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Palaeozoic palaeomagnetic results from Scotland and their bearing on the British apparent polar wander path

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Palaeomagnetic studies of the Lower and Upper Old Red Sandstone (ORS), western Midland Valley, indicate the presence of two principal remanence components, IB and HB. Both components can be demonstrated to be of secondary, post-Upper ORS, origin. Component IB compares with palaeomagnetic results from Upper Carboniferous/Permian dykes and sills in the Midland Valley, whereas HB conforms to palaeomagnetic results from the overlying Lower Carboniferous Lavas.

A combination of HB components from the Lower/Upper ORS and Lower Carboniferous lavas (western Midland Valley) yields a relative pole position near S14 and E322 which compares well with Lower Carboniferous data from the Kinghorn and Burntisland Lavas, eastern Midland Valley (S14 and E332). From Kinghorn, the palaeomagnetic data can be demonstrated to be of primary, Lower Carboniferous, origin. Seen in conjunction with the British polar wander path, the Lower Carboniferous poles reported here seemingly dissociate Middle–Upper Devonian and Upper Silurian/Lower Devonian poles. Owing to the lack of *magnetic* age control in the Middle–Upper Devonian data base, it is argued that the majority of Middle–Upper Devonian data from the British Isles should be reconsidered as Carboniferous magnetic overprints. This carries the implication that any tectonic models based on Middle–Upper Devonian palaeomagnetic results should be considered highly suspicious.

1. Introduction

The Upper Silurian/Lower Devonian palaeofield direction (British Isles) is becoming widely accepted, though the Middle to Upper Devonian palaeofield direction is a matter of dispute (see, e.g., Tarling, 1985). The present study was initiated in an attempt to shed some light on the latter issue.

The Midland Valley is bounded by the Highland Boundary Fault (HBF) and the Southern Upland Fault (Fig. 1), and palaeomagnetic sampling was carried out in the western Midland Valley (sites 1–25), highlighting the Lower and Upper Old Red Sandstone (ORS), and in the eastern Midland Valley (sites 26–44) with emphasis on Lower Carboniferous rocks. Rocks of Middle ORS age are absent in the Midland Valley

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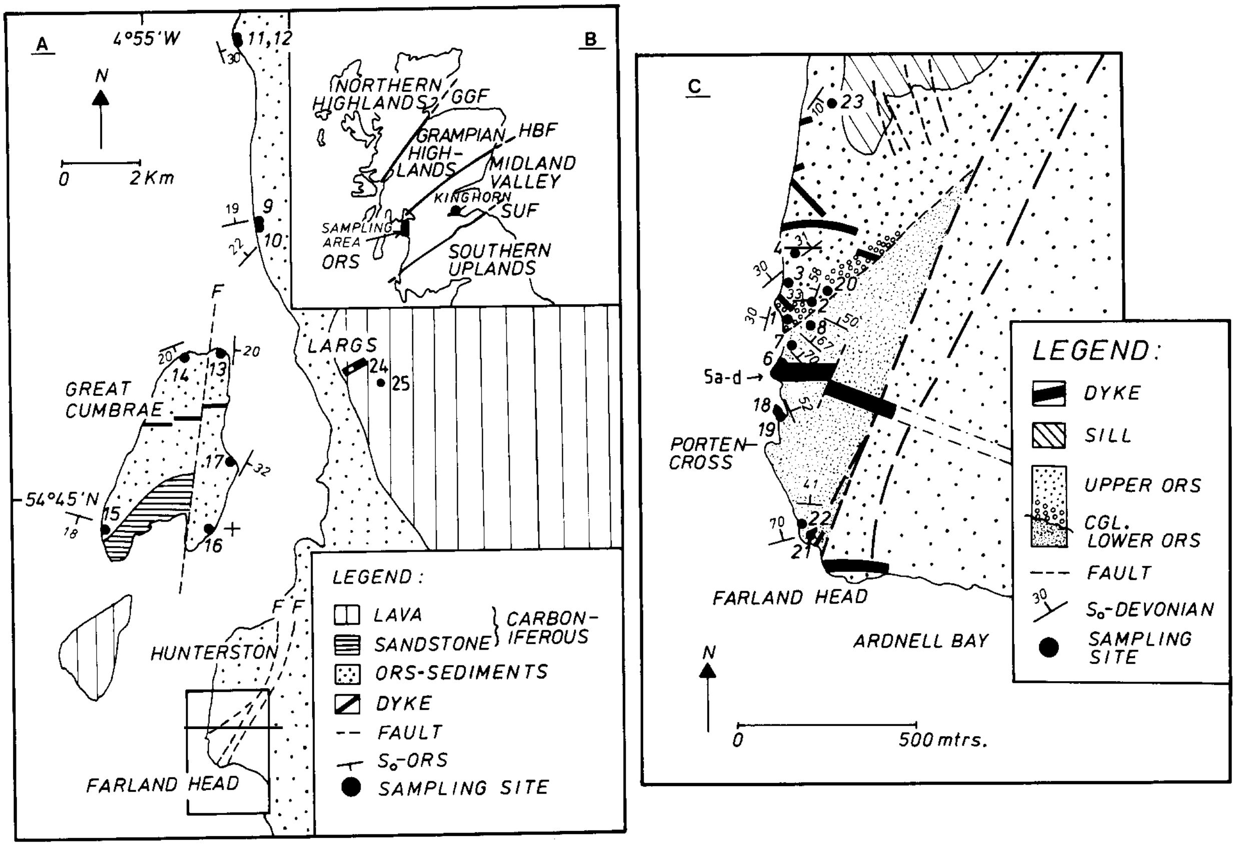

Fig. 1. Sampling details (a,c) in the western Midland Valley (sites 1–25), and the geographic location of the sampling areas within the Midland Valley (b).

