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Magnetic properties of the Lower Old Red Sandstone lavas in the Midland Valley, Scotland; palaeomagnetic and tectonic considerations

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Thermal demagnetization studies of lavas in the Strathmore area of the Midland Valley, Scotland, support overall palaeomagnetic data found in previous studies of these rocks. Reduced directional scatter as compared to some earlier studies, is attributed to more effective demagnetization, resolving some of the directional complexity of previous studies. Combined magnetic fabric and directional analysis suggest that at least some deviating directions may be explained by local tectonism. The existence of almost antiparallel directional groups and field tests give supporting evidence for a "primary" (deuteric) origin of the main magnetization of these rocks. Additionally, a second remanence component having shallow reverse directions of magnetization, is attributed to later remagnetization in Old Red Sandstone time. The Midland Valley results are seen in conjunction with other Palaeozoic palaeomagnetic results and possible geodynamic implications are discussed.

Introduction

The Lower Devonian lavas and sediments of the Midland Valley have been subjected to extensive palaeomagnetic studies for nearly two decades. After a detailed geological mapping by Armstrong and Paterson (1970), Sallomy and Piper (1973) established a magnetic stratigraphy of the Strathmore area. Their relatively scattered dual-polarity directional distributions were in fair agreement with previous results (Embleton, 1968; McMurry, 1970). Furthermore, Sallomy and Piper found two discordant magnetization groups, A and B, interpreted as palaeomagnetic transitional directions. Kono (1979), confirming previous results, interpreted groups A and B as the effects of multi-pole components masking the dipole term, presumably explaining the relatively scattered distribution of magnetization in previous investigations.

The Scottish Old Red Sandstone (ORS) lavas are of vital importance for establishing the structure of the Lower Devonian geomagnetic field and may have great potential significance for evaluating aspects of the tectonic evolution of the British Isles during mid-Palaeozoic. The mean palaeomagnetic pole from the Midland Valley (cf. Sallomy and Piper, 1973) as well as mutually consistent results from the Lorne Plateau (Latham and Briden, 1975) and Cheviot Hills (Thorning, 1974) differ from Middle to Upper Devonian data from the British Isles (Storetvedt et al., 1978; Storetvedt and Carmichael, 1979; Storetvedt and Torsvik, 1983). Storetvedt (1967) and Storetvedt and Halvorsen (1968) expressed doubts about the quality and palaeomagnetic reliability of the Scottish ORS lavas, basically due to scattered and elongated distributions of "cleaned" remanance directions, suggesting that a dual-polarity remagnetization has established stable discordant directions of

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net magnetization at variance with the true palaeomagnetic field axis.

Traditionally, the Midland Valley lavas and sediments and the related suites of lavas in the Lorne Plateau, Glencoe and the Cheviot Hills have been regarded as Lower Devonian continental deposits, post-dating the main Caledonian deformation and the extensive intrusions of calc-alkaline granites and granodiorites. In the Strathmore area the ORS rocks are folded into the Strathmore syncline and the Sidlaw anticline (Fig. 1). The main folding occurred in Middle Devonian, accompanied by overthrusting and faulting in the almost sub-parallel Highland Boundary fault zone (Armstrong and Paterson, 1970). The Lower ORS has been divided into six main stratigraphical groups, comprising mainly sandstone, conglomerates and lavas. The present study deals with lavas and interbedded conglomerates from the Crawton group and the overlying Arbuthnott group, probably representing a total stratigraphic thickness of about 2800 m. K/Ar ages from the Lower ORS lavas range between 394 and 411 Ma (Evans et al., 1971; Thirlwall, 1983). Thirlwall (1981, 1983) pointed out that these ages have to be considered as minimum ages, prefering a Silurian rather than a Devonian age for these volcanics.

For the present study a total of 52 hand samples (M1–M52) and 48 drill cores (M53–M100) were collected from altogether 18 sites (Table I). Sampling in the Crawton Group was confined to the Crawton Volcanic formation in Crawton Bay (Sites 10a–f) and Todhead (Site 11). The sampling in Crawton Bay comprises four main macro-

