Research note

A new method of palaeofield magnitude correction for thermally altered samples and its application to Lower Carboniferous lavas

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Summary. Some lavas of Early Carboniferous age from Scotland and Derbyshire have been analysed for palaeofield magnitude by the application of a new correction to data obtained by the Shaw method. Its application has yielded field magnitude values from data which had previously been rejected. A modern pottery specimen and recent lavas from Sicily and Westman Island have also been analysed.

An average virtual dipole moment (VDM, Smith) of $2.5 \pm 0.4 \times 10^{22}$ A m$^2$ was determined for the Early Carboniferous. This is only 30 per cent of the present-day VDM.

Introduction

All the Carboniferous samples measured showed extensive thermal alteration as a result of the heating involved in the Shaw method (Shaw 1974). This alteration introduced curvature into the plot of natural remanent magnetization (NRM) versus thermoremanent magnetization (TRM) and also into the plot of the anhysteretic remanent magnetization given before heating (ARM 1) versus that given after heating (ARM 2). Both plots use peak af demagnetizing field as a parameter. A technique has been developed which uses the alteration in the post-heating ARM to correct for the alteration in the TRM.

The correction method

A requirement of the Shaw method is that the plot of ARM(1) versus ARM(2), with peak af demagnetization field as parameter, should yield a straight line graph of slope 1. Any data not falling on such a line are rejected.

Kono (1978) developed a correction which involves the multiplication of the field magnitude value obtained from a linear section of the NRM/TRM graph by the inverse slope of the corresponding linear section of the ARM(1)/ARM(2) graph. A number of Lower Carboniferous samples gave plots containing more than one such linear section, each with a different slope. The application of the Kono correction to individual linear sections on the same graph resulted in the same palaeofield magnitude within error limits.
An attempt was made to correct the individual TRM data by multiplying each TRM value by the ratio of its equivalent ARM(1) and ARM(2) values and then plotting a graph using NRM values as ordinates and the TRM x ARM(1)/ARM(2) values as abscissae, the parameter again being peak of demagnetization field.

The maximum of demagnetizing fields used did not remove all magnetization. For this reason the magnetic moment remaining after maximum demagnetization was removed from all the measurements. All four suites of measurements, NRM, ARM(1), TRM and ARM(2), were treated in this way. In the absence of alteration these subtractions result in the ARM(1) to ARM(2) ratio being unity for each peak of demagnetization field value.

In samples where the heating has caused alteration the correction uses the assumption that since ARM(1) and ARM(2) are both given in the same field then after equivalent of demagnetization the ratio of ARM(1) to ARM(2) (after the above subtractions) gives directly the ratio of the change due to heating in the ability of a particular coercive force region to acquire an induced magnetization. For example if the ratio of ARM(1) to ARM(2) is one-half then the TRM value for the same demagnetizing field parameter will have been increased two-fold. Multiplication of the TRM value by the ARM(1)/ARM(2) ratio will give a corrected value for the TRM.

As can be seen, this correction differs from the Kono correction in that it corrects the individual TRM data rather than correcting a best fit average of NRM/TRM data falling on linear slopes. Unlike the Kono correction it can be used when the NRM/TRM graph is curved.

Levi & Merrill (1976) derived a grain size dependence for the ARM to TRM ratios of magnetite-bearing samples. The ratio increases with increasing grain size (Fig. 1). Grain size changes in the small grain size (single domain) region induced by heating will have little effect on the apparent susceptibility ratio. Grain size changes in the large grain size (multi-domain) region will affect the ratio more severely. The apparent susceptibility ratio is identical to the ARM/TRM ratio if, as in this study, the ARMs and TRMs were created in the same weak magnetic field (50 μT).

![Figure 1. Apparent susceptibility ratios XARM/XTRM versus particle size for magnetite bearing samples (from Levi & Merrill 1976).](https://academic.oup.com/gji/article-abstract/80/3/773/572925)
The use of ARM alteration for correcting TRM alteration may therefore be valid for information derived from the single domain region of a sample. The peak of demagnetization field needed totally to demagnetize multidomain grains is 0.1 T (McElhinny 1973) and since the correction is valid only for single (or pseudo-single) domain grains, data derived below 0.1 T of demagnetizing field are not used.