(Bluck, 1980), thus the Lower ORS is unconformably overlain by the Upper ORS which passes up into the Lower Carboniferous Calciferous Sandstone Measure. Sampling in the western Midland Valley embraces a section through the Lower and Upper ORS (Fig. 1). The lower ORS, including red siltstone and sandstone (sites 6–8, 18, 19, 21 and 22), crop out in a small wedge-shaped area at Portencross/Farland Head (Downie and Lister, 1969; Davies, 1972; Bluck, 1973). The rocks are in part sheared (site 21),and form a northeast-plunging synclinal structure. The Lower ORS is faulted against a coarse-grained conglomerate of Upper ORS age. The basal conglomerate (Upper ORS), ~ 30 m thick, passes upward into a series of red and red-brown sandstones (sites 3, 4 and 23). The area is intruded by a number of essentially E–W striking quartz-dolerite dykes and felsic sills of assumed Upper Carboniferous–Permian age. A conspicuous ~ 50-m wide dyke cuts the Lower ORS at Portencross, and sampling was confined to a section traversing this dyke (sites 5a–d) and the immediately adjacent baked Lower ORS (site 6). Near Largs, the Upper ORS passes into a thick sequence of Lower Carboniferous lavas (Calciferous Sandstone Measure). These lavas, however, are substantially altered and weathered, and only one site was sampled (site 25), in addition to a Permo-Carboniferous dyke (Site 24) cutting the lavas (Fig. 1a).

The Lower Carboniferous is characterized by transgression and marine sedimentation, but also contains abundant basaltic lava eruptions (Anderton et al., 1979). A detailed study of the Lower Carboniferous lavas was carried out near Kinghorn (sites 26–37) and Burntisland (sites 38–41). The

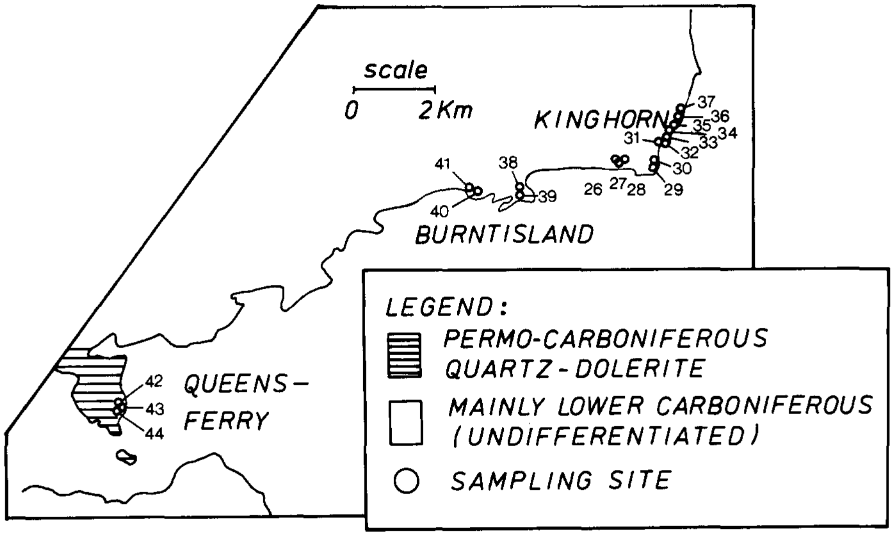

Fig. 2. Sampling details Kinghorn, Burntisland and Queensferry.

Kinghorn Lavas have been examined previously e.g., by Wilson and Everett (1963), but their palaeomagnetic results, however, are commonly omitted in the literature.

At Kinghorn, ~ 30 olivine basalt flows have been identified (Geike, 1900; MacGregor, 1973), generally dipping 20–30° west. Sampling includes a vertical section through 12 of these lava flows. The interbedded sandstones, shales and limestones were not sampled. In addition to Lower Carboniferous Lavas, a Permo-Carboniferous sill near Queensferry (Sites 42–44) was examined (Fig. 2).

2. Laboratory experiments

The natural remanent magnetization (NRM) was measured on Digico and Minispin spinners and a two-axis cryogenic magnetometer. The stability of NRM for a total of 517 specimens was tested by means of step-wise thermal, alternating field (AF) and, to a lesser extent, chemical leaching demagnetization. Characteristic remanence components were calculated by means of least-square analysis. Details of the magneto-mineralogy and the magnetic fabrics are given in Atterås (1986) and Lyse (1987).

2.1. *Western Midland Valley*

The Lower ORS is dominated by a shallow, upward pointing remanence with declinations near south. This magnetization, denoted IB, is often of single-component nature, but more recurrently it occupies the low- to intermediate-blocking temperature spectra (Fig. 3, L283), i.e. below 500–600°C. The high-blocking component, mostly resident in haematite, often proved difficult to identify since the intensity dropped below 0.1 mA m^{-1} at intermediate/high temperatures combined with viscous behaviour. With the aid of the cryogenic magnetometer, however, it proved possible to identify this component, denoted HB. Component HB is characterized by southwest declinations and associated with moderate downward pointing inclinations (Fig. 3, L283). The HB components most commonly show reverse polarity, but normal polarity data have also been identified (Fig. 4a, b). Permo-Carboniferous dyke samples (sites 5a–d and 24) show almost single-component magnetizations, due south with negative inclinations (Fig. 3, L285). This magnetization compares with the IB component in both baked (site 6; Fig. 3, L56B) and unbaked Lower ORS sandstones (Fig. 3, L283).

