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Palaeomagnetic results from the Peterhead granite, Scotland; implication for regional late Caledonian magnetic overprinting

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Palaeomagnetic results from the Peterhead granite (Silurian), NE Grampian Highlands, define a characteristic magnetization with overall parameters of Dec: 180.4°, Inc: 22.3° and a_{95}: 5.2°. These results agree with other "Newer Granite" data from North Scotland. An east–west trending dyke cutting the Peterhead granite shows an extremely well-defined palaeomagnetic direction with Dec: 192.5°, Inc: −19.1° and a_{95}: 1.3°, suggesting a Permo-Carboniferous age. The Peterhead Granite results are seen in conjunction with other Palaeozoic palaeomagnetic data from Scotland. It is concluded that the observed directional spread of characteristic remanence directions previously reported from the Aberdeenshire Gabbros are not related to slow post-orogenic cooling (Watts and Briden), but is rather seen as the result of late Caledonian magnetic overprinting.

1. Introduction

Major magmatic events in the northeastern Grampians, succeeding the Grampian orogenic event, comprise the Early Ordovician Younger Gabbros, the last Grampian granites (c. 450 Ma) and the "Newer Granites" (Bell, 1968; Pankhurst, 1970, 1974, 1979; Dewey and Pankhurst, 1970; Hurford, 1977; Pidgeon and Aftalion, 1978; Harmon and Halliday, 1980). The late Caledonian calc-alkaline "Newer Granites" were extensively emplaced in the Scottish Highlands yielding radiometric ages dominantly in the 400–430 Ma range. In Read's (1961) classification of Caledonian intrusions, the "Newer Granites" were classified as the newer forceful granites and the later permitted granites, post-dating main Caledonian metamorphism and folding. The Peterhead granite, NE Grampians (Fig. 1), is intruded into metasedimentary rocks of the Dalradian Series presumably by stoping and fault subsidence at around 415 Ma (Whole rock Rb/Sr: Bell, 1968; Brown and Locke, 1979). The granite has subsequently been intruded by a c. 50 m thick, east–west trending dolerite dyke.

The present paper forms part of a palaeomagnetic survey of "Newer Granites" and Old Red Sandstone rocks from Scotland, evaluating details in the apparent polar wander path (APW) and aspects of regional crustal dynamics during the Palaeozoic. Recent palaeomagnetic data from "Newer Granites" from both sides of the Great Glen Fault (GGF) have given almost identical remanence directions (Torsvik et al., 1983; Torsvik, 1984), invalidating the idea of a large-scale horizontal movement (c. 2000 km) as suggested by Van der Voo and Scotese (1981). In the present study, the palaeomagnetic data from the Peterhead granite are compared with other Caledonian results from Scotland.

Palaeomagnetic sampling in the Peterhead granite and the cross-cutting dolerite dyke comprises 102 drill-cores and 48 hand samples collected along the coast-line from just north of

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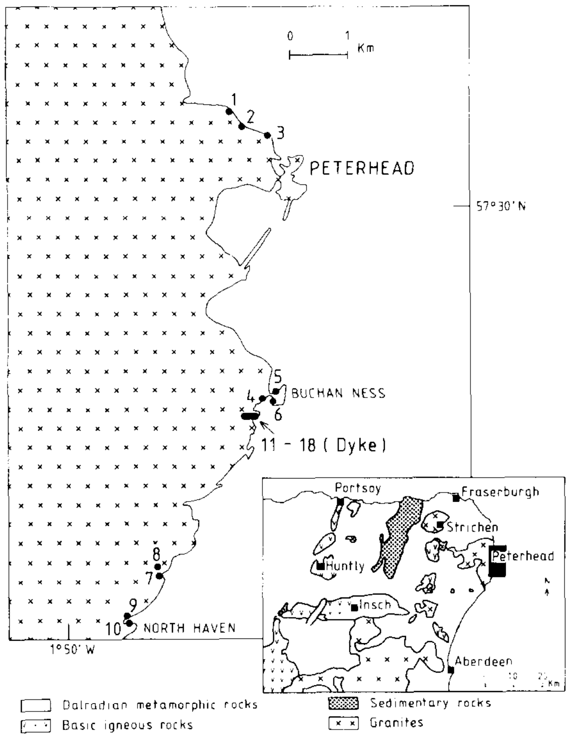

Fig. 1. Geological sketch map of the Peterhead granite, NE Grampians. Sampling locations are denoted by solid circular symbols.

