Palaeomagnetic Results from the Arrochar and Garabal Hill–Glen Fyne Igneous Complexes, Scotland

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Summary

From the Arrochar intrusive complex and its contact aureole 47 cores from \( N = 6 \) sites (mean co-ordinates \( 56^\circ\,14'\,N,\,4^\circ\,48'\,W \) yield a stable NRM direction after magnetic cleaning \( D = 213.3^\circ, I = +36.6^\circ \) (\( k = 166.7 \)). Calculated mean K–Ar age is 418 My. From a total collection of 37 cores from 11 sites in the Garabal Hill–Glen Fyne complex, a mean stable NRM direction after magnetic cleaning \( D = 32.2^\circ, I = -42.5^\circ \) (\( k = 11.1 \)) was determined from \( N = 5 \) sites (mean co-ordinates \( 56^\circ\,18'\,N,\,4^\circ\,47'\,W \)) with supporting evidence from a further two sites. Best estimated radiometric age (Rb–Sr and K–Ar) is 415 My. Palaeomagnetic north pole positions from the two complexes are \( 8^\circ\,S\,36^\circ\,W \) (\( A_{95} = 5^\circ \)) and \( 5^\circ\,N\,146^\circ\,E \) (\( A_{95} = 23^\circ \)) respectively. Complicated mineralogy and petrology reflect the hybrid character of the rocks. The magnetic minerals are correspondingly complex, but all are high temperature phases. Thermal and alternating field demagnetization, and variation of magnetic properties across a contact aureole, confirm the stability and primary origin of NRM in the complexes. Unbaked Dalradian rocks (12 cores) have no systematic NRM.

Reconciliation of Siluro–Devonian data from Western Europe could involve persistent geomagnetic anomalies, large subsequent relative lateral movements between Britain and Norway, revision of geological or magnetic ages of various rocks studied palaeomagnetically, or either rapid shift or brief excursion of the ancient geomagnetic pole.

1. Introduction

Short core samples were drilled and oriented (by Sun and/or magnetic compass and clinometer) at 11 sites in the Garabal Hill–Glen Fyne complex, and five sites in the Arrochar complex, with a view to determining the geomagnetic field direction at the time of intrusion. Dalradian country rocks were sampled at three localities to aid estimation of the age and stability of NRM. The geology and sampling sites are summarized on the map (Fig. 1) which is based on the work of Nockolds (1941) at Garabal Hill–Glen Fyne, and Anderson (1935) at Arrochar. Both these complexes have long been regarded as being of Lower Old Red Sandstone age. Rb–Sr whole rock-mineral isochrons obtained from the porphyritic and medium granodiorites and pyroxene-mica diorite from the Garabal Hill–Glen Fyne complex (Summerhayes 1966) indicate a mean age of \( 392 \pm 4 \) My (using decay constant \( \lambda = 1.47 \times 10^{-11} \) y\(^{-1} \))
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FIG. 1. Palaeomagnetic sampling sites in the Garabal Hill–Glen Fyne and Arrochar igneous complexes and intervening Dalradian schists. The distribution of rock types within the complexes is generalized and slightly modified from Nockolds (1941) and Anderson (1935).

or \(415 \pm 4\) My \((\lambda = 1\cdot39\times10^{-11} \text{ y}^{-1})\). K–Ar age determinations of whole-rock samples from the Arrochar complex (mean 418 My) and a single determination on a biotite from porphyritic grandiorite at Garabal Hill–Glen Fyne at 412 \pm 10\) My (Summerhayes 1966) are more consistent with the longer Rb\(^{87}\) half-life, and suggest that intrusion occurred close to the Silurian–Devonian boundary as dated elsewhere (Fullager & Bottino 1968), though they fall within the Silurian on currently-used time scales.