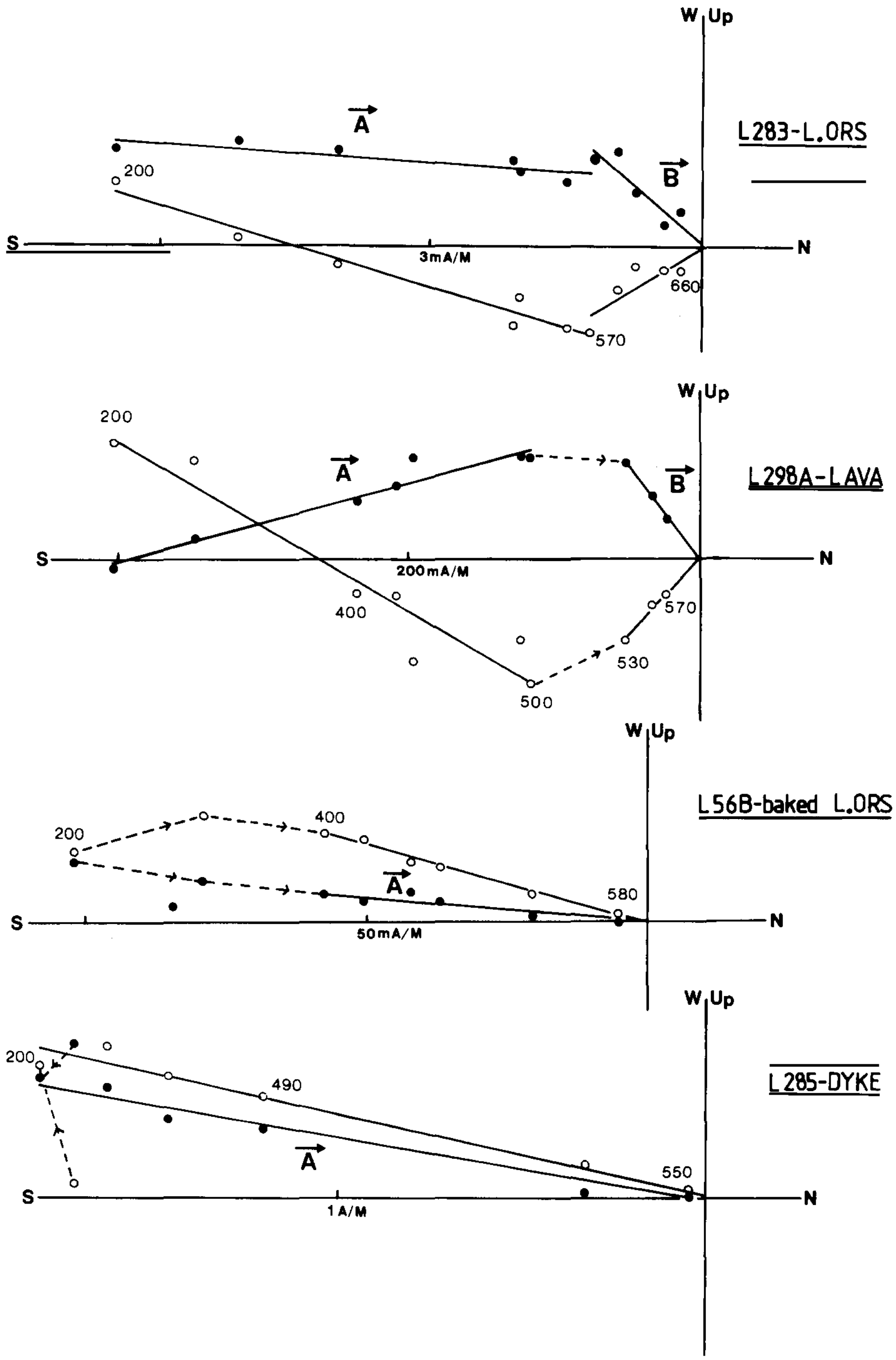

Fig. 3. Examples of thermal demagnetization for samples from the Lower ORS sandstone (L283, site 18), Lower Carboniferous lava (L296A, site 25), baked Lower ORS sandstone (L56B), and Permo-Carboniferous dykes (L285, site 24). In orthogonal vector projections, open symbols (closed symbols) represent points in the vertical (horizontal) plane.

A substantial number of the Upper ORS sites proved unsuitable for palaeomagnetic analysis, but successfully tested sites show a magnetization build-up which is similar to that encountered for the Lower ORS sediments. This pattern is also observed in five conglomerate boulders (Lower