Peterhead to North Haven: sampling in the granite gave a total of 86 samples from altogether 10 locations, while a total of 64 dyke samples were collected from 8 sites. Dyke samples have been collected in several profiles along the northern margin of the E–W trending dyke (south of Buchan Ness). Sampling in the contact granite was not successful due to the relatively hard and coarse-grained nature of that rock.

2. Laboratory experiments

The natural remanent magnetization (NRM) was measured by Digico and Molspin spinner magnetometers. Stability of NRM was investigated by means of stepwise thermal and alternating field (AF) demagnetization. Thermal demagnetization was carried out in a Schonstedt furnace and AF demagnetization was performed by using two and three axes tumblers, shielded by three layers of mu-metal (1.5 m in length). From the Peterhead dyke a total of 30 specimens were thermally demagnetized while 34 specimens were AF demagnetized. The demagnetization programs for the granite specimens included 35 and 50 specimens, respectively.

Stereographic presentation of thermal and AF cleaned palaeomagnetic directions from the Peterhead dyke along with examples of thermal (P-81,89) and AF (P-43) demagnetization results are shown in Fig. 2. The well clustered group of remanence directions strikes nearly due south and has negative (upward pointing) inclinations of about 20°. For the investigated dyke almost all samples yield discrete high blocking temperatures in the 550–580°C range and median destructive AF fields ($M_{1/2}$) of about 20 mT.

Variation of NRM intensity (Jn), $M_{1/2}$ and Q' (Jn/k) in the northern margin of the dyke, shows an increase in $M_{1/2}$ at the contact while the values of Jn and Q' are decreasing (Fig. 3). These variations can be explained by oxidation and formation of haematite. Thus, thermomagnetic curves from the contact zone (0–3 m) give two Curie temperatures, at 580°C (magnetite) and 680°C (haematite), respectively (cf. P-47, Fig. 4). During heating and cooling some of the magnetite tends to oxidize to haematite, and a lowering of the Curie temperature of about 50°C is observed. Also, the mode of acquisition of isothermal remanent magnetization (IRM) supports the presence of haematite.

Samples from the contact zone give remanence coercive forces (RCF) in excess of 40 mT, and median destructive fields of the same order. On the other hand, samples further away from the contact show single Curie temperatures at around 580°C, but again a systematic lowering of the Curie point occur after heat treatment at 700°C. IRM-curves show saturation within fields of 100–150 mT giving lower RCF values (typically about 20 mT) and $M_{1/2}$ than for samples in the contact zone. A Lowrie–Fuller test (Lowrie and Fuller, 1971) suggests that single-domain magnetite (titanium poor titano-magnetite) is the principal carrier of remanence.

Thermal and AF demagnetization studies of the Peterhead granite are difficult due to low NRM intensity (1–2 mA m^{-1}) and viscous behaviour at higher temperatures. Owing to troublesome magnetomineralogical changes during heating, most of the specimens were AF demagnetized.

Examples of thermal and AF demagnetization are given in Figs. 5 and 6 (note the indicated noise level, shaded, and that some vector diagrams are optimally projected). Successfully tested samples define a southerly directed magnetization (frequently superimposed by a "present day" VRM), but the within-site inclination may vary considerably, from almost horizontal to moderately-steeply positive. Thermal and AF treatment give similar results.

Js–T and IRM-H curves (Fig. 7) show that both magnetite and haematite are present in most samples. Heating introduces an increase of low coercive material, giving rise to an increase in IRM intensity from typical values of 4–8 A m^{-1}, as well as decreasing the remanence coercive forces (RCF). These observations are compatible with the formation of secondary magnetite.

