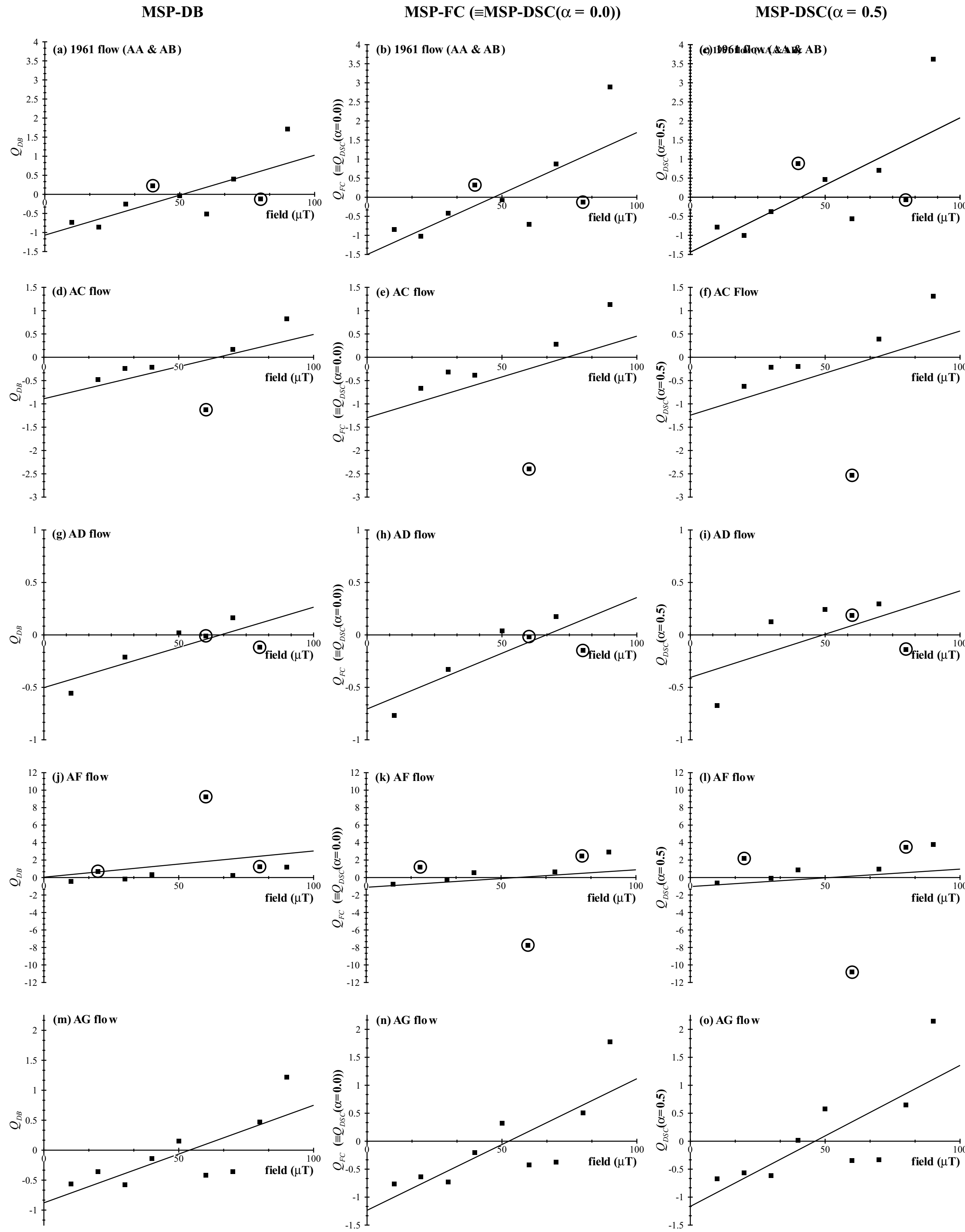

Figure 8. Palaeointensity estimates for the five flows in this study. In the left-hand column are plotted the Q_{DB} ratios versus field from which the MSP-DB estimates are calculated, similarly for the middle column the Q_{FC} ratios, and in the right hand column the Q_{DSC} ratios. In this paper the optimal value of α (eq. 3) was found to be zero, therefore, for this paper MSP-FC = MSP-DSC, as MSP-FC ≡ MSP-DSC ($\alpha = 0.0$). In the right-hand column α was set to 0.5, as this was the default value suggested by Fabian & Leonhardt (2010). The rejection criterion introduced in Section 5.1 has not been applied, although the rejected points are ringed. Note the difference in scales on the *y*-axis.