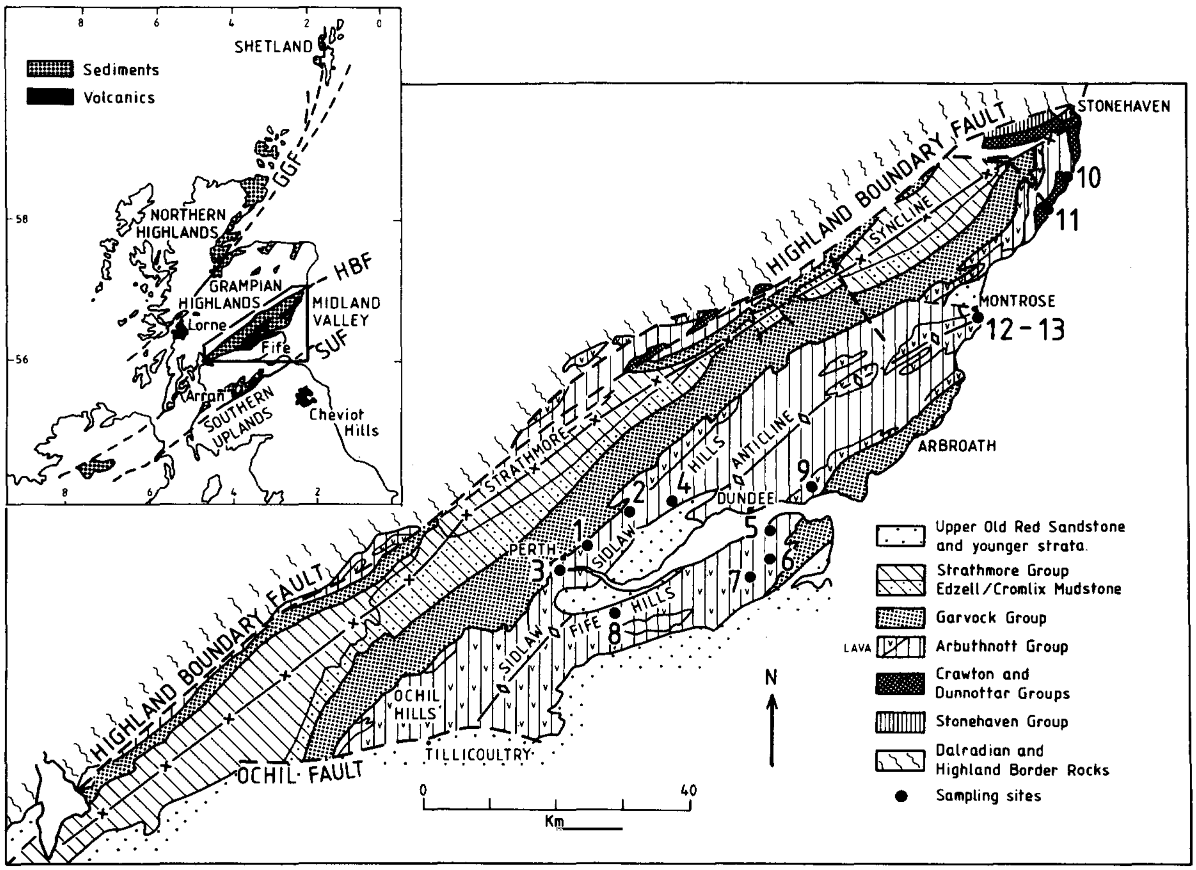

Fig. 1. Geological sketch map of the Strathmore region, Scotland. Sampling locations are denoted by solid circular symbols. Simplified after Armstrong and Paterson (1970).

TABLE I

Sampling details from the Strathmore area, N. Midland Valley

Site	Rock-type	Sampling area	Sample no.
1	Basalt	Virginhall	M 1–M 6
2	Basalt	Collace	M 7–M11
3	Basalt	Friarton	M12–M16
4	Q. Dolerite	Hilton on Knapp	M17–M21
5	Andesite	Tayside	M22–M25
6	Andesite	Tayside-Brackmont	M26–M29
7	Dacite	Lucklaw Hill	M30–M33
8	Andesite	Abernethy	M34–M37
9	Andesite	Ethiebeaton	M38–M41
10a	Basalt	Crawton—Flow 4	M42–M43, M88–M98
10b	Conglomerate	Crawton	M53–M57
10c	Basalt	Crawton—Flow 3	M44–M45
10d	Basalt	Crawton—Flow 2	M72–M78
10e	Basalt	Crawton—Flow 1	M58–M64
10f	Conglomerate	Crawton	M46–M47, M79–M87 (contact)
11	Basalt	Todhead	M48–M49, M99–M100
12	Basalt	Scurdie Ness	M50–M52
13	Basalt	Scurdie Ness	M65–M71

porphyric olivine-basalt and basic andesite flows, interbedded with conglomerates. The Arbuthnott Group is represented by sites 1–9 and 12–13, consisting mainly of olivine basalts and andesites in addition to quartz-dolerite (Site 4) and dacite (Site 7). The sampling sites are situated on both limbs of the almost symmetrical Sidlaw anticline, trending northeastwards from the Ochill Hills to Montrose (cf. Fig. 1) and generally dipping between 10 and 30°.

2. Demagnetization results

Measurement of natural remanent magnetization (NRM) was carried out using a Digico spinner magnetometer. One hundred and sixty specimens were stepwise thermally demagnetized in a commercial Schonstedt furnace with a residual field in the cooling chamber of less than 15 nT. Furthermore, 25 specimens were demagnetized by alternating field (AF) utilizing two and three axes tumblers.

2.1. *Arbuthnott group*

The distribution of natural remanent magnetization (NRM) is scattered (Fig. 2a), but partial thermal demagnetization improves the remanence grouping. With the exception of sites 1 and 4 most specimens display almost antiparallel fairly steeply inclined magnetization directions. Upon thermal treatment some specimens reveal a single-component behaviour, but the majority of tested samples reveal multi-component features. Examples of thermally tested samples of lavas from the Tayside district (sites 5–8) are shown in Fig. 3a, b. Above 400–450°C orthogonal vector diagrams suggest the isolation of an eastward directed, upward pointing magnetization of intermediate inclination. Low temperature blocking components ($T < 350$°C) usually display poorly defined northerly steep/intermediate positive (downward inclined) magnetizations. In general, the blocking temperatures do not exceed 550–600°C, but specimen M24c1, for example, clearly demonstrates the presence of blocking temperatures above 600°C.

Figure 3c, d shows typical examples of thermal demagnetization results from the Montrose area (sites 12 and 13), defining almost single-component magnetizations covering the entire range of blocking temperatures, the characteristic direction being nearly antiparallel to those of Fig. 3a, b.

Site 1 (Virgin-Hall; olivine basalt) and site 4 (Hilton on Knapp; quartz dolerite) directions dif-

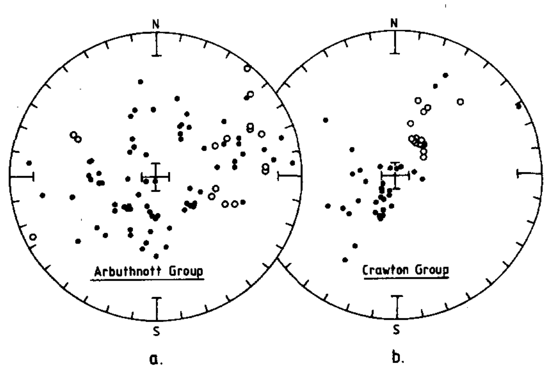

Fig. 2. Directional distribution of natural remanent magnetization (NRM) from the Arbuthnott (a) and Crawton (b) groups. Open (closed) symbols are upward (downward) pointing magnetizations.