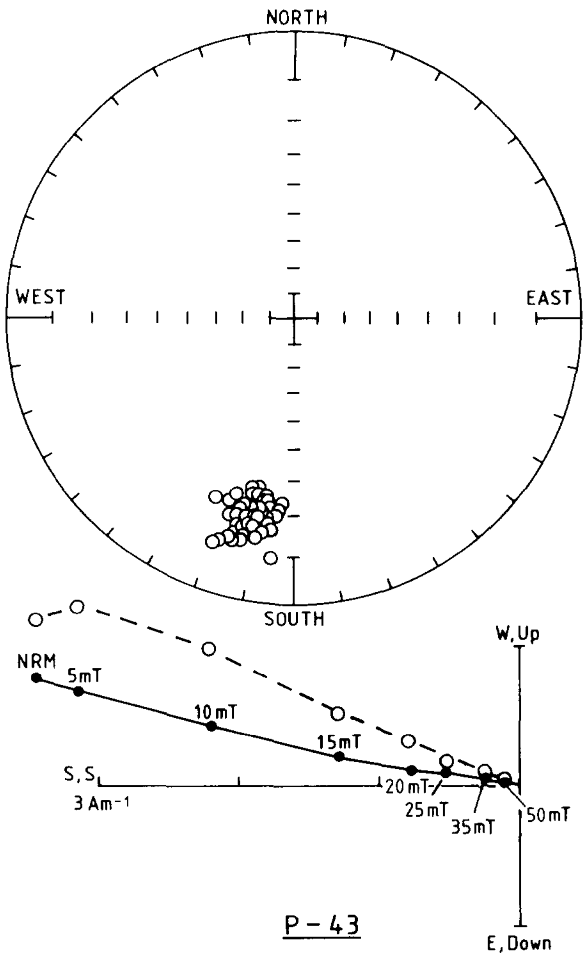

Fig. 2. Stereographic representation of characteristic remanence directions from the Peterhead dyke along with typical examples of thermal (P-81, P-89) and AF (P-43) demagnetization. In the stereoplot open (closed) symbols are upward (downward) pointing magnetizations. In the orthogonal vector projections open (closed) symbols represent points in the vertical (horizontal) plane.

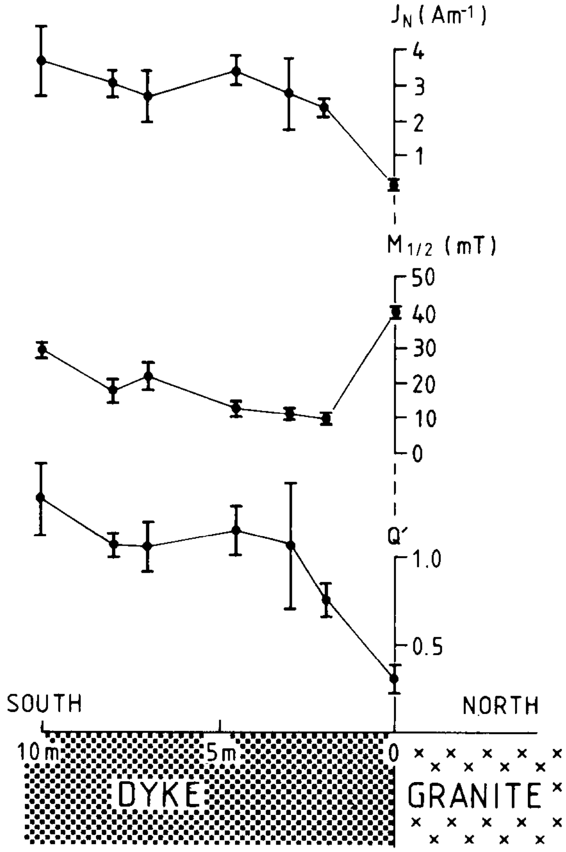

Fig. 3. Variation in intensity of NRM (Jn), median destructive field ($M_{1/2}$) and Q' (Jn/k) along N-S profiles in the northern contact zone of the Peterhead dyke. Sampling in the contact granite was not successful.

Demagnetization experiments suggest that magnetite is the bulk remanence carrier, the major blocking temperature range being below 550–580°C, but remanence analysis at $T > 600$°C was difficult due to the low intensity of magnetization (< 0.4 mA m^{-1}), and to pronounced viscous behaviour at these temperatures.

3. Discussion of remanence results

The characteristic remanence directions of the Peterhead dyke define a very clustered group of reverse polarity. Magnetite is the principal carrier of remanence, but in the contact zone haematite has formed through oxidation, probably at the time of cooling. There is no evidence of more than one stable component of magnetization. The directional data (cf. Table I) are almost identical with results from the Exeter lavas (Cornwell, 1967; Zijderveld, 1967) and from the Whin Sill (Storetvedt and Gidskehaug, 1969) which represent the widespread magmatic activity in NW Europe in

TABLE I

Palaeomagnetic data from the Peterhead granite and cross-cutting dyke (present study) along with recent data from the granites of Helmsdale (Torsvik et al., 1983), Foyers and Strontian (Torsvik, 1984) *