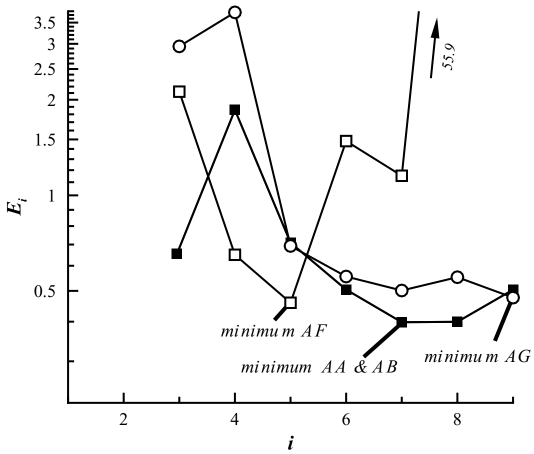

Figure 9. E_i versus i, for three of the lava flows (AA and AB, AF and AG). E_i is defined in eq. (5), and i is the number of samples used to make the determination. The minimum value of E_i is used to reject possible outliers associated with large errors as discussed in Section 5.1. For flow AG no points are rejected, for AA and AB (1961) flow two points are rejected and three for the AF flow (AF initially only had eight samples). For a linear trend, the error on the linear fit for $i \leq 2$ is meaningless and the plot is truncated.

introduced two alterations to the proposed method of Fabian & Leonhardt (2010): (1) we use vector addition/subtraction in our calculations (Table 2) and (2) we have introduced and applied a new criterion that attempts to improve the robustness of the estimates by preferentially removing outliers based on the error analyses of the linear fits. The second addition was the more significant (Table 2), and was introduced to remove 'outliers', which were common to our samples. Outlying behaviour was generally observed in samples that displayed high levels of chemical alteration during the experiment, that is, the wide dispersion in the samples' response was likely because of chemical alteration of the magnetic minerals within the samples.

With the exception of one flow (AF), which displayed significant alteration during the experiment, the palaeointensity estimates determined using the MSP-DB protocol determined using the E_i minimization procedure were all within ± 3 μT of the expected estimate, and the MSP-FC [$\equiv$MSP-DSC ($\alpha = 0.0$)] all lie within ± 4 μT of the actual value of 49.5 μT. Generally, there was no significant difference between the MSP-DB and the domain-state corrected estimates, although the one flow, that is, AG (Bátshraun), which had the most MD-like hysteresis parameters displayed a slight improvement on the application of the domain-state corrections (Table 2).

One problem that still remains is how to assess the degree of chemical alteration in the samples on heating. In this study, we tried to assess this using thermal demagnetization of ARM, however, it is clear from these experiments that there is significant variation between sister samples, making such experiments non-definitive. We support the final measurement step, that is, m_4, suggested by Fabian & Leonhardt (2010), as this repeat step provides a measurement of chemical alteration during the experiment through eq. (4). However, the most likely heating step where chemical alteration occurs is on the initial heating step, that is, between m_0 and m_1. It is difficult to assess the degree of alteration over this step; room temperature susceptibility can be measured before and after heating, but again this does not provide a definitive answer.

In conclusion, with the exception of the flow AF (Mývetningahraun), which displayed significant alteration and erratic behaviour during the experiment, both the original MSP-DB and the domain-state corrected estimates provide estimates comparable with those published on other historical lavas (Dekkers & Böhnel 2006; Michalk *et al.* 2008). The new criterion proposed in this paper that preferentially removes outliers improves the quality of the palaeointensity estimates.

ACKNOWLEDGMENTS

This work was funded by the Royal Society. We would like to thank Margaret Hartley and Karin Strohecker for field assistance in Iceland. Some measurements were made at the Institute for Rock Magnetism, University of Minnesota, which is funded by the National Science Foundation, W. M. Keck Foundation and the University of Minnesota.

REFERENCES

Biggin, A.J. & Poidras, T., 2006. First-order symmetry of weak-field partial thermoremanence in multi-domain ferromagnetic grains. 1. Experimental evidence and physical implications, *Earth planet. Sci. Lett.,* **245,** 438–453.

Böhnel, H., Dekkers, M. & Delgado-Argote, L., 2009. Comparison between the microwave and multispecimen parallel difference pTRM palaeointensity methods, *Geophys. J. Int.,* **177,** 383–394.