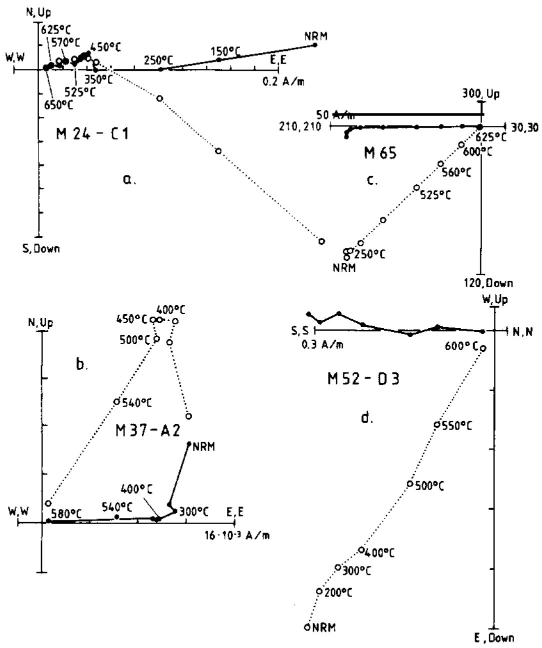

Fig. 3. Examples of thermal demagnetization (Arbuthnott group) from the Tayside (a and b) and Montrose (c and d) region. Throughout this paper open (closed) symbols in the orthogonal vector diagrams represent points in the vertical (horizontal) plane. Furthermore, all diagrams show directions without tectonic correction. Note that some diagrams are optimal vector-projected (cf. M65).

fer from the results generally obtained. Samples from site 1 define almost horizontal and eastward directed single-component magnetizations (cf. Table II). Site 4 exhibits two southwest directed components; one with downward steep/intermediate inclinations and the second with a nearly horizontal magnetization (cf. M 17-A1 and M 21-B1 of Fig. 4). Thus, site 4 records both the steep/intermediate reverse magnetization characterizing the lavas of the Strathmore area, as well as an almost horizontal reverse component.

2.2. *Crawton group*

Distribution of NRM from the Crawton group (sites 10a–f, 11) clearly demonstrates the general pattern of both normal and reverse field components, but with certain northeast/southwest elongations probably due to superposition of the two magnetizations (Fig. 2b). Characteristic remanence

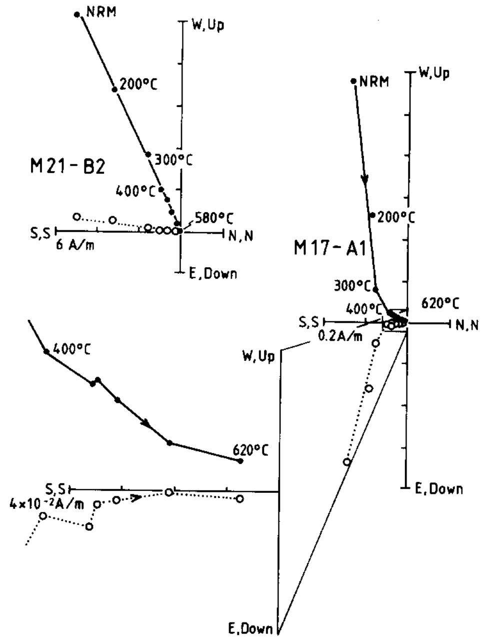

Fig. 4. Further examples of thermal demagnetization from the Arbuthnott group (site 4).

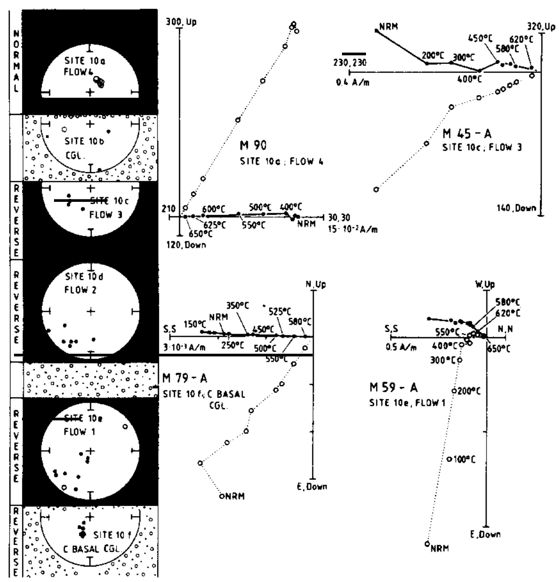

Fig. 5. Examples of thermal demagnetization from the Crawton group (Crawton Bay) along with stereoplots of characteristic remanence directions from individual lava-flows (Flows 1–4), interbedded conglomerate (site 10b) and the contact zone of the basal conglomerate.

TABLE II

Characteristic direction from the Strathmore region

Arbuthnott Site	Specimen	Group	D	I	Tilt-corrected D	Tilt-corrected I	Group
1	M1b2		073	−3	072	+6	
	M1c1		076	−5	076	+5	
	M2a3		075	+2	073	+12	
	M2b1		077	+10	072	+20	
	M3a2		068	+6	064	+13	
	M3c2		069	+6	066	+13	
	M4a		068	+3	066	+11	
	M4c		066	−4	066	+3	
	M5a2		066	+10	061	+16	
	M5b2		065	+8	061	+14	
	M6a2		060	−11	063	−5	
	M6b2		062	−1	061	+5	
2	M7a2		161	+36	175	+52	1
	M7b2		163	+31	175	+46	1
	M8a		179	+41	198	+50	1
	M8b		182	+35	197	+44	1
	M9a3		169	+43	189	+56	1
	M9b2		145	+45	158	+64	1
	M11a3		184	+21	193	+30	1
	M11b2		189	+23	199	+30	1
3	M14a2		199	+33	213	+39	1
	M16a		220	+47	240	+45	1
	M16b		226	+38	240	+35	1
4	M17a1	I	260	+30	263	+21	1
		II	210	+10	212	+9	2
	M17d2	I	240	+58	252	+51	1
		II	215	+10	217	+8	2
	M19b		214	+40	222	+37	1
	M20a1		213	+40	222	+38	1
	M20a2		226	+23	230	+19	1
	M20b2		200	+34	207	+34	1
	M20c2		205	+40	214	+39	1
	M21b1	I	228	+38	235	+33	1
		II	195	+14	198	+16	2
	M21b2		245	−2	244	−9	2
	M21c1	I	225	+27	229	+23	1
		II	220	−5	219	−8	2
5	M22a		025	+30	034	+34	?
	M22b		315	+60	314	+75	?
	M23b		324	+62	333	+76	?
	M24b2		068	−28	060	−33	1
	M24c1		072	−20	066	−26	1
	M25a2		060	−20	054	−23	1
	M25b2		065	−28	057	−32	1
	M25b4		069	−26	061	−31	1
	M25c2		070	−20	064	−25	1