Rock formation	N	K	α_{95}	D(°)	I(°)	Pole position		dp	dm
						Lat.	Long.		
Peterhead granite: (present study)	38	19	5.2	180.4	22.3	N20.9	E177.8	2.9	5.5
Helmsdale granite: (Torsvik et al., 1983)	17	32	6.0	181.2	1.5	N31.1	E174.9	3.0	3.0
Foyers granite: (Torsvik, 1984)	41	15	5.7	188.0	9.2	N27.2	E166.5	2.9	5.8
Strontian granite: (Torsvik, 1984)	41	18	5.2	190.0	22.5	N21.1	E164.0	2.9	5.5
Strontian/Helmsdale combined: (west of GGF)						N26.2	E169.2		
Peterhead/Foyers combined: (east of GGF)						N24.0	E172.1		
All four granites combined:						N25.1	E170.6		
Peterhead dyke (present study)	64	184	1.3	192.5	−19.1	N41.3	E161.8	0.7	1.3

* D(°) = mean declination, I(°) = mean inclination, K = precision parameter, α_{95} = radius in the 95% circle of confidence.

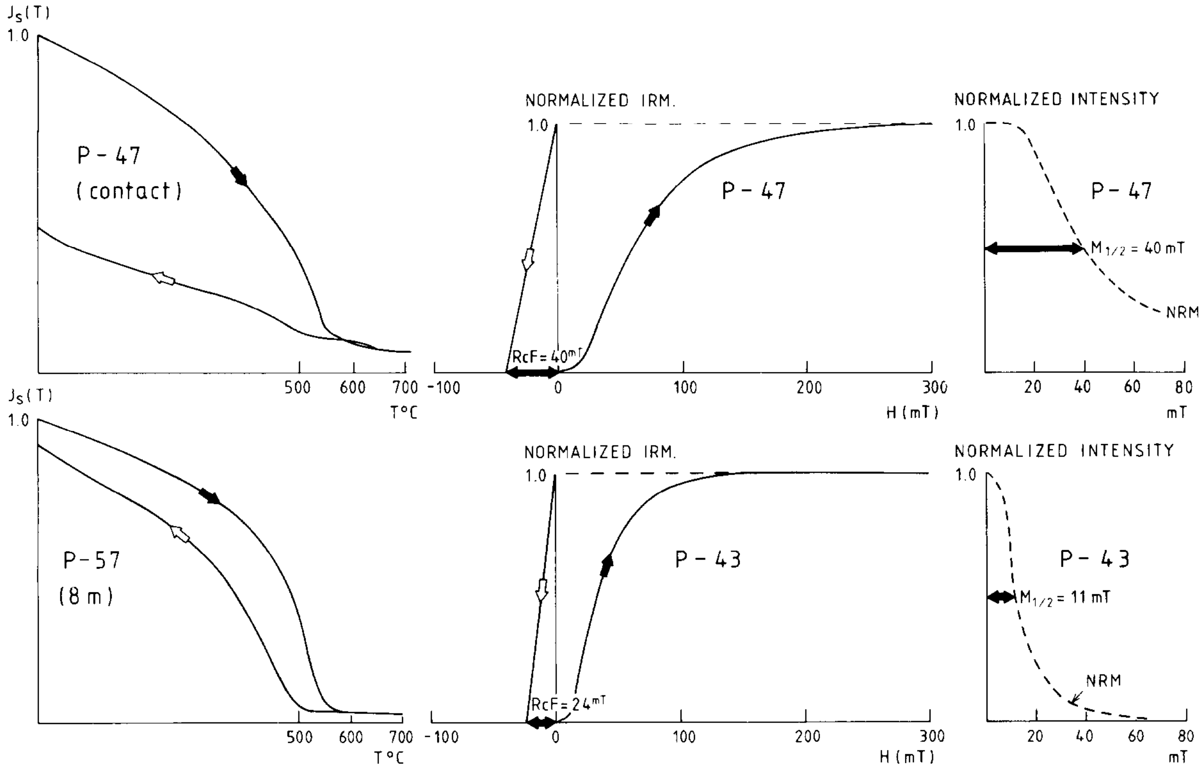

Fig. 4. Thermomagnetic and IRM acquisition curves from dyke specimens, sampled in the dyke contact (P-47) and 8 m from the contact (P-57, P-43), respectively.