Coe, R.S., 1967. The determination of paleointensities of the Earth's magnetic field with emphasis on mechanisms which could cause non-ideal behavior in Thellier's method, *J. Geomag. Geoelectr.,* **19,** 157–179.

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

Dekkers, M.J. & Böhnel, H.N., 2006. Reliable absolute palaeointensities independent of magnetic domain state, *Earth planet. Sci. Lett.,* **248,** 508–517.

Dunlop, D.J., 1998. Thermoremanent magnetization of nonuniformly magnetized grains, *J. geophys. Res.,* **103,** 30 561–30 574.

Dunlop, D.J., Zhang, B.X. & Ozdemir, O., 2005. Linear and nonlinear Thellier paleointensity behavior of natural minerals, *J. geophys. Res.,* **110,** B01103, doi:01110.01029/02004JB003095.

Fabian, K., 2000. Acquisition of thermoremanent magnetization in weak magnetic fields, *Geophys. J. Int.,* **142,** 478–486.

Fabian, K., 2001. A theoretical treatment of paleointensity determination experiments on rocks containing pseudo-single or multi domain magnetic particles, *Earth planet. Sci. Lett.,* **188,** 45–58.

Fabian, K. & Leonhardt, R., 2010. Multiple-specimen absolute paleointensity determination: an optimal protocol including pTRM normalization, domain-state correction, and alteration test, *Earth planet. Sci. Lett.,* **297,** 84–94.

Folgerhaiter, G., 1899. Sur les variations séculaires de l'inclinaison magnétique dans l'antiquité, *J. Phys.,* **8,** 660–667.

Hjartardóttir, Á., Einarsson, P. & Sigurdsson, H., 2009. The fissure swarm of the Askja volcanic system along the divergent plate boundary of N Iceland, *Bull. Volcano.*, **71,** 961–975.

Jackson, M.J., Worm, H.-U. & Banerjee, S.K., 1990. Fourier analysis of digital hysteresis data: rock magnetic applications, *Phys. Earth planet. Inter.,* **65,** 78–87.

Koenigsberger, J.G., 1938a. Natural residual magnetism of eruptive rocks—part 1, *Terr. Magn. Atoms. Elec.,* **43,** 119–130.

Koenigsberger, J.G., 1938b. Natural residual magnetism of eruptive rocks—part 2, *Terr. Magn. Atoms. Elec.,* **43,** 299–320.

Levi, S., 1977. The effect of magnetite particle size on paleointensity determinations of the geomagnetic field, *Phys. Earth planet. Inter.,* **13,** 245–259.

Michalk, D., Biggin, A. & Knudsen, M., 2010. Application of the multispecimen palaeointensity method to Pleistocene lava flows from the Trans-Mexican Volcanic Belt, *Phys. Earth planet. Inter.,* **179,** 139–156.

Michalk, D., Muxworthy, A.R., Böhnel, H., MacLennan, J. & Nowaczyk, N.R., 2008. Evaluation of the multispecimen parallel differential pTRM method: a test on historical lavas from Iceland and Mexico, *Geophys. J. Int.,* **173,** 409–420.

Muxworthy, A.R. & Roberts, A.P., 2007. First-order reversal curve (FORC) diagrams, in *Encyclopedia of Geomagnetism and Paleomagnetism,* pp. 266–272, eds Herrero-Bervera, E. & Gubbins, D., Springer, Dordrecht.

Roberts, A.P., Pike, C.R. & Verosub, K.L., 2000. First-order reversal curve diagrams: a new tool for characterizing the magnetic properties of natural samples, *J. geophys. Res.,* **105,** 28 461–28 475.

Shcherbakov, V.P. & Sycheva, N.K., 1997. Fulfillment of the Thellier's laws of independence and additivity of partial thermoremanent magnetization for interacting single domain grains, *Izv. Akad. Nauk SSSr Fiz. Zemli,* **4,** 83–88.

Thellier, E., 1941. Sur la vérification d'une méthode permettant de déterminer l'intensité du champ magnétique terrestre dans la Passé, *Comp. Ren. Heb. Séan. Acad. Sci.,* **212,** 281–283.

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

Xu, S. & Dunlop, D.J., 2004. Thellier paleointensity theory and experiments for multidomain grains, *J. geophys. Res.,* **109,** B07103, doi:10.1029/2004JB003024.

Yu, Y.J. & Dunlop, D.J., 2006. Testing the independence of partial thermoremanent magnetizations of single-domain and multidomain grains: implications for paleointensity determination, *J. geophys. Res.,* **111,** doi:10.1029/2006JB004434.