Crawton Site	Specimen	Group	D	I	Tilt-corrected D	Tilt-corrected I	Group
10a	M42b1		035	−57	042	−45	1
	M42b2		040	−57	046	−45	1
	M43a1		060	−62	062	−49	1
	M43a2		055	−62	058	−49	1
	M43b2		054	−62	057	−49	1
	M43c1		048	−56	052	−43	1
	M43c2		053	−62	057	−49	1
	M88		030	−59	039	−48	1
	M89		029	−61	039	−50	1
	M90		027	−59	037	−48	1
	M91		035	−59	043	−47	1
	M92		034	−59	042	−47	1
	M96		030	−58	039	−47	1
	M97		025	−57	035	−46	1
	M98		040	−57	046	−45	1
10b	M53		115	+46	128	+53	
	M54		257	−35	259	−46	
	M57		170	0	167	−3	
10c	M44b		202	+40	208	+30	1
	M45a		250	+38	249	+25	1
	M45b		234	+30	235	+17	1
	M45d		238	+35	238	+22	1
10d	M72		221	+10	221	−2	2
	M73		241	+27	241	+14	2
	M74		210	+10	210	−1	2
	M75		211	+15	212	+4	2
	M76		206	+20	208	+10	2
	M77		244	+2	244	−11	2
	M78		175	+29	181	+24	2
10e	M58a		240	+10	240	−3	2
	M58b		235	+8	235	−5	2
	M59a	I	200	+65	214	+55	1
		II	216	−5	215	−14	2
	M59b	I	200	+70	217	+59	1
		II	205	+28	208	+18	2
	M60b		200	+10	201	+1	2
	M61a		230	+20	231	+7	2
	M63a	I	254	+65	251	+52	1
		II	055	−8	055	+4	2
10f	M79a		201	+50	209	+40	1
	M80		201	+43	208	+33	1
	M81		224	+71	232	+59	1
	M82b		223	+57	228	+45	1
	M84		198	+49	207	+40	1
	M86		210	+59	219	+48	1
	M87		205	+45	211	+34	1

TABLE II (continued)

Arbuthnott Site	Group Specimen	D	I	Tilt-corrected D	Tilt-corrected I	Group
6	M26a2	263	+32	255	+38	1
	M26c	264	+43	253	+50	1
	M27a2	252	+42	241	+46	1
	M27b2	262	+35	254	+41	1
	M29a	264	+27	258	+34	1
	M29c	266	+25	261	+32	1
7	M32a1	088	−41	075	−50	1
	M32a2	088	−30	079	−39	1
	M33a1	093	−41	081	−51	1
	M33a2	091	−43	078	−52	1
8	M34a	059	−75	357	−68	1
	M34b	073	−73	007	−71	1
	M35a	073	−47	049	−53	1
	M35c	071	−47	047	−52	1
	M36a2	055	−62	019	−59	1
	M36b2	055	−62	019	−59	1
	M37a2	085	−58	049	−66	1
	M37b2	084	−56	051	−64	1
9	M38a2	053	−53	033	−52	1
	M40a2	076	−40	063	−46	1
	M40b2	065	−43	050	−46	1
	M40a3	082	−42	069	−49	1
12	M50a	227	+41			1
	M51a	210	+51			1
	M52a3	185	+53			1
	M52a3	183	+56			1
	M52c1	185	+66			1
	M52c2	186	+58			1
	M52d1	189	+58			1
	M52d3	183	+59			1
13	M65	208	+45			1
	M67	232	+50			1
	M68	228	+49			1
	M69	220	+56			1
	M70a	224	+53			1
	M70b	223	+54			1
	M71	221	+55			1

Crawton Site	Group Specimen	D	I	Tilt-corrected D	Tilt-corrected I	Group
	M46a	192	+11	193	+3	
	M46b	190	+5	190	−2	
	M47a2	074	+10	074	+22	
	M47a3	074	+3	074	+15	
	M47b2	088	−5	088	+7	
	M47b3	079	+2	079	+14	
11	M48b1	030	−36	038	−22	1
	M48b2	025	−40	035	−27	1
	M49a2	060	−47	064	−28	1
	M49b2	041	−58	054	−40	1
	M99	022	−45	035	−32	1
	M100	025	−49	039	−35	1

directions and examples of thermal demagnetization of Crawton Bay samples are shown in Fig. 5. Thermal data from flow 4 (see specimen M90) reveal an extremely stable and well-defined steep normal component with high blocking temperatures in the range 625–650°C. These results agree with those of site 11 (Todhead Point). Data from the underlying conglomerate, sampled near the top of flow 3 (to avoid thermal effects from flow 4), display a "scattered" distribution of stable components, thus giving a positive conglomerate test. Flow 3 exhibits reverse polarity components directed almost antiparallel to those of flow 4, though thermal demagnetization results suggest a somewhat more complex magnetization structure. Thus, vector projections of specimen M45-A data indicate partly overlapping blocking temperature spectra of at least two components, but the linear segment above 450°C defines a reverse direction of magnetization in agreement with results from the Arbothnott group. Flows 1 and 2 define low temperature, steeply inclined magnetizations (probably partly of recent origin), in addition to high temperature components that are practically horizontal and with southwesterly declinations. Magnetization directions in the contact zone (0–5 cm) of the basal conglomerate coincide fairly well with data from flow 3, while sampling at some distance from the contact (0.5 m) does not reveal this characteristic Midland Valley magnetization (cf. specimens M46 and M47; Table II). Thus, the basal conglomerate tends to give a positive conglomerate test as well as providing a tentative contact test.

3. Some rock magnetic properties

Saturation magnetization versus temperature (J_s–T) carried out in air ($H = 0.5$T) has uncovered several types of behaviour. Heating and cooling curves may differ substantially within a site, and the 60 specimens investigated may be grouped into three categories. With reference to Fig. 6 these are:

(A) Single high Curie temperatures (T_c) in the range 525–575°C. On cooling a 5–25% decrease in total J_s is observed along with a systematic lowering of T_c by 10–50°C. This type of behaviour, which has only been found in the Arbuthnott group, is indicative of titanium poor titanomagnetite (TM) or almost pure magnetite. Isothermal remanent magnetization (IRM) curves have saturating fields in the range 0.15–0.2 T, and remanence coercive forces (RCF) are typically about 20–30 mT. Thermal treatment introduces only minor changes in the coercivity spectra, and low field susceptibility shows minimal changes during thermal treatment.