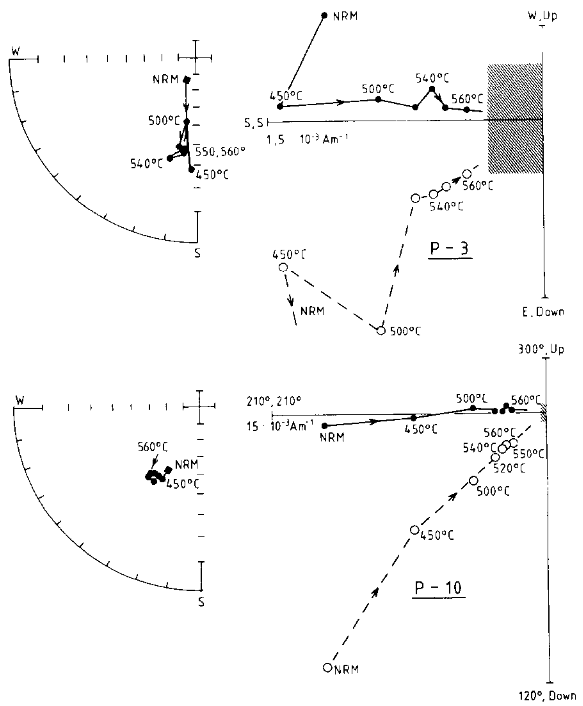

Fig. 5. Examples of thermal demagnetization from the Peterhead granite. Noise level is shaded in the orthogonal vector plots. Note the plane of projection (210, 210) for specimen P-10.

Upper Carboniferous–Lower Permian time. It is concluded therefore that the investigated dyke is of Permo–Carboniferous age.

The distribution of the characteristic magnetizations of the Peterhead granite is relatively scattered, but the majority of tested samples define southerly magnetizations, with a c. 20–30° downward inclination (Fig. 8). Colatitude and longitude plots (Lewis and Fisher, 1982) suggest a Fisherian distribution (Fisher, 1953), though a certain spread in the inclination data is present (cf. the colatitude plot). The magnetization tends to be governed by magnetite, but the influence of haematite may be important.

The directional data from the Peterhead granite match fairly well with those of the "Newer Granites" of Helmsdale (Torsvik et al., 1983),