2. Arrochar Complex

Sampling and results from the Arrochar complex are summarized in Table 1. All samples were of medium grained diorite except at site L where a traverse of 32 samples was made from about 10 m within the intrusion, across the contact with the Dalradian schist country rock, and continued a further 170 m across the metamorphic aureole.

2.1 Results from the intrusion

Total NRM directions were well grouped around a mean \(D = 211^\circ, I = +53^\circ\) (Fig. 2 (a), Table 1) with Fisherian precision estimate \(k = 23\). Deviations from the mean were pronounced only at site K, where the samples were more weakly magnetized \((\approx 10^{-5} \text{ gauss})\) than elsewhere \((\approx 10^{-3} \text{ gauss})\).
## Table 1

**Arrochar Complex: summary of NRM measurements before and after magnetic cleaning**

<table>
<thead>
<tr>
<th>Site</th>
<th>No. of cores</th>
<th>$N$ (specimens)</th>
<th>Total NRM</th>
<th>a.f. cleaned</th>
<th>Palaeomagnetic North Pole</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$N$</td>
<td>$R$ $k$ $a_{95}$ $D$ $I$</td>
<td>$N$ $R$ $k$ $a_{95}$ $D$ $I$</td>
<td></td>
</tr>
<tr>
<td>H</td>
<td>4</td>
<td>7</td>
<td>6·89 52·7 8·4 221·6 +41·9</td>
<td>150–600</td>
<td>4 3·99 297·5 5·3 221·0 +36·8</td>
</tr>
<tr>
<td>J</td>
<td>3</td>
<td>6</td>
<td>5·73 18·3 16·1 214·2 +44·4</td>
<td>150–200</td>
<td>3 2·98 85·2 13·4 220·8 +35·6</td>
</tr>
<tr>
<td>K</td>
<td>4</td>
<td>8</td>
<td>6·35 4·3 30·5 160·8 +69·9</td>
<td>400</td>
<td>4 3·81 15·6 24·0 207·5 +43·2</td>
</tr>
<tr>
<td>L (&lt; intrusion)</td>
<td>14</td>
<td>16</td>
<td>13·67 6·4 15·8 214·7 +58·4</td>
<td>300–600</td>
<td>8 7·68 21·8 12·1 210·6 +35·5</td>
</tr>
<tr>
<td>R</td>
<td>4</td>
<td>8</td>
<td>7·89 60·9 7·1 213·5 +43·9</td>
<td>250</td>
<td>4 3·97 98·4 9·3 211·8 +36·9</td>
</tr>
<tr>
<td>Lc (&lt; Dalradian)</td>
<td>18</td>
<td>20</td>
<td>15·90 4·6 17·1 203·8 +65·5</td>
<td>300–600</td>
<td>8 7·62 18·4 13·3 207·8 +31·2</td>
</tr>
<tr>
<td>Intrusion</td>
<td>5 sites</td>
<td></td>
<td></td>
<td>a.f. cleaned</td>
<td>5 4·98 192·5 5·5 214·5 +37·7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4·83 23·0 16·3 210·6 +52·9</td>
<td></td>
<td></td>
<td>($d\phi = 3·8, d\chi = 6·5$)</td>
</tr>
<tr>
<td>Intrusion and aureole</td>
<td>6 sites</td>
<td>5·80 25·6 13·5 209·7 +55·1</td>
<td>a.f. cleaned</td>
<td>6 5·97 166·7 5·2 213·3 +36·6</td>
<td>8·4 S 36·1 W</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>($d\phi = 3·6, d\chi = 6·1$)</td>
</tr>
</tbody>
</table>

Mean site co-ordinates 56° 14’ N, 4° 48’ W.