(B) This group shows typically 70–80% loss in J_s during cooling with inversion temperatures in the range of 400–600°C. T_c as high as 670°C may be present, and low-field susceptibility measurements demonstrate large alterations in bulk magnetic properties. The almost complete break-down of the initial magnetic phase upon heating is probably due to inversion of titanomaghemite (maghemite) to haematite. Initial IRM–H curves reflect the presence of a low-coercivity mineral fraction (saturated below 0.1 T). Heating to 680°C shows a decrease in the low-coercivity spectra as well as in IRM intensity, and there is an increase in initial RCF from about 10 to 30–50 mT. Type B has almost exclusively been found in flows 1–3 of the Crawton volcanics.

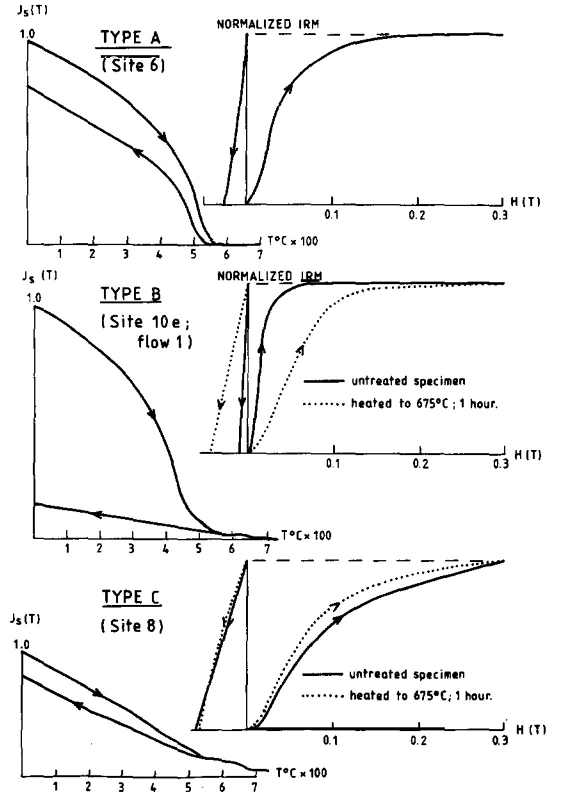

Fig. 6. Typical examples of thermomagnetic and IRM aquisition curves. See text for details.

(C) Two distinctly different Curie-temperatures, 550–575°C and c. 675°C, respectively, are present. Thermomagnetic curves are reversible above 550–570°C (due to a stable haematite phase), but the phase with lower T_c has a certain irreversibility (loss of J_s after heat treatment). IRM curves tend to be dominated by haematite (suggested by the distinct unsaturated phase below 0.3 T). The IRM intensity is usually lowered after heating to

680°C, along with minor changes in RCF, typically around 50–60 mT. The low-coercivity fraction is probably almost pure magnetite (exsolved titanomagnetite). Type C is typical for specimens with high magnetic stability.

4. Anisotropy of magnetic susceptibility

The anisotropy of initial magnetic susceptibility (AMS) was measured in 12 localities, using a low field susceptibility bridge. The magnetic susceptibility (k) is a symmetric, second order tensor expressed as a triaxial susceptibility ellipsoid. The origin and shape of the ellipsoid results generally from either magnetocrystalline or shape anisotropy (dimensionally oriented grains). Shape anisotropy are of importance in rocks containing minerals with high intrinsic susceptibility, for example magnetite. On the other hand, magnetocrystalline anisotropy is attributed to low susceptibility minerals, i.e., pyrrhotite and haematite (Uyeda et al., 1963). The orientation of the susceptibility ellipsoid is described by Kmax, Kint and Kmin which are the principal axes of susceptibility. Parameters used to describe the shape of the ellipsoid may vary considerably (cf. Tarling, 1983), and in this paper the magnetic fabric is defined by P_1 (Foliation = Kmax/Kint), P_2 (Anisotropy degree = Kmax/Kmin), P_3 (Kint/Kmin) and E (Eccentricity = P_1/P_2; $E < 1$ prolate and $E > 1$ oblate). For convenience the total degree of anisotropy is frequently expressed as $(P_2 - 1) * 100\%$.

The degree of anisotropy varies in the investigated lavas, ranging from 0.5 to 9%, and the shape of the magnetic ellipsoids is oblate (Fig. 7c). The consistency and quality of the magnetic fabric data may vary within a site, but almost all localities with $P_2 > 1.02$ revealed a fairly well defined magnetic foliation plane (Kmax–Kint; Fig. 7a, b).

Magnetic foliation planes from individual locations are shown in Fig. 8. The low degree of anisotropy in the investigated lavas, and the fairly close relationship with tectonic field data indicate that the magnetic fabric in most sites may reflect the relict "bedding" plane (flow banding and/or compactional origin). The best match between the magnetic fabric and tectonic field data are found at sites 4–7 and 10, all showing shallow inclined foliation planes dipping either SE and NW. On the other hand, the strike of the foliation plane at site 11 (cf. Fig. 7b) is almost identical to that determined from geological observations, but the dip differs by c. 30°. The Sidlaw anticline is generally

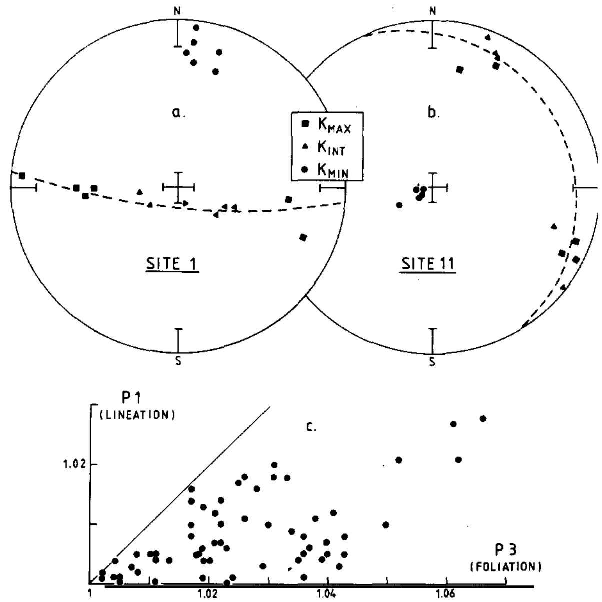

Fig. 7. Stereoplots showing orientation of principal susceptibility axes from sites 1 and 11 (a and b) and Flinn diagram (c) covering all measured specimens. Great circles in a and b define best fitted magnetic foliation planes.