Figures 2 and 3. Analysis of recent samples using the Shaw method, (a) and (b), and the new correction, (c). Units of magnetization are $10^{-5} \text{A m}^2 \text{kg}^{-1}$. 
Tests results

The Cardiff SQUID magnetometer (Shaw, Share & Rogers 1984) has been used to apply the Shaw technique to a number of modern samples; the data from four of these samples are shown in Figs 2 and 3. Samples W2.1 and W3.1 are lavas from the 1973 Westmann Island eruption, E1923.7A is a lava from the 1923 Mount Etna flow and TEST.1A is a pottery sample. For each sample the TRM and ARM's are given in the same direction as the sample's NRM. This avoids the effects of magnetic anisotropy and is standard procedure on the Cardiff SQUID.

The data from each sample have been plotted on three graphs. Graphs (a) and (b) are plots of ARM(1)/ARM(2) and NRM/TRM data in the manner of the Shaw method. Graph (c) shows the same data plotted after the application of the new correction.

Table 1. Intensity values obtained from the recent samples. Comparison to known fields. Samples prefixed W are from the Westmann Island flow of 1973, E1923.7A is from the 1923 flow on Mount Etna and TEST.1A is a modern pottery specimen fired in the laboratory oven prior to analysis.

<table>
<thead>
<tr>
<th>Rock code</th>
<th>Shaw method</th>
<th>New correction</th>
<th>Known values</th>
</tr>
</thead>
<tbody>
<tr>
<td>W3.1</td>
<td>No result possible</td>
<td>50.7 ± 2.3</td>
<td>51*</td>
</tr>
<tr>
<td>W2.1</td>
<td>48.9 ± 2.6</td>
<td>52.8 ± 3.6</td>
<td>51±</td>
</tr>
<tr>
<td>E1923.7A</td>
<td>No result possible</td>
<td>49.6 ± 2.4</td>
<td>See note</td>
</tr>
<tr>
<td>TEST.1A</td>
<td>No result possible</td>
<td>47.7 ± 0.3</td>
<td>50±</td>
</tr>
</tbody>
</table>

*Value of the field measured on Westmann Island in 1973.
†Value of the field in the Cardiff laboratory oven.

No measurement has been found for the 1923 field on Sicily. The 1954 field value for Sicily was $43.2 \times 10^{-6}$T and a 1983 measurement on Mount Etna gave a value of $47.5 \times 10^{-6}$T.
Figures 4, 5, and 6. Analysis of Lower Carboniferous lavas using the Shaw method, (a) and (b), and the new correction, (c). Units of magnetization are $10^{-3}$ A m$^3$ kg$^{-1}$.

Sample W3.1 shows considerable thermal alteration resulting from the laboratory heating. This alteration is obvious in graphs (a) and (b); graph (c), however, gives a good straight line.

Sample W2.1 shows only minor alteration of a linear nature, the slope of the ARM(1)/ARM(2) graph being slightly less than unity. Consequently, a result has been attempted
using the slope of graph (b), the normal method for obtaining results from the Shaw technique. The result from graph (c) agrees well with that of W3.1.

Thermal alteration for E1923.7A is not so pronounced as W3.1 but a result is only possible from graph (c).

Finally the test sample, TEST.1A, shows clearly the effects of a non-linear thermal alteration. Graph (c) again gives a good straight line.

The results obtained from the correction compare very well with the known values of the fields in which the NRMs were acquired. The results and the known values are given in Table 1, together with any results that were obtained from graphs (b).

The Lower Carboniferous lavas

Figs 4, 5 and 6 show data obtained from six Lower Carboniferous lavas. These samples have all been altered during the TRM acquisition as can clearly be seen, the alteration introducing noticeable curvature into the ARM(1)/ARM(2) and NRM/TRM graphs. After correction, straight line graphs have been obtained in all cases.