The standard palaeomagnetic notation is followed in this paper (see, for example, Irving (1964))
Progressive partial demagnetization of selected samples in alternating fields up to approximately 600 Oersteds peak (Figs 2(b), 2(c), 3(a)) enabled the removal of magnetically soft components of NRM. Associated changes of direction, except at site K, were small, being confined to a shallowing of inclination as would occur if a soft component directed along the present geomagnetic field were being removed. Low alternating fields were sufficient to change NRM directions at site K considerably, leaving a stable component in direction concordant with that at the other sites. All these measurements were made with spinner and astatic magnetometers at Birmingham and using an a.f. demagnetizer designed by the author. The magnetic cleaning reported in Table 1 was carried out at Leeds, using an a.f. demagnetizer similar to that described by McElhinny (1966) and a P.A.R. SM-2D spinner magnetometer. The optimum field for magnetic cleaning was chosen for each site on the basis of results in Fig. 2(b). As the illustration shows, the choice was not critical, so the pilot specimens were re-treated at Leeds in slightly higher fields than before, and the results included in Table 1. (This is the reason for the variety of field amplitudes used for...
Fig. 3. Progressive partial alternating field (a) and thermal (b) demagnetization of specimens from the Arrochar complex.

cleaning, which is immaterial to the results). The mean direction is now \(D = 214, I = +38\) which is 15° shallower inclination than the mean total NRM direction, and this change is accompanied by improvement in \(k\) from 23 to 192. (This is largely attributable to removal of anomalously directed components at site K).

Thermal demagnetization of two specimens (Fig. 3(b)), carried out by Dr M. W. McElhinny at the Australian National University, confirms that the bulk of the NRM is stable; directions throughout thermal demagnetization are similar to those indicated by the magnetically cleaned specimens. A relatively small soft component at site L—comparable to that observed during a.f. demagnetization—was removed by thermal cleaning at 300 °C, but this was negligible in the sample from site H. The bulk of the NRM in each sample was removed by thermal cleaning at 550 °C, probably indicating that titanomagnetite is the major carrier of remanence. But in both cases a small proportion of NRM persisted even after cleaning at 650 °C, and maintained the same direction as the lower blocking temperature fraction, indicating the presence of hematite.

2.2 Results from the contact aureole

At site L perfect exposure of the contact of the intrusion with the (already regionally metamorphosed) Dalradian schists and continued good outcrops some 170 m into the contact metamorphic aureole, provided an opportunity to make a 'contact test' of the origin and stability of the NRM in the intrusion and the adjacent baked rocks (Figs. 2(d) and 4). Total NRM directions (with only two exceptions) are in accord with the stable NRM direction in the intrusion (Table 1, Fig. 2(d)). The decisive evidence that the NRM in the schists is at least mainly associated with the intrusion, rather than to regional effects, is illustrated in Fig. 4. Although smooth variations of magnetic properties with distance from the intrusive contact are not evident, two general correlations are seen: total NRM intensities are higher near the intrusion than further away; hardness in alternating fields is much greater in specimens close to the contact. Specimens further than 50 m from the contact have stable NRM in the direction characteristic of the intrusion, but this can be removed by a.f. demagnetization at a maximum of 1000 Oe (peak). Within 40 m of the intrusion alternating fields of 1500 Oe (peak) are insufficient to destroy this systematically directed remanence.
These extremely high coercivities, and the sharp cut-off of this effect, which coincides with the disappearance of obvious induration of the schists, might be evidence of the presence of ilmenohematite or hematite. The origin might then be ascribed to CRM due to recrystallization—with or without metasomatism—accompanying the intrusion, rather than a simple thermal effect. Alternatively partial thermoremanence of highly elongated magnetite grains such as might occur in these texturally anisotropic rocks, could exhibit these high coercivities (Morrish & Yu 1955); the NRM might then be purely PTRM.

Thermal demagnetization and identification of the magnetic fraction would discriminate between these alternatives, and might also show more clearly the decreasing effect of the intrusion with distance from its contact; a portion of the collection has been retained for such work in the future. That the effect of the intrusion does not extend indefinitely into the Dalradians is clear from the random NRM at site S (Section 3.2).