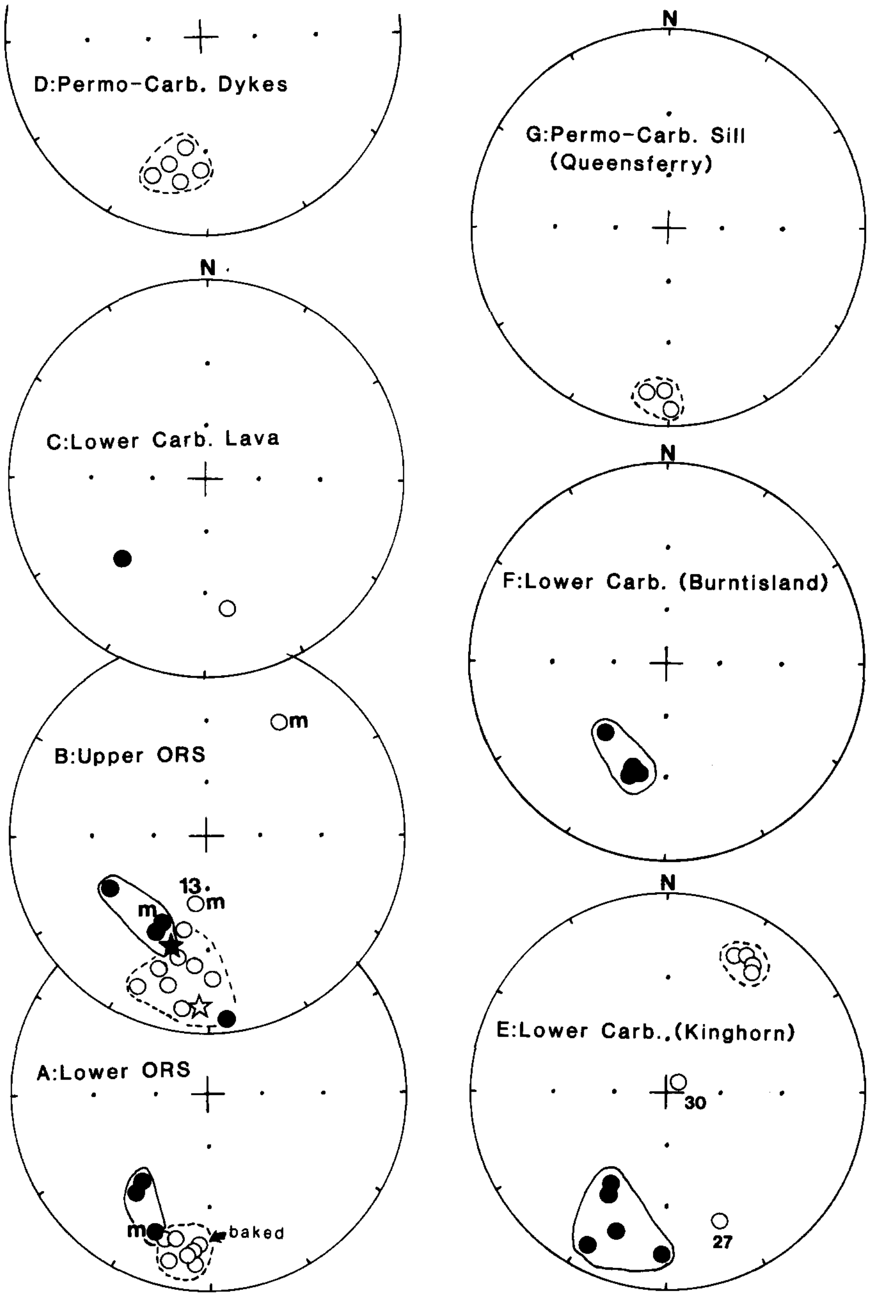

Fig. 4. Distribution of in situ site-mean directions. Within-site dual-polarity results are marked with m in (a) and (b). Site mean-values from conglomerate boulders are shown with stars (b). Note that conglomerate boulders show a similar magnetic signature as the Lower and Upper ORS sandstones. Sites 27 and 30 in (e) are excluded in the final statistics (Tables II and III). In equal-angle stereographic projections, open (closed) symbols represent negative (positive) inclinations.

TABLE I

Palaeomagnetic results from western Midland Valley (mean geographic sampling co-ordinates: N54.8, W5)

	In situ				Tectonic correction				*N*
	Mean declination	Mean inclination	α_{95}	*k*	Mean declination	Mean inclination	α_{95}	*k*	
Lower ORS									
IB [a]	190	−12	3.9	185	186	+34	7.6	48	7
HB	211	+25	11.3	51	182	+78	21.8	14	3
Upper ORS									
IB [b]	190	−16	8.2	29	190	−3	10.4	18	10
HB [b]	213	+31	12	27	222	+26	25	6	5
Lower and Upper ORS combined									
IB	190	−14	5.1	45	188	+12	10.2	11	17
HB	212	+29	8.3	35	217	+47	23.3	4	8
Lower Carboniferous Lava									
IB	170	−23	5.7	35.4	171	−27	5.7	35.4	17 *
HB	226	+29	4.8	48.1	223	+29	4.8	48.1	18 *
Permo-Carboniferous Dykes									
	190	−22	6.8	85	–	–	–	–	5

[a] Includes baked sandstone.
[b] Includes conglomerate boulders;
N = number of sites (samples *); α_{95} = 95% confidence circle (Fisher, 1953); *k* = precison parameter.

ORS sandstone boulders), thus providing a *negative* conglomerate test (site 20). Additionally, one site (13), showed a steeply inclined and 'anomalous' dual-polarity magnetization, probably of Tertiary origin, and not discussed in this account.

Lower Carboniferous lava specimens (site 25) show a remanence build-up closely similar to that encountered in both the Lower and Upper ORS (Fig. 3, L298A; Fig. 4), although the IB component is somewhat more southeasterly directed than IB directions recorded in the Lower and Upper ORS.

The Lower and Upper ORS sediments and Lower Carboniferous lavas are dominated by the IB component, which accords well with Permo-Carboniferous dyke magnetizations (Table I; Fig. 4). This, along with *negative* conglomerate and fold-tests (Fig. 5) clearly point toward a remagnetization. The HB component is solely recorded from the ORS and Lower Carboniferous rocks (Fig. 4). The HB component, as in the case of the IB component, gives a *negative* fold-test for the Lower and Upper ORS (Table I). This, combined with a *negative* conglomerate test in the Upper ORS, indicates that the HB component is also of secondary origin.

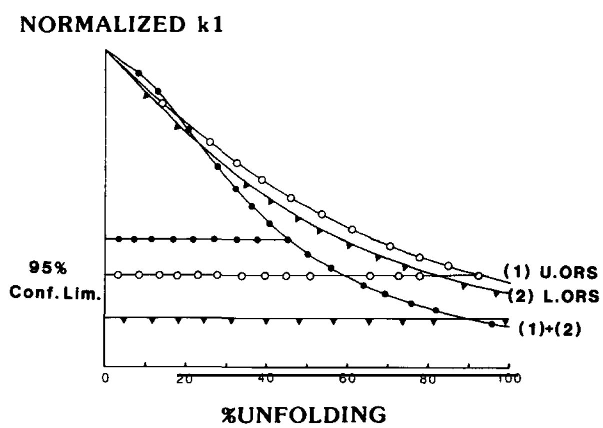

Fig. 5. Variation in precision parameters (normalized) of the IB component during step-wise unfolding. Upper ORS IB components and a combination of Lower/Upper ORS HB components show a negative fold-test at the 95% level. A similar result obtains for the HB components, which combined with negative conglomerate tests demonstrate the secondary nature of both the IB and HB component (cf. text and Table I).

