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On the origin and the tectonic implications of magnetic overprinting of the Old Red Sandstone, Shetland

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SUMMARY

The magnetic signature of the Old Red Sandstone (ORS) and post-orogenic plutonics on Shetland is influenced by three principal components, *A* (pole: S51, E003), *B* (pole: S24, E340) and *C* (pole: S10, E003). As evidenced from negative fold tests, *A* is secondary, and most likely thermochemical in origin, presumably associated with hydrothermal fluids circulating in faults and crush zones subsequent to Permian–Early Triassic extensional reactivation of older Caledonian fault structures. From the ORS, the *B* component also can be proven to represent a magnetic overprint. The secondary nature of component *B*, and the fact that it reasonably can be correlated on both sides of the Walls Boundary Fault, commonly assumed to be the continuation of the Great Glen Fault, argues against recent suggestions of mega-shearing within the Great Glen Fault system. The precise time of acquisition of *B* is uncertain, but we consider a lower Carboniferous age synchronous with late-post orogenic plutonic activity (334–358 Ma) to be most likely. This implies that the *B* component carried by the plutonic rocks may represent a primary cooling event. *C* is exclusively carried out by Middle Devonian andesites and basalts from the Esha Ness Peninsula. It is evidently of post-fold origin, and we relate this earliest magnetic overprinting to Middle–Upper Devonian (Svalbardian) tectonism which affected the North Atlantic domain during this period.

Key words: Great Glen Fault, magnetic resetting, Old Red Sandstone, palaeomagnetism.

1 INTRODUCTION

The Old Red Sandstone (ORS) of Shetland can be divided into three groups, the Western, Central and Eastern Groups (Mykura 1976; Flinn 1985), each bounded by major fault zones (Fig. 1). The Western Group is located west of the St Magnus Bay Fault or Melby Fault (MF). Basal sediments of the Western Group (Melby Formation) are conformably overlain by basic lavas, tuffs and ignimbrites (Sites 10–16; Esha Ness Peninsula). Palaeontological evidence suggests that the Western Group can be correlated with the *Middle Devonian* ORS of the Orkney Islands (Donovan *et al.* 1978). Thus, the Western Group is commonly assumed to be part of the Orcadian Basin. The Central Group, bounded by the MF and the Walls Boundary Fault (WBF), embraces a ~10 km sequence of sediments (Sites 1–3) and interbedded lavas (Sites 4 and 5) and tuffs of *Lower Devonian* age. The Central Group is strongly folded, metamorphosed and intruded by plutonic rocks (Sites 6–9). The Eastern Group lies to the east of the WBF and the Nesting Fault (NF) and includes sandstone (sites 17–20) and flagstones of probable *Middle–Upper Devonian* age.

The present proximity of the three ORS Groups is probably not original, and considerable strike–slip faulting has been postulated along the WBF, NF and the MF (Flinn 1977; Mykura 1976; Miller & Flinn 1966). Flinn (1961, 1969, 1970, 1975, 1977) originally postulated that the WBF was a dextral strike–slip fault and a continuation of the Great Glen Fault (GGF). Little land based evidence is available along the WBF and the suggested dextral displacement of 65 km is inferred from aeromagnetic data south of the Shetland Isles. Cataclastic rocks associated with the WBF