Fig. 4. Variation of magnetic properties across the contact aureole of the Arrochar complex at site L. (a) Total NRM intensity plotted against distance from contact. (b) A.f. demagnetization curves.
<table>
<thead>
<tr>
<th>Site</th>
<th>Rock type</th>
<th>No. of cores</th>
<th>N</th>
<th>R</th>
<th>k</th>
<th>$\alpha_3$</th>
<th>D</th>
<th>I</th>
<th>Peak Field (Oe)</th>
<th>Palaeomagnetic North Pole</th>
<th>a.f. cleaned</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Xenolithic diorite</td>
<td>4</td>
<td>8</td>
<td>2.63</td>
<td>4.63</td>
<td>47.6-157.6</td>
<td>355.3</td>
<td>71.8</td>
<td>665-800</td>
<td>2.7N 134.5 E</td>
<td>3.35</td>
</tr>
<tr>
<td>B</td>
<td>Medium granite</td>
<td>7</td>
<td>4</td>
<td>2.63</td>
<td>4.91</td>
<td>352.1</td>
<td>15.5</td>
<td>28.0</td>
<td>665-700</td>
<td>1.1S 146.5 E</td>
<td>2.43</td>
</tr>
<tr>
<td>C</td>
<td>Peridotite</td>
<td>6</td>
<td>6</td>
<td>5.95</td>
<td>19.6</td>
<td>474-45.6</td>
<td>400-500</td>
<td>700</td>
<td>3.26</td>
<td>1.5S 57.5</td>
<td>3.38</td>
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<tr>
<td>D</td>
<td>Main Gabbro</td>
<td>3</td>
<td>3</td>
<td>2.93</td>
<td>29.4</td>
<td>123.2</td>
<td>27.6</td>
<td>700</td>
<td>1.5S 57.5</td>
<td>1.19</td>
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</tr>
<tr>
<td>E</td>
<td>Pyroxene-mica diorite</td>
<td>4</td>
<td>8</td>
<td>7.83</td>
<td>40.8</td>
<td>8.8</td>
<td>230.8</td>
<td>420</td>
<td>3.24</td>
<td>3.35</td>
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<td>4</td>
<td>3.71</td>
<td>10.5</td>
<td>29.8</td>
<td>46.7</td>
<td>57.5</td>
<td>4.37</td>
<td>56.9</td>
<td>3.38</td>
</tr>
<tr>
<td>G</td>
<td>Peridotite</td>
<td>6</td>
<td>6</td>
<td>3.33</td>
<td>10.5</td>
<td>14</td>
<td>46.7</td>
<td>57.5</td>
<td>4.37</td>
<td>56.9</td>
<td>3.38</td>
</tr>
<tr>
<td>H</td>
<td>Pyroxene-mica diorite</td>
<td>3</td>
<td>4</td>
<td>3.65</td>
<td>10.5</td>
<td>14</td>
<td>46.7</td>
<td>57.5</td>
<td>4.37</td>
<td>56.9</td>
<td>3.38</td>
</tr>
<tr>
<td>I</td>
<td>Porphyritic granite</td>
<td>3</td>
<td>6</td>
<td>3.33</td>
<td>10.5</td>
<td>14</td>
<td>46.7</td>
<td>57.5</td>
<td>4.37</td>
<td>56.9</td>
<td>3.38</td>
</tr>
<tr>
<td>J</td>
<td>Main Gabbro</td>
<td>3</td>
<td>3</td>
<td>2.93</td>
<td>29.4</td>
<td>123.2</td>
<td>27.6</td>
<td>700</td>
<td>1.5S 57.5</td>
<td>1.19</td>
<td></td>
</tr>
<tr>
<td>K</td>
<td>Main Gabbro</td>
<td>4</td>
<td>8</td>
<td>7.77</td>
<td>29.9</td>
<td>10.3</td>
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<td>56.9</td>
<td>3.88</td>
<td>53.3</td>
<td>3.38</td>
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<tr>
<td>L</td>
<td>Main Gabbro</td>
<td>4</td>
<td>4</td>
<td>3.95</td>
<td>11.4</td>
<td>65.3</td>
<td>44.7</td>
<td>388</td>
<td>3.24</td>
<td>3.35</td>
<td></td>
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<tr>
<td>M</td>
<td>Peridotite</td>
<td>8</td>
<td>10</td>
<td>6.72</td>
<td>27.2</td>
<td>36.2</td>
<td>185.6</td>
<td>48.1</td>
<td>1.1N 176.7 E</td>
<td>3.95</td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>Dalradian adjacent to granodiorite</td>
<td>10</td>
<td>2</td>
<td>1.64</td>
<td>4.3</td>
<td>352.1</td>
<td>53.4</td>
<td>3.35</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>O</td>
<td>Dalradian 1.5 km south of granodiorite outcrop</td>
<td>4</td>
<td>4</td>
<td>2.69</td>
<td>4.3</td>
<td>352.1</td>
<td>53.4</td>
<td>3.35</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P</td>
<td>Dalradian adjacent to granodiorite</td>
<td>10</td>
<td>2</td>
<td>1.64</td>
<td>4.3</td>
<td>352.1</td>
<td>53.4</td>
<td>3.35</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Q</td>
<td>C, E (Reversed) N, P, Q sites</td>
<td>5</td>
<td>4</td>
<td>4.65</td>
<td>11.6</td>
<td>23.5</td>
<td>41.8</td>
<td>52.3</td>
<td>3.35</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Mean co-ordinates of sites A, C, D, N, P: 56° 18' N, 4° 47' W.
3. Garabal Hill–Glen Fyne complex