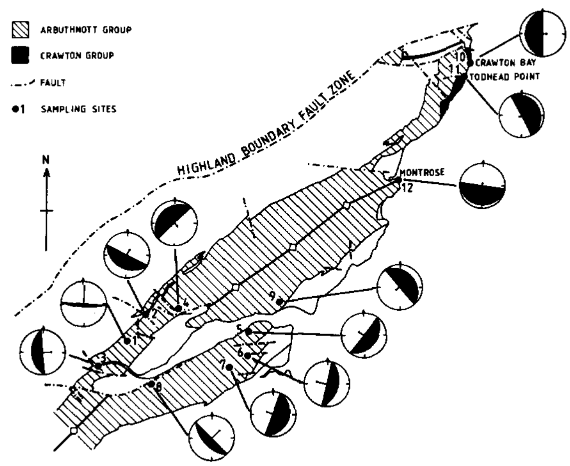

Fig. 8. Magnetic fabric data from the investigated area. Orientation and downward dip of the magnetic foliation planes are shown in stereoplots.

a rather open and symmetrical fold, dipping 10–30° in either SE or NW directions, but it is evident from Fig. 8 that the foliation planes from, for example, sites 1 and 2, on the western limb, differ from the general pattern. If these magnetic fabrics have entirely or nearly bedding parallel origin, they imply considerable horizontal/vertical rotational movements. On the other hand, the recorded fabric may have been partly or completely overprinted during folding/deformation stages, related to shear movements along the numerous faults in the area tracing generally NE–SW and E–W.

5. Fold test

The majority of tested lavas yield intermediate-steeply inclined, almost antiparallel normal and reverse magnetizations (group 1, Fig. 9a) in agreement with previous studies in the Midland Valley. Additionally, the present investigation has uncovered a minor group of shallow, reverse magnetizations (group 2, Fig. 10a), frequently superimposed on group 1 data. This latter group comprises results from sites 4 and 10d, e (cf. Table II).

Tectonic tilt correction based on field evidence improves the directional distribution parameters and antiparallism of group 1 (Fig. 9b), suggesting a primary or at least a pre mid-Devonian origin of

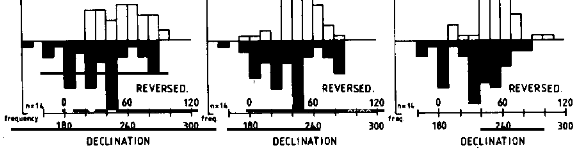

Fig. 9. Characteristic remanence directions (group 1) and declination histograms of normal and reverse data of group 1. (a) no tectonic correction, (b) structural correction using field data and (c) tilt correction according to magnetic fabric.

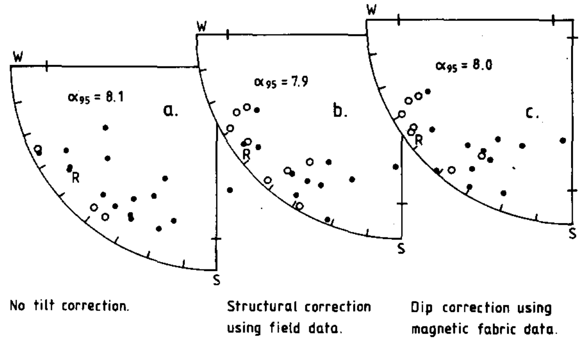

Fig. 10. Distribution of remanence directions for group 2.

the major part of the stable remanence. A certain elongation in the remanence populations may indicate errors in the applied tilt corrections, or alternatively, the existence of unresolved multicomponent magnetizations. Tilt correction using magnetic foliation planes (Fig. 9c) also improves the directional distribution and in particular the antiparallism if site 2 is disregarded.

Site 1 data (not included in Fig. 9) are almost horizontal with declination E–ENE. To accomodate these directions into the typical directional pattern (group 1) we may unfold the magnetic foliation plane in addition to imposing a clock-wise tectonic rotation. The results from site 2 data are steeply reverse, but would be in better agreement with the general data-set if a c. 20° clockwise rotation had been applied. Deviating magnetic foliation planes accompanied by discordant remanence directions may be linked to the general E–W pattern of faulting in this area. Site 1 is located close to the Pitroddie Glen fault, and the southern margin of the fault has probably been downfaulted (Harry, 1956).

The anomalous magnetic fabric of site 8 should be treated with caution due to the low degree of anisotropy (mean $P_2 = 1.018$) and a certain spread in the Kmin directions. The corresponding remanence directions are not perfectly matched with the general pattern through simple structural tilting (better match by applying magnetic fabric data), suggesting that a tectonic rotation may have occurred.

In general, magnetic foliation planes correspond fairly well to the structural field observations, and therefore the identification of some anomalous sites, with respect to both magnetic fabric and remanence directions, suggest a tectonic explanation. Thus, some of the observed scatter in characteristic directions of magnetization, especially from the southern part of the investigated area, is probably due to local tectonic movements.

As Group 2 directions come from sites that also yield Group 1 results, these observations can not be explained by local tectonism. Also, these sites have similar structural and magnetic fabric data. Owing to the limited number of sites and their almost coinciding tectonic dip it remains uncertain whether this fairly flatlying magnetization of group 2 has a post- or pre-folding origin.