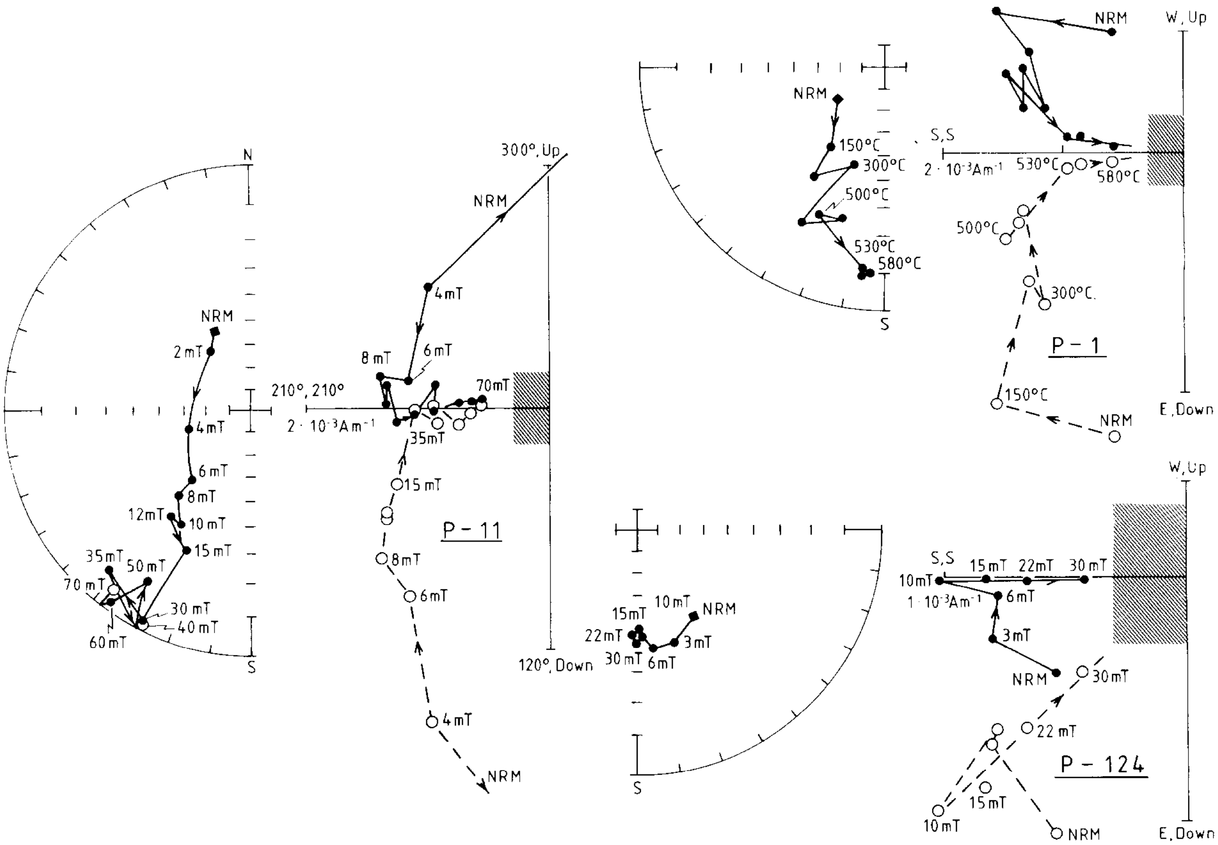

Fig. 6. Further thermal (P-1) and AF (P-11, P-124) demagnetization results from the granite. Specimens P-1 and P-11 display southerly, shallow inclined components at high temperature/high field. On the other hand, specimen P-124 shows an intermediate steep characteristic remanence component.

Strontian and Foyers (Torsvik, 1984). The results from these four granite bodies, located on both sides of the Great Glen Fault (GGF), are listed in Table I. No systematic palaeomagnetic discordance across the Fault is seen, as would have been the case if the model of Van Der Voo and Scotese (1981), involving a 15–20° left lateral offset along the GGF, had been relevant.

As seen from Fig. 9 the "Newer Granites" represent a fairly well defined group, giving virtual geomagnetic poles (VGP) in an intermediate position between "typical" Ordovician results and Lower ORS data from the British Isles. These four granites probably define an average Silurian magnetization axes of dominantly reverse field polarity. The granites of Arrochar and Garabal Hill (Briden, 1970) show both reverse and normal field polarity, the results matching fairly well the Lower ORS rocks. This may imply that the remanence acquisition age of the Arrochar and Garabal Hill granites are of lower ORS age.

In the northeast Grampians, the Aberdeenshire Gabbros have been investigated by various authors (Blundell and Read, 1958; Sallomy and Piper, 1973a; Carmichael and Storetvedt, 1981). Carmichael and Storetvedt (1981) argued for a multicomponent magnetization (formed by a combination of thermochemical and exsolution processes) giving rise to at least two dominantly horizontal magnetization axes of both polarities, while a recent review of all previous data and some new results (Watts and Briden, 1984) suggests that the

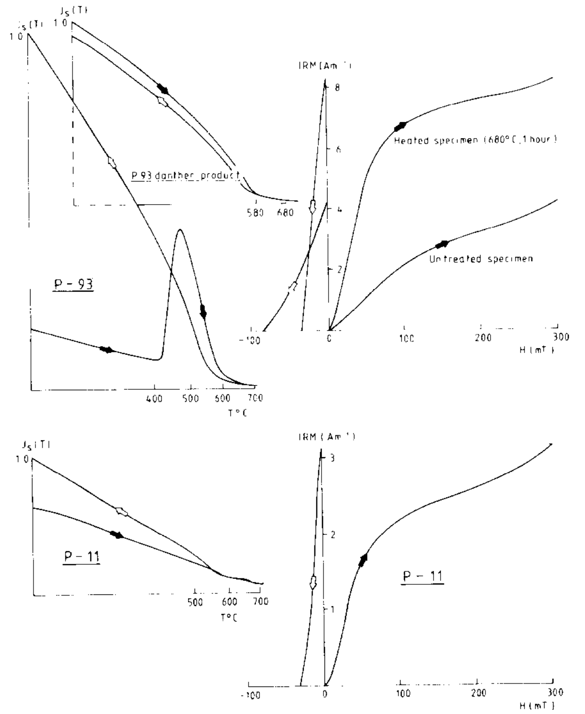

Fig. 7. Examples of thermomagnetic and IRM acquisition curves from the granite. Both magnetite and haematite are identified, and in some instances secondary production of magnetite is observed (P-93). The daughter product shows almost reversible heating and cooling curves. Production of magnetite is clearly shown in the IRM curves, by an increase in the low coercivity spectra (< 0.1T) and a decrease in RCF.

observed elongated distribution of reverse site-mean directions (cf. VGP poles in Fig. 9) may arise from post-cooling structural movement and/or APW associated with slow cooling. Furthermore, Watts and Briden (1984) argued that the inferred palaeomagnetic younging trend correlates with K/Ar cooling ages.