3.1 Results from the intrusives

The rock-types sampled from the Garabal Hill–Glen Fyne complex ranged from ultrabasics to granodiorites—a much wider variation than at Arrochar—and the palaeomagnetic results are correspondingly more complex. Some of this extra complexity may be due to the exposed character of the sampling sites, most of which were natural outcrops on the tops of ridges. This contrasts with the Arrochar sites all of which were in quarries or streams at low topographic levels. The total NRM results (Table 2) illustrate this; the more precisely defined site mean directions were obtained from ultrabasic and basic rocks (D, E, N, P) and of these N and P are from a stream at a tunnel mouth—the only artificial exposures which were sampled.

The site mean directions of total NRM are randomly oriented and, taken together, give no palaeomagnetic information. Interpretation is more usefully discussed in the light of a.f. demagnetization results (Table 2, Fig. 5).

The behaviour in alternating magnetic fields is very irregular. At only five sites did stable end-directions clearly emerge, and these same sites were the only ones with significant mean directions ($p = 0.05$) after magnetic cleaning (Fig. 5 (c)). These data give $D = 32^\circ$, $I = -43^\circ$ for the complex, with $z_{95} = 24^\circ$. This is 175° from the mean for the Arrochar complex, i.e. the two results are of opposite polarity.

At site F, specimens chosen for progressive a.f. and thermal demagnetization both indicated stable end-directions in agreement with the above result (Fig. 5 (b)). However other specimens failed to agree, and the statistical significance of results at this site was insufficient to justify their use.

At the remaining five sites, no clear stable end-directions were isolated. Initial directions at site B were grouped close to the present geomagnetic field; this NRM was highly unstable, over 99 per cent being removed in a peak alternating field of 600 Oe. The ultrabasics of site E (Fig. 5 (a)) were initially magnetized in a direction similar to that in the Arrochar complex, i.e. antiparallel to the stable sites in the Garabal Hill complex. These however proved unstable in alternating fields and because several interpretations are possible, results are not included in the final result.