Table 2. Compilation of results from Lower Carboniferous lavas. The first nine samples are from the Scottish Midland Valley; the others are from Derbyshire.

<table>
<thead>
<tr>
<th>ROCK CODE</th>
<th>MEAN D</th>
<th>MEAN I</th>
<th>K</th>
<th>q50</th>
<th>VGP POSITION</th>
<th>INTENSITY</th>
<th>VDM (x10^22 A m^-2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CG2</td>
<td>183.7</td>
<td>0.4</td>
<td>74.9</td>
<td>5.2</td>
<td>251.4 E, 33.7 S</td>
<td>2.05 ± 0.12</td>
<td>0.44 ± 0.04</td>
</tr>
<tr>
<td>CG3</td>
<td>175.8</td>
<td>43.0</td>
<td>140.5</td>
<td>3.3</td>
<td>001.4 E, 08.8 S</td>
<td>6.00 ± 0.23</td>
<td>1.37 ± 0.05</td>
</tr>
<tr>
<td>CG10*</td>
<td>349.7</td>
<td>44.3</td>
<td>129.4</td>
<td>6.0</td>
<td>194.1 E, 50.1 N</td>
<td>2.49 ± 0.07</td>
<td>0.48 ± 0.01</td>
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<tr>
<td>CG12A*</td>
<td>212.8</td>
<td>31.5</td>
<td>297.4</td>
<td>5.3</td>
<td>333.9 E, 11.9 S</td>
<td>8.40 ± 0.32</td>
<td>1.93 ± 0.07</td>
</tr>
<tr>
<td>CG30</td>
<td>179.0</td>
<td>34.0</td>
<td>136.5</td>
<td>10.6</td>
<td>358.7 E, 15.3 S</td>
<td>4.90 ± 0.68</td>
<td>1.08 ± 0.15</td>
</tr>
<tr>
<td>CG34</td>
<td>174.4</td>
<td>7.5</td>
<td>182.6</td>
<td>6.4</td>
<td>002.2 E, 30.1 S</td>
<td>6.60 ± 0.41</td>
<td>1.74 ± 0.10</td>
</tr>
<tr>
<td>CG36</td>
<td>91.1</td>
<td>59.8</td>
<td>132.7</td>
<td>6.4</td>
<td>059.4 E, 32.1 N</td>
<td>4.87 ± 0.13</td>
<td>0.84 ± 0.02</td>
</tr>
<tr>
<td>CO1</td>
<td>179.1</td>
<td>58.2</td>
<td>200.3</td>
<td>2.6</td>
<td>356.5 E, 04.9 N</td>
<td>5.86 ± 0.09</td>
<td>1.15 ± 0.02</td>
</tr>
<tr>
<td>QD1</td>
<td>182.6</td>
<td>-1.6</td>
<td>162.5</td>
<td>9.7</td>
<td>352.6 E, 34.7 S</td>
<td>8.53 ± 0.19</td>
<td>1.67 ± 0.05</td>
</tr>
<tr>
<td>PL1*</td>
<td>189.0</td>
<td>41.8</td>
<td>56.1</td>
<td>12.4</td>
<td>349.8 E, 12.2 S</td>
<td>25.05 ± 0.94</td>
<td>5.31 ± 0.20</td>
</tr>
<tr>
<td>PL2</td>
<td>196.3</td>
<td>41.6</td>
<td>63.5</td>
<td>11.6</td>
<td>343.0 E, 11.5 S</td>
<td>25.41 ± 1.03</td>
<td>6.05 ± 0.25</td>
</tr>
<tr>
<td>BW1</td>
<td>223.4</td>
<td>-20.8</td>
<td>142.7</td>
<td>4.3</td>
<td>304.1 E, 13.8 S</td>
<td>30.94 ± 1.66</td>
<td>7.78 ± 0.42</td>
</tr>
<tr>
<td>BR1</td>
<td></td>
<td>POOR ORIENTATION</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>ML1</td>
<td>542.7</td>
<td>38.6</td>
<td>193.5</td>
<td>3.8</td>
<td>203.4 E, 53.4 N</td>
<td>1.85 ± 0.09</td>
<td>0.40 ± 0.02</td>
</tr>
</tbody>
</table>