2.2. *Eastern Midland Valley*

Palaeomagnetic results from the Kinghorn Lavas (sites 26–37) confirm the major findings of Wilson and Everitt (1963). At least three palaeofield reversals are recorded in this lower Carboniferous sequence (Figs. 6 and 7), and the majority of samples are characterized by shallow dipping magnetizations with declinations oriented NNE–SSW (Fig. 7). The basal lava flows from Kinghorn (sites 26–28) are dominated by low temperature and coercivity components, and numerous samples proved unsuitable for demagnetization and detailed remanence analysis (Fig. 7, KH-90). The basal lava-flows exhibit low Q' ratios (NRM/susceptibility), medium destructive fields less than 7 mT and remanence coercive forces around 10 mT. These 'bulk' parameters are the lowest recorded from the Kinghorn lavas (Fig. 6). It is also noted that the basal lava-flow in successive lava units generally shows minimum values, indicating 'reheating' (prolonged cooling), attendant on the effect of reducing the magnetic stability seemingly through grain growth and low-temperature oxidation (maghemitization). The basal flows are characterized by coarse-grained (up to 0.1–0.2 mm) titanomagnetite providing strong evidence of low-temperature oxidation (maghemitization). Curie temperatures near 500 ° C were recorded.

Apart from sites 26–28, the tested samples show high remanence stabilities. Minor low-blocking components may be present, but most commonly almost single-component magnetizations (Fig. 7, KH-16) are observed. The principal remanence carrier is titanium-poor titanomagnetite, and remanence stability can be observed up to 580 ° C. Some viscous behaviour, however, was often observed above 450 ° C, related to modest amounts

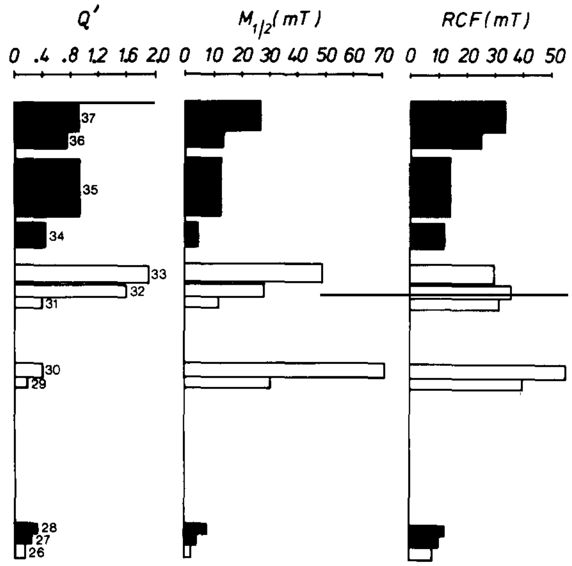

Fig. 6. Average values of Q' (NRM/susceptibility), $M_{1/2}$ (median destructive field) and RCF (remanence coercivity force) for the tested lava-flows from Kinghorn. Black and white denote reverse and normal polarity directions respectively (cf. Fig. 7 for vertical scale).

TABLE II

Palaeomagnetic results from eastern Midland Valley (mean geographic sampling co-ordinates: N56.2, W3.1)

	In situ				Tectonic correction				N [b]
	Mean declination	Mean inclination	α_{95}	k	Mean declination	Mean inclination	α_{95}	k	
Kinghorn									
Normal [a]	031	−15	3.7	357	027	−26	8.6	66.3	4
Reverse	201	+19	12.0	27.1	198	+26	10.4	35.9	5
Combined	026	−18	7.3	41.4	022	−26	6.9	45.1	9
Burntisland									
	200	+32	10	49	214	+41	11.1	39.7	4
Queensferry									
	182	−9	5.2	240.9	–	–	–	–	3

[a] Polarity.

[b] N = number of sites; see Table I for explanation of other symbols.