There was no common characteristic shape of a.f. demagnetization curve at the five sites accepted for the final analysis. Coercivity spectra at ‘stable’ sites C, D and
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N, for example, were indistinguishable from those at random sites G, M and Q. At sites A and B over 99 per cent of NRM was removed in 600 Oe (peak) alternating field and this can confidently be ascribed to IRM. No underlying stable component was found at site B, but at site A the high coercivity fraction appeared to be stable and its direction belonged to the group. This component was not isolated by thermal demagnetization. Thermal demagnetization shows typical TRM characteristics except at site A, where the critical blocking temperatures range uniformly between room temperature and 650 °C. These data cast doubt on the correctness of excluding site F and including site A in the final analysis, but the decisions do not critically affect the calculated mean NRM direction or error estimates.

As at Arrochar, the most notable feature of the thermal demagnetization data is the retention of the same direction, though small intensity, above magnetite Curie temperatures and at least to 650 °C in all the samples, indicating the ubiquitous occurrence of hematite.

3.2 Results from adjacent Dalradian rocks

Results from site S adjacent to the porphyritic granodiorite (Fig. 1, Table 2) support the view that chemical rather than thermal effects dominate the magnetization of the Dalradian rocks in the contact aureole. Although the neighbouring igneous rocks to site S are porphyritic granodiorites in which no stable NRM has been identified, this should not prevent the acquisition of PTRM in the baked rocks if
temperature is the dominant agency. However the Dalradians here are more acid than at site L, due to back veining and injection of the intrusives. Total NRM directions at site S are scattered around the present geomagnetic field direction, and are unstable in alternating fields.

At site T, about halfway between the two intrusive complexes studied here, NRM was weak, random, and unstable against alternating fields. The instability of the Dalradians at sites S and T (Fig. 6(b)) contrasts with the high stability at site L adjacent to the intermediate to basic rocks of the Arrochar complex (Fig. 4(b)).

4. Petrological observations

The petrography of these bodies is extremely complicated and reflects a complex petrogenesis. Non-equilibrium assemblages are widespread. In general the sequence of intrusion begins with the ultrabasic rocks and proceeds to basic and finally acid stages (Nockolds 1941). The earlier bodies (i.e. the more basic and ultrabasic) show signs of metamorphism by intrusion of the later, acid phases. The intermediate and acid rocks show many signs of hybridization, by way of incorporating more basic material. Thus the opaque minerals only appear to be truly magmatic in the more silicic rocks. Discrete subhedral primary titanomagnetites are seen from site M, in the porphyritic granodiorite which is magnetically unstable. A quartz-diorite at site L shows discrete euhedral titanomagnetites which are original, but also contains iron ores in skeletal replacement of clinopyroxene. Another specimen merely 25 cm away, in a more basic xenolith, is clearly a metamorphic and hybridized rock, containing opaque phases associated with the reaction of clinopyroxenes and amphiboles. At this same site a specimen from the zone of mixing at the contact shows this process taken to extremes, with biotite and chlorite now being the dominant mafic minerals. All the other samples from the Arrochar complex exhibit chloritization and secondary opaque phases consistent with the contention of MacGregor (1931) and Johnstone & Wright (1957) that the medium diorite is thermally metamorphosed by the later more acid intrusives at Arrochar.

Of the ultrabasic rocks site E—serpentinized peridotite—shows opaques related to the serpenitization; this may itself be a moderately low temperature event, and may account for the instability of NRM at this site. The observation that the NRM polarity at this site is opposite to that elsewhere in the Garabal Hill–Glen Fyne complex could suggest that serpenitization was not synchronous with the emplacement of the intermediate to acid parts of the complex. The other ultrabasics, sites C and P, are strongly metamorphosed to amphibolite and hornfels respectively, and the opaques are associated with amphiboles. Gabbros at sites D and Q show signs of alteration, and at the latter (which is close to the main granodiorite mass) of possible hydrothermal veining. This evidence all supports the view that hybridization is the principal cause of petrological variation in these complexes, but throws little or no light on Nockolds (1941) contention that the pyroxene-mica diorite was the closest in composition to the parental magma of these rocks.