*Averaged from two results. All others averaged from three. Present-day VDM is 8.02 x 10^22 A m^-2.
Three samples were measured from each of these lavas and the averaged results are given in Table 2, together with the averaged results of any other of the Lower Carboniferous lavas that have yielded stable data from above a 0.1 T peak of demagnetizing field. These results have been converted to virtual dipole moments which are also included in the table together with the virtual geomagnetic pole for each lava.

The majority of the results are representative of a geomagnetic field strength much weaker than the present-day value, varying between 6 and 22 per cent of the present strength. There are three exceptions, viz, Derbyshire lavas which have recorded VDMs on a par with the present-day value.

Fig. 7 places the results in chronological order. Craig (1980) suggests that Campsie Fells lavas, from where the Scottish samples originate, were extruded over a 5 Myr period from the beginning of the Viséan epoch of the Early Carboniferous (333–352 Ma). The Derbyshire lavas occur within a stratigraphic sequence that is split by the boundary between the D1 and D2 faunal zones that are used as stratigraphic markers. This boundary occurs mid-way through the Viséan, suggesting that the Derbyshire lavas immediately post-date the Scottish lavas.

The composition of the Scottish lavas classifies them as alkali-olivine basalts, hawaiites and mugearites, the younger lavas being the least basic of the group. One of the samples, QD1, is from a quartz-dolerite dyke. The Derbyshire lavas are all of a similar composition classifying them as olivine basalts. There seems to be no correlation between lava composition and suitability for intensity results, at least one intensity result pertaining to each of the lava types represented.

Discussion

The advantages of the new correction method are clear. Its ability to correct individual data points is important because non-linear thermal alteration is a frequent consequence of the heating used in the Shaw technique. It is certain that many data remain unused because of such alteration. Checks must be made, however, that the NRM is a single component NRM and has a stable direction. Non-linearity can occur if the NRM does not satisfy these two constraints. This non-linearity cannot be corrected by the method. All field magnitude results reported here were derived from samples with single component NRMs. Figs 8 and 9 show respectively directional results from a Carboniferous lava and the pottery test sample.

Figure 8. Directional data of a typical Carboniferous lava from Table 2. The NRM has remained stable throughout the demagnetizing sequence. This type of single component behaviour is a prerequisite for field magnitude analysis.
Previous corrections could only be used on data showing linear alteration, the result being that in the past a number of potential intensity determinations could have been overlooked.

The data presented here show alteration representative of the type that can occur during laboratory TRM acquisition. They have all yielded satisfactory results when the correction has been applied.

The pole positions obtained from the Lower Carboniferous lavas are in good agreement with the Early Carboniferous values listed in McElhinny (1973), containing normal, reversed and intermediate positions.

The intensity results from these lavas raise an interesting point. The average VDM (Smith 1967) for these lavas is $2.5 \pm 0.4 \times 10^{22} \text{ A m}^2$, but this includes results from three Derbyshire lavas which have recorded VDMs much higher than the average. Ignoring these high values the average VDM is $1.0 \pm 0.1 \times 10^{22} \text{ A m}^2$, about 13 per cent of the present-day value. This is in agreement with results presented by other workers (Carmichael 1967; Schwartz & Symons 1967) for the Carboniferous. The three strong results have an average VDM of $6.4 \pm 0.4 \times 10^{22} \text{ A m}^2$, or 80 per cent of the present-day value.

Roberts & Shaw (1984) have found a similar range of results from Icelandic Tertiary lavas, a number of lavas recording significantly high field values. This type of field behaviour is therefore not confined to the early Carboniferous and may be a general feature of the palaeomagnetic field.

Acknowledgments

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References