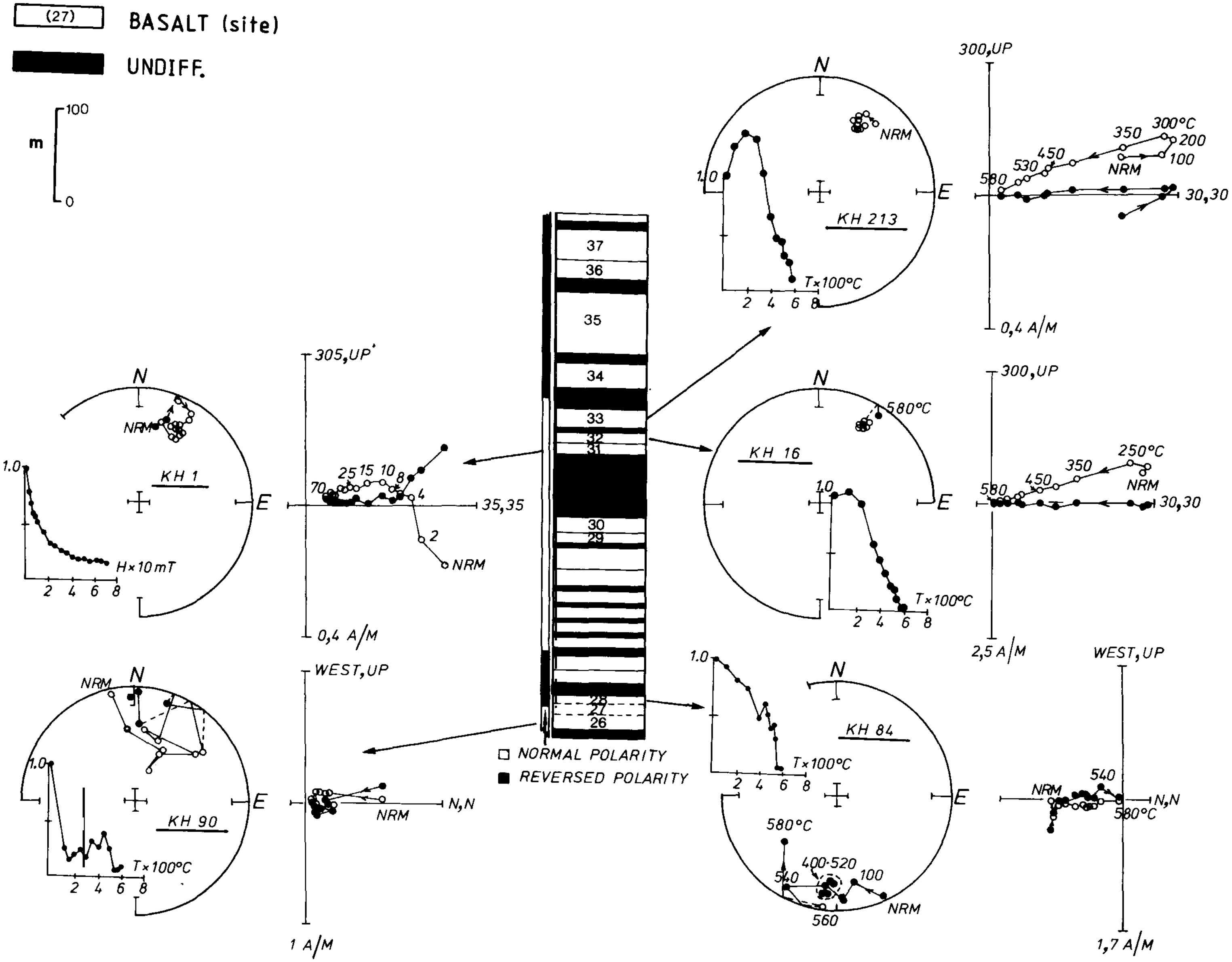

Fig. 7. Examples of thermal and AF demagnetization from the Kinghorn Lavas (cf. text). Sample KH-90 (site 26) illustrates unstable behaviour during thermal demagnetization, a characteristic feature of the basal lava-flows. The indicated polarity pattern is based on this study, and palaeomagnetic data given in Wilson and Everett (1963) (vertical scale approximated).

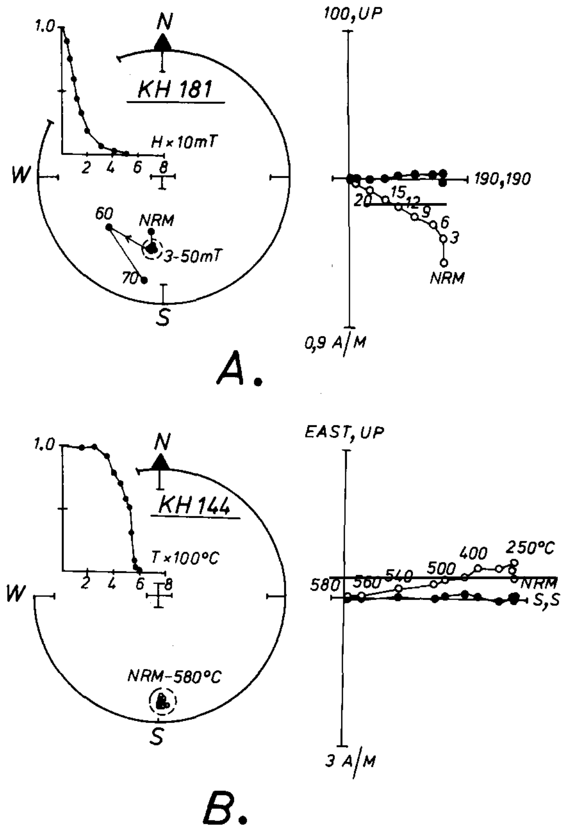

Fig. 8. Examples of AF and thermal demagnetization of a sample from the Burntisland lavas (a) and the Queensferry sill (b).

of titano-maghaematite undergoing inversion during heating. Alternate field demagnetization (Fig. 7, KH-1) gave directional results in agreement with thermal treatment.

Individual lava-flows display a uniform polarity, but a few samples, notably those located at site 33, show a dual-polarity interplay. The early stages of thermal treatment indicate the removal of a reverse field component, after which the normal field direction is isolated above 300 °C (Fig. 7, KH-213).

Apart from sites 27 and 30 (excluded in the statistical analysis), *in situ* site-mean directions (Fig. 4e) define a magnetization axis near NE–SW. Although there are minor variations in the regional 'bedding' (measured in interbedded sandstone, shale and limestones) between individual lava units, the statistical parameters are not significantly affected in a conservative fold-test (Table II). There appears to be no doubt, however, that these magnetizations relate to a 'primary' Lower Carboniferous palaeofield, because of:

(i) the stratigraphically related polarity pattern with well defined dual-polarity;

(ii) the variation of bulk parameters throughout the Kinghorn lavas (Fig. 6), which indicate a 'primary' cooling pattern.

No secondary mechanism (apart from self-reversals) would produce this multiple polarity pat-

TABLE III

Final statistics (interpreted magnetic ages) and virtual geomagnetic pole positions

	Declination	Inclination	α_{95}	k	N	Pole Latitude	Pole Longitude	dp/dm
Lower Carboniferous								
Eastern Midland Valley [a]	205	+31	7.0	30.8	13	S14.1	E332.2	4/8
Western Midland Valley [b]	213	+29	7.6	37.8	9	S14.3	E322.2	5/8
Upper Carboniferous – Permian								
Eastern Midland Valley [c]	182	−9	5.2	240.9	3	S38.3	E354	3/5
Western Midland Valley [d]	189	−17	4.4	44.3	23	S43.3	E342.7	2/5

[a] Combined, tectonically corrected, site-mean data from Kinghorn and Burntisland.
[b] In situ site-mean data from Lower and Upper ORS (HB) and tectonically corrected Lower Carboniferous data (HB).
[c] In situ Queensferry sill data.
[d] In situ Lower and Upper ORS (IB), lower Carboniferous lava (IB) and Permo-Carboniferous dyke data.

tern, and any strong regional remagnetization would have firmly biased both normal and reverse polarity data.