K/Ar ages of metamorphic micas (biotite, muscovite) in the Scottish Highlands show a wide range of ages, dominantly in the 390–470 Ma range (Dewey and Pankhurst, 1970). This time interval is unlikely to represent a single isotopic event. Partial overprinting (i.e., partial loss of Argon) or cooling during post-orogenic uplift are more likely, the latter explanation being favoured by most workers. If the K/Ar ages are related to post-orogenic uplift, the K/Ar dates represent the time elapsed since the dated mineral cooled through its Ar blocking temperature, forming a metamorphic veil post-dating major tectonomorphism (Armstrong, 1966).

In slowly cooled deep seated plutons or metamorphic rocks the blocking temperature isochrons of magnetization in magnetite would be at significantly greater depths than biotite age isochrons (as also noted by Watts and Briden), due to blocking temperature contrasts (say 200–300°C), unless the magnetization have a chemical or thermochemical origin (in that case discussion of blocking temperatures becomes irrelevant). Magnetization in magnetite blocked through progressive cooling may certainly record changes in the geomagnetic field, giving rise to a spread of site-mean directions. However, in view of available palaeomagnetic data from the "Newer Granites" and other Palaeozoic data from the British Isles, the interpretation of the data from the Aberdeenshire Gabbros given by Watts and Briden (1984) may have an alternative explanation. The present author is inclined to believe that the observed spread of remanence directions in these rocks is basically due to late Caledonian thermochemical activity (with associated magnetic resetting) continuing into the Lower Devonian.

Watts and Briden (1984) stated that the younging trend of palaeomagnetic directions lie along the published British APW path (cf. Briden and Duff, 1981; Turnell and Briden, 1983), but does not comment on the fact that their "433–448 Ma" cluster (Fig. 9) is almost identical to that of most Lower Devonian rocks from Scotland. Characteristic directions from the Peterhead granite (Fig. 8) show a certain spread towards steeper and more westerly directions, but lack the shallow south-southeasterly directions that are seen in the Aberdeenshire Gabbros. The latter data may indeed represent the Ordovician field, but the presumably younger directions, partly similar to the Peterhead results and partly matching the palaeomagnetic data of the Lower Devonian volcanics of Scotland, are unlikely to favour APW in the 430–470 Ma range (minimum ages).

The "Newer Granites" and the Lower Devonian rocks from the British Isles reveal two significantly different VGP groups (Fig. 9). In the opinion of the present author, the relative polar