6. Remanence stability and local remagnetization

Stability of magnetization reflects both the petrological composition as well as the history of a rock unit. Lavas in the Strathmore area show distinct differences in oxidation state, and alternating weathered (reddish) and relatively fresh lavas in the same pile, suggest an Old Red Sandstone weathering age. Titanomagnetites (TM) appear to be principal carriers of the remanant magnetization in most basalts. High magnetic stability in oxidized basalts have frequently been explained by grain-size effects due to deuteric oxidation and subsequent formation of ilmenite lamellae in the titanomagnetite (Larson et al., 1969), but the physical basis of this theory is controversial (Tucker and O'Reilly, 1980). Medium to high grade deuteric oxidation features are common in the investigated flows (TM classes 2–5; Ade-Hall et al., 1971).

Although effective grain-size reduction through exsolution may be of major importance in the investigated rocks, the highest magnetic stability is clearly linked with the presence of haematite which may either be deuteric or of later secondary origin. However, the fact that magnetization directions residing in haematite are consistent with "magnetite" components suggest a dominantly deuteric origin. Olivine is generally altered (Harry, 1956) forming haematite along grain boundaries, but Fe oxides as inclusions are rare. Oxidation of synthetic olivine at high temperatures (500°C), apparently produces single-pseudosingle domain magnetite inclusions with a strong and stable remanence (Hoye and Evans, 1975), and thin needles of haematite and magnetite may precipitate at higher temperatures (Champness, 1970). In turn, magnetite may undergo further oxidization to haematite.

In Crawton Bay, group 2 directions are represented by flows 1 and 2. On the other hand, the baked basal conglomerate, shows directions in fair agreement with the characteristic magnetization of the Midland Valley lavas (group 1). Thus, the observed shallow remanence components of flows 1 and 2 rule out the possibility of these being transitional field directions imposed during a reversal of the geomagnetic field. An explanation in terms of partial remagnetization is favoured. Flow 4 in Crawton Bay (Fig. 5) which has TM Class 2–3 contain single-component magnetization, discreet high blocking temperatures and type C Curie-curves. Although internal differences exist in the underlying lava flows (1–3), they dominantly display type B Curie-curves with inversion temperatures in the 400–500°C range, indicative of the presence of titanomaghemite (maghemite). Haematite may be present, as observed by blocking temperatures exceeding 600°C. X-ray diffraction patterns of magnetically extracted material suggest a dominating cubic phase with a unit cell parameter of 8.33 Å, indicative of titanomaghaemite. The opaque mineralogy of flows 1 and 2 lack signs of high-temperature deuteric oxidation and are dominated by precipitated haematite, sphene and needles of ilmenite. The observed mineralogy is presumably at least partly due to low temperature oxidation (maghemitization). Flow 3 is less altered than flows 1 and 2, probably explaining their lower magnetic stability as compared with more strongly oxidized lavas. The basal contact conglomerate is likely to have retained the original magnetization while the overlying flows 1 and 2 probably attained their present magnetization at some subsequent time in the Devonian.

7. Discussion and conclusions

The overall palaeomagnetic data are given in Table III. In comparison with previous studies by

Sallomy and Piper (1973) and Kono (1979) the main magnetization of the present investigation (group 1) shows improved grouping. Fold and conglomerate tests along with laboratory experiments suggest a "primary" (deuteric) or at least a pre-mid-Devonian age of magnetization for group 1. These results refute the criticism of the Old Red Volcanics (Storetvedt, 1967; Storetvedt and Halvorsen, 1968; Torsvik et al., 1983).

On the other hand, the shallow reverse field directions (group 2) seems to have been imposed through subsequent remagnetization, and in some instances the "original" remanence has been completely erased. Shallow, normal field directions from site 1 differ from group 2 as well as from group 1 data. This directional discordance may in principle be attributed to complete remagnetization in a transitional field direction (spot reading), but magnetic fabric data favour a tectonic explanation, presumably associated with movements on the Pitroddie Glen fault. However, we can not overlook the possibility that both the magnetic fabric and the remanent magnetization are governed by magnetic overprinting. In any case, the data from site 1 have been excluded from the final directional analysis.

The apparent polar wander path (APW) from the British Isles involves rapid movements within the Palaeozoic (Piper, 1979; Turnell and Briden, 1983; Briden et al., 1984). For the Midland Valley volcanics group 2 directions are rare, but these shallow SW–NE directed magnetizations are compatible with palaeomagnetic results of Old Red Sandstone sediments from elsewhere in Scotland, for example with Middle Devonian data from the Northern Highlands. Thus, the available results may be satisfactorily explained by a Lower Devonian "primary" magnetization (group 1), which in some areas have been partly overprinted by remanence of younger Old Red Sandstone age (cf. Fig. 11a).

The present results give additional evidence for the near equatorial VGP positions of Lower ORS rocks for the British Isles, and indicate rapid APW from Ordovician to Middle–Upper Devonian time. This is clearly demonstrated from the palaeomagnetic discrepancy between the 400–430 Ma "newer granites" and the Lower ORS data, suggesting that the equatorial VGP position held by the Lower ORS volcanics is likely to cover a relatively short period of time, say in the order of 10 Ma. The intermediate palaeomagnetic inclinations (group 1) are not generally recorded in Lower ORS sediments of NW Europe. The reason for the

TABLE III

Overall palaeomagnetic data for the Strathmore region

	N	K	α_{95}	D	I
Group 1					
(a) Normal directions	43	16.9	5.2	057.2	−51.4
(b) Normal (tilt corr. using field data)		24.6	4.3	050.2	−46.2
(c) Normal (tilt corr. using magnetic fabric)		18.6	4.9	054.9	−46.4
(d) Reverse directions	55	11.6	5.5	214.5	+48.4
(e) Reverse (tilt corr. using field data)		15.3	4.8	220.6	+46.0
(f) Reverse (tilt corr. using magnetic fabric)		14.2	5.0	218.0	+45.8 *
Normal and Reverse combined (b and e)	98	17.9	3.3	224.9	+46.2
Pole: N 2.2 E318.2 dp = 2.7 dm = 4.3					
Group 2					
Tectonically uncorrected	19	15.7	8.1	219.0	+12.0
Pole: S19.8 E315.3 dp = 4.2 dm = 8.2					
Tilt corr. using field data		16.5	7.9	220.0	+3.0
Tilt corr. using magnetic fabric		16.2	8.0	221.0	+6.0

D = mean declination; I = mean inclination; N = number of specimens; K = precision parameter; α_{95} = 95% confidence circle.