Only reverse remanence components have been identified from Burntisland (sites 38–41). Directional stability commonly ceased above 400–450 °C, and AF demagnetization proved more effective (Fig. 8a). The palaeomagnetic results compare with those from the Kinghorn lavas (Table II; Fig. 4e–f), thus remanence results from Kinghorn and Burntisland have been combined in the final statistical analysis (Table III).

From the Queensferry sill (sites 42–44), mostly single-component remanences with near-south declinations and shallow *upward* pointing inclinations are observed (Fig. 8b). Thermal unblocking spectra and Curie temperatures near 580 °C show that magnetite is the principal remanence carrier. The palaeomagnetic results from this Permo-Carboniferous sill (Table II; Fig. 4g) clearly differ from the Kinghorn/Burntisland lavas.

3. Discussion

The predominant magnetization (IB) in both the Lower and Upper ORS, western Midland Val-

TABLE IV

Selected late Silurian/early Devonian to Permian palaeomagnetic data from the British Isles which are shown in Fig. 9

No.	Formation	Pole		Reference
		Latitude	Longitude	
Upper Silurian – Lower Devonian				
1	Lorne Plateau	N02	E321	Latham and Briden, 1975
2	Garabal Hill/Glen Fyne	S05	E326	Briden, 1970
3	Arrochar Complex	S08	E324	Briden, 1970
4	Midland Valley ORS	S04	E320	Sallomy and Piper, 1973
5	Strathmore Lavas	N02	E318	Torsvik, 1985a
6	Cheviot combined	N01	E329	Thorning, 1974
7	Sarchlet-1	S09	E326	Storhaug and Storevedt, 1985
Middle – Upper Devonian [a]				
8	Caithness	S27	E329	Storetvedt and Torsvik, 1983
9	John O'Groats	S24	E325	Storetvedt and Carmichael, 1979
10	Esha Ness	S20	E315	Storetvedt and Torsvik, 1985
11	Eday Group	S08	E346	Robinson, 1985
12	Sarchlet-2	S28	E346	Storhaug and Storetvedt, 1985
13	Man of Hoy B_1	S14	E334	Storetvedt and Meland, 1985
14	Rackwick B_2	S23	E326	Storetvedt and Meland, 1985
16	Strathmore overprint	S20	E315	Torsvik, 1985a
25	Foyers ORS (recalculated)	S30	E327	Kneen, 1974
26	Bristol	S32	E338	Morris et al., 1973
Lower Carboniferous				
15	Kinghorn-Burntisland	S14	E332	This study
24	Largs-1	S14	E322	This study
Upper Carboniferous – Permian				
17	Exeter Lavas	S46	E345	Cornwell, 1967
18	Wackerfield dyke	S49	E349	Tarling and Mitchell, 1973
19	Whin sill	S44	E339	Storetvedt and Gidskehaug, 1969
20	Peterhead dyke	S41	E342	Torsvik, 1985b
21	Queensferry sill	S38	E354	This study
22	Argyllshire dykes	S35	E355	Esang and Piper, 1984
23	Largs-2	S43	E343	This study

[a] Apart from pole No. 11 and possibly pole 13, these poles are argued to represent Carboniferous remagnetizations (cf. text).