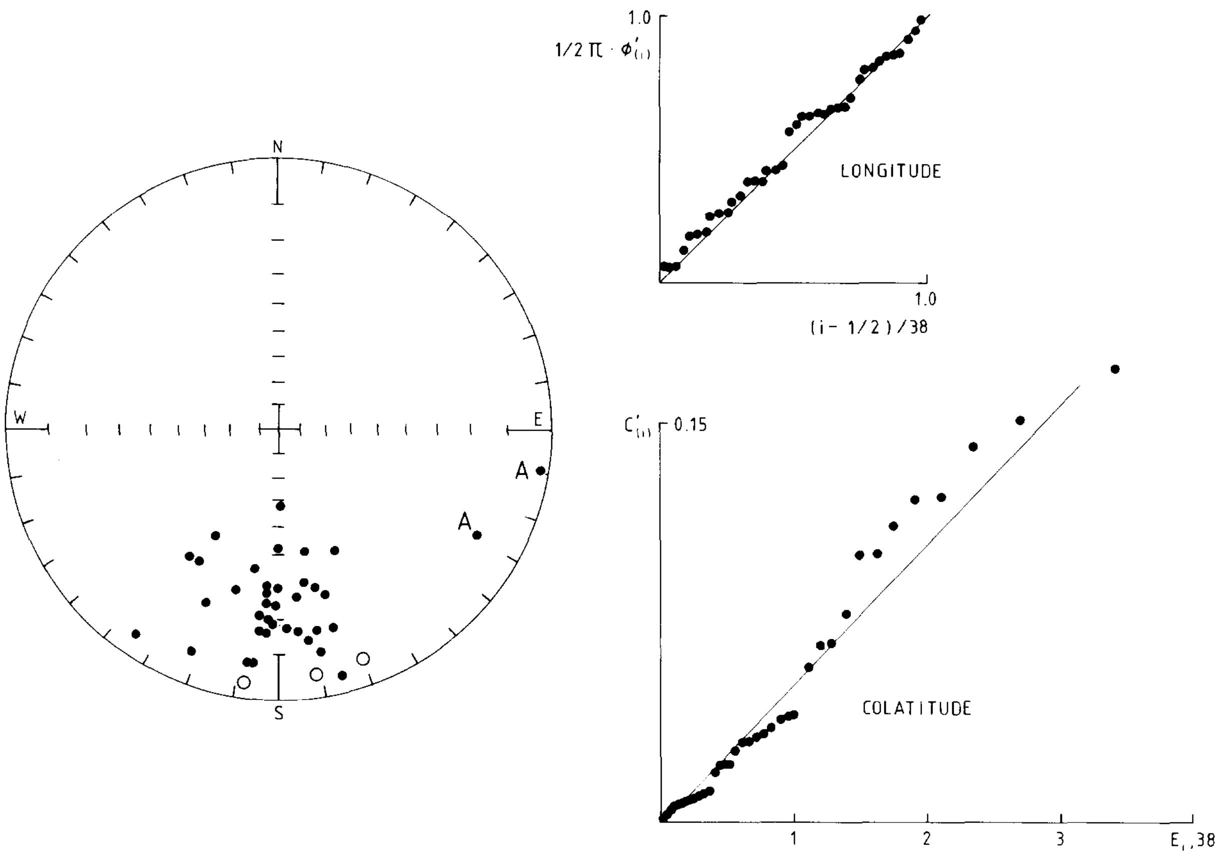

Fig. 8. Distribution of characteristic remanence directions in the granite along with colatitude and longitude plots (cf. Lewis and Fisher, 1982). Directions noted by (A) in the stereoplot are excluded in the statistical analysis (Table I).

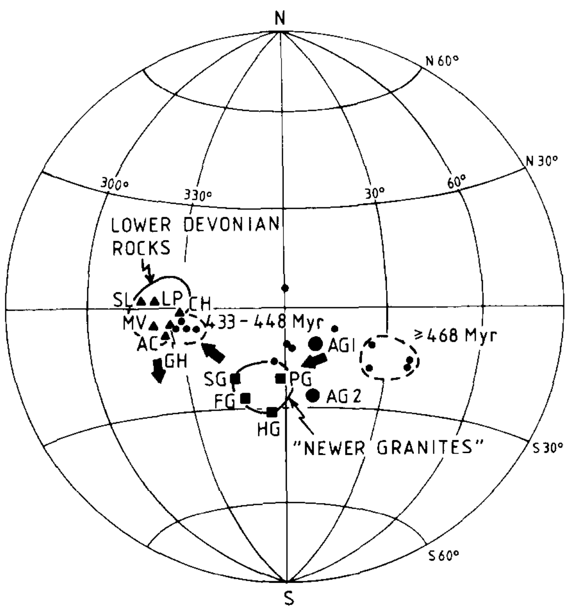

Fig. 9. Silurian (squares) and Lower Devonian (triangles) pole positions from the British Isles, along with poles from the Ordovician Aberdeenshire gabbros (circles). K/Ar ages denote thermochrons coinciding with the sampling sites in the Aberdeenshire gabbros, as given by Watts and Briden (1984; cf. Fig. 5). Pole positions from the Aberdeenshire gabbros given by Sallomy and Piper (1973a) and Carmichael and Storetvedt (1981) are denoted by AG1 and AG2, respectively. The Silurian poles are as follows: HG = Helmsdale Granite (Torsvik et al., 1983); FG = Foyers Granite (Torsvik, 1984); SG = Strontian Granite (Torsvik, 1984); PG = Peterhead Granite (present study). The Lower Devonian poles includes: MV = Midland Valley Lavas and Sediments (Sallomy and Piper, 1973b); SL = Strathmore Lavas (Torsvik, 1985); LP = Lorne Plateau Lavas (Latham and Briden, 1975); AC = Arrochar Complex (Briden, 1970); GH = Garabal Hill Complex (Briden, 1970); CH = Cheviot Hill Lavas and Granites (Thorning, 1974). The suggested APW path from Ordovician through Silurian into Lower Devonian is marked by arrows.

pattern as outlined in Fig. 9 is likely to represent the true APW for the time interval between Ordovician and the earliest Devonian, at least north of the Iapetus suture zone. This polar path is similar to that given by Briden et al. (1984), except for the position of the "Newer Granites", suggesting that the path should have a more southerly trend than previously assumed. Based on Fig. 9 the palaeomagnetic younging trend in NE Scotland are unlikely to reflect crustal cooling and uplift in the Ordovician (Watts and Briden, 1984), but is rather caused by magnetic overprinting in Silurian–Lower Devonian times. A major part of the magnetization in the Aberdeenshire Gabbros is considered to be significantly younger than the K–Ar ages, the sources for the suggested thermochemical overprints being the extensive Newer Granite and Lower ORS magmatism in NE Scotland.

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