Investigations of the opaque petrology of some specimens was made by Dr J. M. Ade-Hall at the University of Liverpool. The principal opaque phases are brown ilmenite and titanomagnetite—unoxidized ($M = 1$) and non-granulated ($G = 1$) according to the notation of Ade-Hall et al. (1968). In some of the Garabal Hill rocks, grains of titanohematite and hemoilmenite on two size scales occur: irregular exsolution bodies of each of these phases contain fine exsolution bodies of the other. This is the type of material which Merrill & Grommé (1969) associated with self-reversal in marginal plutonic rocks of the Bucks Batholith. There, the polarity of the magnetite fraction was opposite to that in the high Curie-point phase. In the Garabal Hill rocks, no evidence of dual polarity is found with the possible exception of site F.
where intensity increases with increasing alternating field above 600 Oe without change of remanent direction. Also in some dioritic and granodioritic rocks hematization of titanomagnetite occurs, sometimes in irregular blebs and sometimes in fine lamellae. This type of occurrence is not seen in all the samples which thermal demagnetization shows to possess high Curie point phases. The high blocking temperature remanence may thus originate entirely or in part within blue-black peripheral alteration rims of some ilmenites. Clothwork alteration of ilmenite is widespread in all the polished sections investigated. These types of phases in basalts have been correlated by Ade-Hall (1969) with deep burial, to the extent associated with alteration to albite-epidote hornfels facies. In the case of the plutonic rocks of the present study, depth of emplacement rather than burial, or the complex intrusive history, may be indicated by these textures.

Palaeomagnetically the importance of these petrological considerations is that the magnetic phases are of high temperature origin. The inference to be drawn is that NRMs date from the final intrusional cooling, since subsequent strong heating is ruled out by evidence from the contact aureole. The observation that, with one minor exception, each intrusion exhibits a single polarity of stable NRM implies that this final stage of cooling was short compared with the time involved in completing their emplacement. This is also in line with the large scatter of stable NRM directions within the larger, more varied Garabal Hill-Glen Fyne complex compared with Arrochar, where the calculated error in mean direction ($\alpha_q = 5.5^\circ$) is unusually low and could imply that only a short time interval has been recorded palaeomagnetically.

5. Conclusions

5.1 The age of stable NRM

There are six main lines of evidence indicating that the age of NRM is indistinguishable on a geological time scale from the age of the rocks themselves. First it is difficult to envisage a thermal history in which both Rb-Sr and K-Ar whole-rock and mineral ages would be older than NRM which is demonstrably stable, in many cases to 550 °C and 650 °C. Second, petrographic evidence indicates that the magnetic grains in general attained their present texture, structure and size during the intrusional cooling of the complexes themselves. Third, the existence of precisely opposite polarities in two complexes of approximately equal age is more likely to arise from TRM acquired at the very slightly different times of intrusional cooling than to any subsequent metamorphic event which would leave a more complicated magnetic imprint on the region. Fourth, the stability of NRM is consistent with TRM or CRM and not with viscous PTRM acquired far below the Curie point over a realistic time-interval. Fifth, the axis of magnetization is consistent with results from lavas of Lower Old Red Sandstone age in Scotland, of which stability has been demonstrated by a.f. demagnetization and successful application of a bedding tilt test (McMurray 1968). Sixth, and most decisive, is the evidence of the effect of the Arrochar intrusion upon the adjacent metamorphics at site L_c.

For these reasons the quoted mean directions in the two complexes may, with the usual reservations concerning the small number of sampling sites and the short time intervals which they may represent, be best estimates of the geomagnetic field direction approximately 415 My ago.