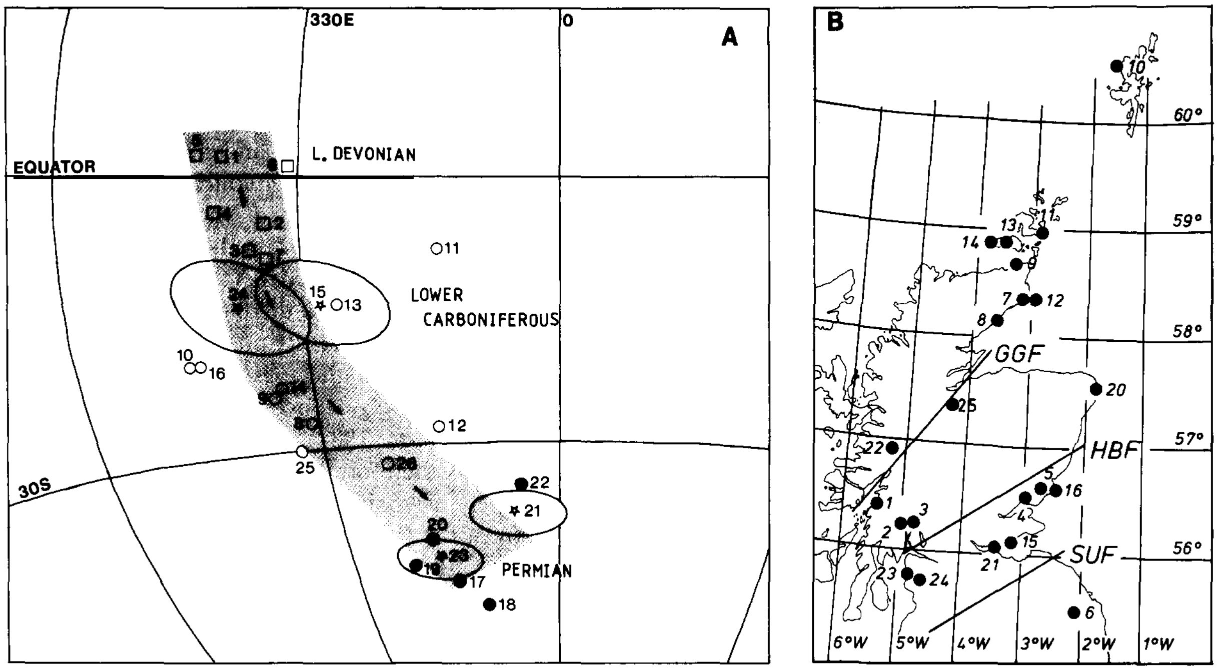

Fig. 9. Selected Upper Silurian–Lower Devonian (open squared symbols) to Permian poles from the British Isles (A). Results from the present study (poles 15 and 24, 21 and 23; open stars) are shown with dp/dm semi-confidence ellipses. Note that the Lower Carboniferous data (poles 15 and 24) dissociate the majority of claimed Middle–Upper Devonian poles (open circular symbols, e.g. 8–10, 12, 14, 16, 25 and 26, cf. Table IV and text) rather than forming a continuation toward the Upper Carboniferous–Permian poles (closed circular symbols; 17, 18 and 20–23). (B) Shows the corresponding sampling localities in Northern England and Scotland. GGF = Great Glen Fault, HBF = Highland Boundary Fault, SUF = Southern Uplands Fault.

ley, is of secondary origin, as evidenced from *negative* fold and conglomerate tests. Component IB is further observed as a partial overprint in the Lower Carboniferous rocks (site 25). The IB component matches Permo-Carboniferous dyke directions (western Midland Valley), as well as those of the Queensferry sill (eastern Midland Valley) and other Upper Carboniferous/Permian results from the British Isles (Tables III and IV; Fig. 9).

The combined palaeomagnetic data from the Lower Carboniferous Kinghorn and Burntisland lavas correspond to the Lower Carboniferous results from the western Midland Valley. In the Kinghorn area this magnetization is clearly of primary, Lower Carboniferous, origin. The Lower Carboniferous magnetic signature corresponds to the HB component recorded in the Lower and Upper ORS. This, along with the *negative* fold and conglomerate tests, suggests that the Lower and Upper ORS were remagnetized in Lower Carboniferous time. This was probably promoted via thermochemical remagnetization related to the combined effects of a high geothermal gradient and the certainty that the lower Carboniferous lavas covered the entire sampled ORS region. It should be emphasized, however, that primary Lower ORS directions have been identified in the northeastern part of the Midland Valley (e.g. Sallomy and Piper, 1973; Torsvik, 1985a), thus the total magnetic overprinting reported here must be considered to be of local nature.

A number of Devonian poles have been reported from the British Isles, some a few decades ago; the latter have not been subjected to step-wise demagnetization and modern analytical procedures, and are clearly in need of re-examination. The near-equatorial latitudinal position of the British Upper Silurian/Lower Devonian pole is widely accepted (Table IV; Fig. 9), but the Middle to Upper Devonian poles are highly controversial.

This controversy is to a large extent related to palaeomagnetic data from the Orcadian ORS basin, North Scotland. The magnetic signature of the Orcadian ORS and its substrate is complex (see, e.g., Turner and Archer, 1975; Tarling et al., 1976; Turner, 1977), and this complexity is most likely caused by pervasive late Palaeozoic/Mesozoic magnetic overprinting. The characteristic magnetization component related to this event has been denoted *A* (Storetvedt and Carmichael, 1979). The magnetic age and origin of *A* is not firmly established, but various attempts have been made to link these remagnetizations with event(s) of reactivation and hydrothermal fluxes relating to the Great Glen Fault System (e.g., Torsvik et al., 1983; Storetvedt, 1987). Additionally, Storetvedt and co-workers argue for the presence of an underlying magnetization, *B*, considered as representing the primary Middle–Upper Devonian palaeofield direction. Magnetization *B* differs substantially from the Lower ORS palaeofield direction, and if correct, would indicate rapid APW in Devonian times. However, *B* has been questioned by various authors, and, for example, van der Voo and Scotese (1981) and Tarling (1985) argue that *B* relates to instrumental noise, whereas others have ignored this component when constructing the British APWP. Some of the reported *B* magnetizations are questionable or indeed inadequately documented in the literature, though others seemingly are of good quality. The Lower Carboniferous pole-positions reported here (Table III; Fig. 9) most efficiently dissociate Lower Devonian and Middle–Upper Devonian poles (e.g., Orcadian *B* poles), rather than forming a continuation of the APWP toward Upper Carboniferous–Permian time. Owing to the fact that the 'Middle–Upper Devonian' magnetizations provide no statistically convincing field tests, their *magnetic age* and origin remain uncertain, and could therefore be Carboniferous in origin (cf. Fig. 9 and Table IV). A palaeomagnetic re-examination of Middle Devonian lavas and sediments from Shetland clearly shows the presence of a high-blocking magnetization which accords with Lower ORS data from the British Isles (Torsvik et al., in preparation). This magnetization, however, is contaminated by the typical Orcadian *B* magnetization, which can be demonstrated to be of *post-folding* origin. This suggests to us that the Middle–Upper Devonian palaeofield is broadly similar to the Lower Devonian palaeofield, i.e., less than 10–15° of polar wander took place during Devonian time. Thus, in conclusion, we opine that the majority of claimed Middle–Upper Devonian poles from the British Isles are doubtful, and should be reconsidered as Carboniferous magnetic overprinting, unless there exists a loop in the late Palaeozoic APWP. Consequently, tectonic modelling based on the existing 'Middle–Upper Devonian' data, e.g. concerning the Great Glen Fault (Storetvedt, 1987), should be treated with caution. It is therefore recommended that all Middle–Upper Devonian and Lower Carboniferous rocks from the British Isles should be re-examined with emphasis on detailed stability testing.

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