* Site 2 data have been corrected according to field data, cf. text.

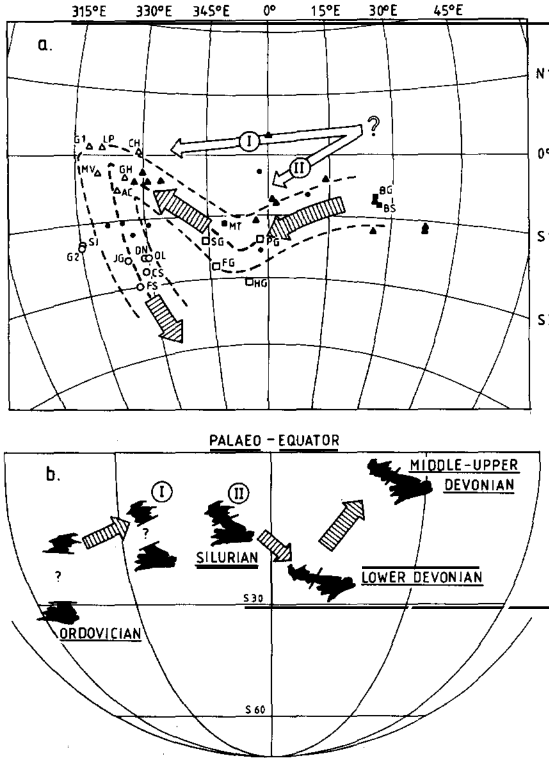

Fig. 11. (a) Ordovician to Middle–Upper Devonian pole positions from the British Isles (north of the Iapetus suture). Closed squares are as follows: BG, BS are the Ordovician Ballantrae Gabbros and Sepentinites (Piper, 1978); MT = Metamorphic Torridon, Caledonian overprinting on the Precambrian Torridon group, NW Scotland (Torsvik and Sturt, in prep); undenoted solid circular symbols show different phases from the Borrolan Complex, NW Scotland (Turnell and Briden, 1983), inferred to define a segment of the Palaeozoic APW path. Furthermore solid triangles (undenoted) represent site means from the Ordovician Aberdeenshire Gabbros (Watts and Briden, 1984). The inferred youngest of these poles are fairly similar to the Lower Devonian volcanics and thought to have been acquired through slow post-orogenic cooling (Watts and Briden, 1984). An alternative explanation of the latter spread of poles is of course late Caledonian overprinting (Torsvik, 1985). The Silurian "newer granites" are shown by open squares and are as follows: HG = Helmsdale Granite (Torsvik et al., 1983); FG = Foyers Granite (Torsvik, 1984); SG = Strontian Granite (Torsvik, 1984); and PG = Peterhead Granite (Torsvik, 1985). The Lower Devonian poles (open triangles) are: GH = Garabal Hill (Briden, 1970); AC = Arrochar Complex (Briden, 1970); CH = Cheviot Hills (Lavas, granites and M. Andesites; Thorning, 1974); LP = Lorne Plateau (Latham and Briden, 1975); MV = Midland Valley lavas (Sallomy and Piper, 1973) and G1 = group 1 of the present study. Middle–Upper Devonian poles are as follows (open circles): OL = Orkney Lavas (Storetvedt and Petersen, 1972); DN = Duncansby Neck (Storetvedt et al., 1978); JG = John O'Groats Sandstone (Storetvedt and Carmichael, 1979); CS = Caithness Sandstone (Storetvedt and Torsvik, 1983); FS = Foyers Sandstone (recalc. after Kneen, 1973); SI = Shetland Ignimbrites (Storetvedt and Torsvik, 1985); G2 = group 2 of the present study. Open arrows (and strictly arrow I) are a generalized polar pattern of rock-formations south of the Iapetus suture (cf. Briden et al., 1984 and text for further details).

(b) Palaeogeographical reconstruction (latitudinal) of the British Isles (Scotland) in the Ordovician to Middle–Upper Devonian time (orthographic projection). The Ordovician position of Scotland is according to the assumed oldest magnetizations from the Aberdeenshire Gabbros (Watts and Briden, 1984). The Silurian position is according to the "newer granites" (open squares in a), the Lower Devonian with reference to Lower Devonian with reference to Lower Devonian Volcanics (open triangles in a) and finally the Middle–Upper Devonian based on Scottish Middle–Upper ORS rocks (open circles in a). Longitudinal positions are arbitrary, and latitudinal positions of the southern margin of Iapetus are only optional (drawn 10° south of Scotland in the Ordovician). Palaeo-trend of the Iapetus suture is almost east-west in the Ordovician, and consequently strike-slip movements (oblique subduction) can not be palaeomagnetically detected.

palaeomagnetic differences between volcanics and sediments is probably that the volcanics acquired their stable magnetization at around the time the rocks cooled, while sediments may have undergone a more longlasting and complex magnetization history covering a major time span in the Devonian.

The APW path and palaeo-geographical reconstruction of the British Isles (arbitrary longitude) as outlined in Fig. 11a, b is only based on palaeomagnetic data North of the Iapetus Suture zone (assuming the suture zone is south of the Cheviot Hills). Results from the Scottish "newer granites" suggest that major post-Silurian transcurrent displacement along the Great Glen fault (Torsvik, 1984, 1985) has not taken place, in agreement with the conclusion of Briden et al. (1984). Some palaeo-latitudinal separation across the Iapetus suture has been inferred from Ordovician poles (Briden et al., 1973, 1984). With reference to Briden et al. (1984), open arrows (Fig. 11a) indicate a generalized Ordovician to Lower-Devonian polar pattern south of the suture zone. Seen in conjunction with the Scottish "newer granites" (except Arrochar and Garabal Hill–Glen Fyne complexes which palaeomagnetically assign an age conforming to the Lower-Devonian volcanics), it is not unlikely that any polar discordances in the Ordovician may also have existed in Silurian time. Thus, closure of the Iapetus ocean (? oblique subduction and strike-slip) during the Silurian with final continental suturing in the Lower Devonian is plausible.

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