5.2 The geomagnetic field in Western Europe during the late Silurian and early Devonian

Controversy over the Lower Devonian palaeomagnetic field directions in Eurasia was first aroused by the discrepancy between the results of Stubbs (1958) on lavas from
the Midland Valley of Scotland, and Creer (1957) on Old Red Sandstone sediments. This controversy has continued ever since, with Creer (1968), Chamalaun & Creer (1964), and lately McMurry (1968, 1970) and Embleton (1968, 1969) contending that Stubbs' pole (about 10° S 142° E) was essentially correct; by contrast Storetvedt (1968) favours a pole in the vicinity of 20° N 160° E.

At each stage in the controversy new data has been produced. McMurry's (1968) and Embleton's (1968) data essentially supersede Stubbs' result, having been derived mainly from the same sampling localities. The finding by Storetvedt & Gjellestad (1966) and Lie et al. (1969) of mutually indistinguishable directions in two Old Red Sandstone sections in Norway stated to be 'Upper Silurian' and 'Lower to Middle Devonian' respectively, extends the controversy into the Silurian. Although some of the apparent discrepancies could be resolved if a rapid polar shift occurred during mid-Devonian times (Embleton 1969) the argument mainly hinges on whether there has been widespread remagnetization of sediments throughout Eurasia, or whether the lavas have been remagnetized. It appears to be common ground that the Old Red Sandstones of the Anglo-Welsh cuvette have been largely remagnetized in Permo-Carboniferous times, and the same is likely to have happened to the Silurian sediments, of which a small collection was made by Creer (1957), immediately underlying some of his Old Red Sandstone sampling horizons. All the published data, which are still considered to provide good estimates of the late Silurian–early Devonian geomagnetic field, are summarized in the form of pole positions in Fig. 7. Also illustrated are the

![Fig. 7. Palaeomagnetic pole positions for Siluro-Devonian rocks from Britain and Norway. Present study:](https://academic.oup.com/gji/article-abstract/21/5/457/753034)

- O Arrochar intrusion (south poles); ☆ mean.
- □ Arrochar contact aureole (south pole).
- ● Garabal Hill–Glen Fyne (north poles); ★ mean.
- ◊ Garabal Hill–Glen Fyne (site E, total NRM; south pole).
- T Both complexes, thermally cleaned.

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results of the present study, which introduces the first evidence from intrusive rocks. These rocks are fresh and massive, and were not subjected to the 'weathering' effect which Creer (1968) and his associates suggest was the cause of partial remagnetization of the Old Red Sandstone sediments. Evidence has been presented here to show that these intrusives have not been subjected to widespread metamorphism which Storetvedt (1968) has suggested might have caused complete, or almost complete, remagnetization of the Scottish lavas.

The present results are decisively in closer agreement with the pole positions determined from Britain (Chamalauan & Creer 1964; McMurry 1968; Embleton 1968), than with the Norwegian data. The virtual identity of these new results with those of McMurry is particularly noteworthy, since the latter is the more comprehensive survey of the lavas, incorporating stability evidence and a decisive bedding tilt test, and because such a field test was not possible in the intrusive rocks, which are some 25 km from the nearest contemporaneous bedded rocks.

The alternative conclusions, based on the current data, may involve one or more of the following:

(i) A persistent geomagnetic anomaly was maintained between Britain and Norway throughout the late Silurian and early Devonian. (This essentially implies a failure of the geocentric dipole field model).

(ii) Britain and Norway belonged to different crustal plates between which large relative movements have since occurred.

(iii) The Norwegian rocks have entirely older or younger magnetic ages than those studied in Britain. (The stratigraphic ages of the sedimentary and volcanic rocks is far from perfectly known. Nor are these ages fully integrated with radiometric time scales. The possibility of remagnetization of either all British or all Norwegian rocks is included under this heading, and the possibility of a rapid polar shift is also associated with this interpretation).

(iv) The magnetic pole made a brief excursion at the time of intrusive and extrusive igneous activity in Scotland (such data as is available suggests that older and younger poles from Britain lie in the vicinity of the Norwegian Siluro-Devonian poles in Fig. 7).

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References