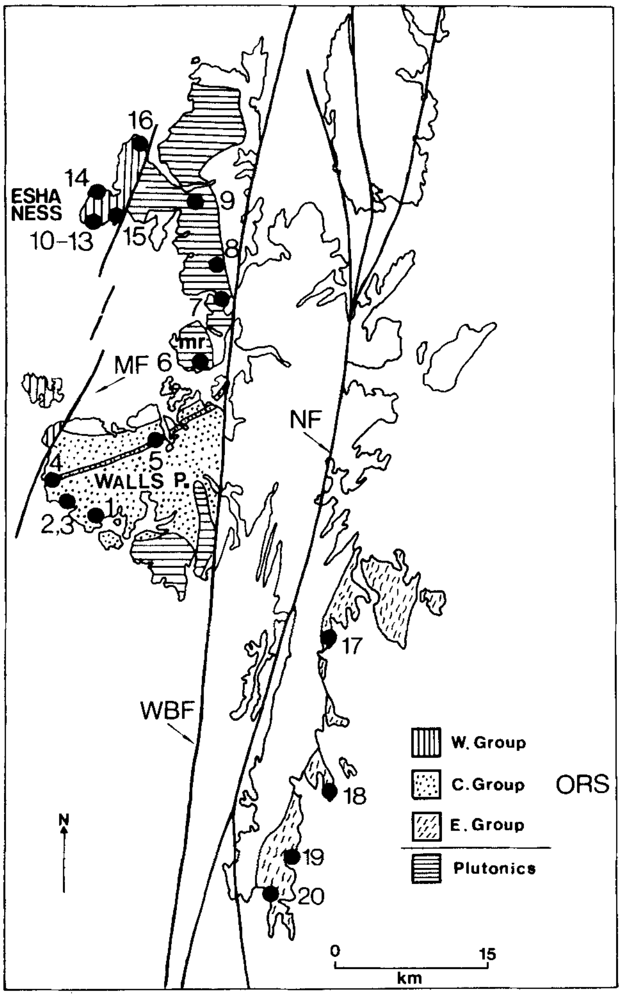


Figure 1. Geological sketch map of Shetland (simplified after Flinn 1985) showing the distribution of the Old Red Sandstone and post-orogenic plutonic rocks. Numbered sampling sites are shown as circular symbols. MF = Melby fault; WBF = Walls Boundary Fault; NF = Nesting Fault; mr = Mucle Roe granite.

include the ORS, but as the WBF cuts assumed Mesozoic rocks in the Fitful Basin (Bott & Browitt 1975). Flinn (1977) argues that the dextral displacement occurred during or after the Mesozoic.

The MF has also been interpreted as a strike–slip fault (Mykura 1976), but Flinn (1985) reasons that it is a reverse fault, juxtaposing the *Lower Devonian* Central Group and the younger *Middle–Devonian* Western Group. This implies that the Western Group (Orcadian Basin) originally extended over the Central Group.

The ORS in the North Atlantic area has undergone variable tectonic deformation, and this Devonian tectonism extends from the Arctic Caledonides (Spitsbergen) southward to northern Scotland. On Shetland, the Walls Peninsula Basin (Central Group) has been the subject of two periods of intense folding, D_1 with an E–W axis and D_2 with a N–S axis, followed by *post*- or possibly *syn*-kinematic intrusive activity. These essentially post-orogenic intrusions are solely located west of the WBF, and they form a N–S trending complex extending from the Walls Peninsula to North Roe. Plutonic rocks include gabbros, diorites (Sites 7–9) and granites (Site 6) along with dyke rocks ranging in composition from olivine–dolerite to acid felsite (Mykura 1976). K/Ar age determinations on these plutonics range from 358 to 334 Ma (Miller & Flinn 1966), and suggest plutonic activity well into the early Carboniferous, though in reality they may represent cooling/uplift ages. The plutonic rocks are unfoliated and cut fold-structures in the ORS, thus providing a minimum age for the deformation of the ORS.

The Middle to Upper Devonian geomagnetic field direction for the British Isles area is not well known, and Torsvik *et al.* (1989b, c) suggest that many of the claimed Middle–Upper Devonian poles record Late Palaeozoic remagnetization events. Therefore, tectonic models for the Great Glen Fault based on the existing 'Devonian' data should be considered with caution. The uncertainty in the age of remanence in the Devonian rocks stems from the lack of reliable palaeomagnetic stability tests. In this account we have attempted to resolve this problem by carrying out a detailed palaeomagnetic study of folded Devonian sediments and lavas from Shetland. However, the results suggest that a protracted thermal history has obliterated the primary Devonian remanence in these rocks.

2 PALAEOMAGNETIC EXPERIMENTS

2.1 Central ORS

Walls Peninsula sandstone and volcanics

Sites 1–3 were sampled in grey and reddish sandstones of the Walls Peninsula (Fig. 1). Sites 2 and 3 embrace an E–W fold (D_1) with a westerly plunge of 22°. An axial plane cleavage is locally developed, but the sampled areas show only a weak fracture cleavage. Sites 2 and 3 carry almost single component magnetizations with near South declinations and negative (upward pointing) inclinations (Figs 2a and b). On the other hand, Site 1 samples did not provide sensible palaeomagnetic results. It is evident that the characteristic remanence components from Sites 2 and 3 are of post-fold origin due to the steady increase of α_{95} during stepwise unfolding (Fig. 2d). The test is *negative* at the 99 per cent confidence level, and this characteristic magnetic overprint is denoted component *A*. The thermal unblocking spectra and results of thermomagnetic analyses suggest that magnetite and haematite are the principal remanence carriers.

Component *A* is also a characteristic feature of the volcanics (Sites 4 and 5) of the Walls Peninsula, but additionally Site 4 carries a SW directed remanence with a downward dipping inclination (Figs 2e and f). This component, denoted *B*, occupies the high-blocking temperature part of the spectra when *A* and *B* are identified at the sample-level. A three-component magnetization build-up is protrayed in Fig. 2(e)—a poorly defined low blocking component is confined to temperatures below 200 °C, an intermediate component (*A*) is randomized in the 200–555 °C range, and finally the high blocking component (*B*) is identified above 575 °C.

Plutonics

Site 6 was sampled from the Muckle Roe granite, a reddish fine-grained granite/granophyre (Fig. 1). All samples are dominated by component *A*, but this component clearly has

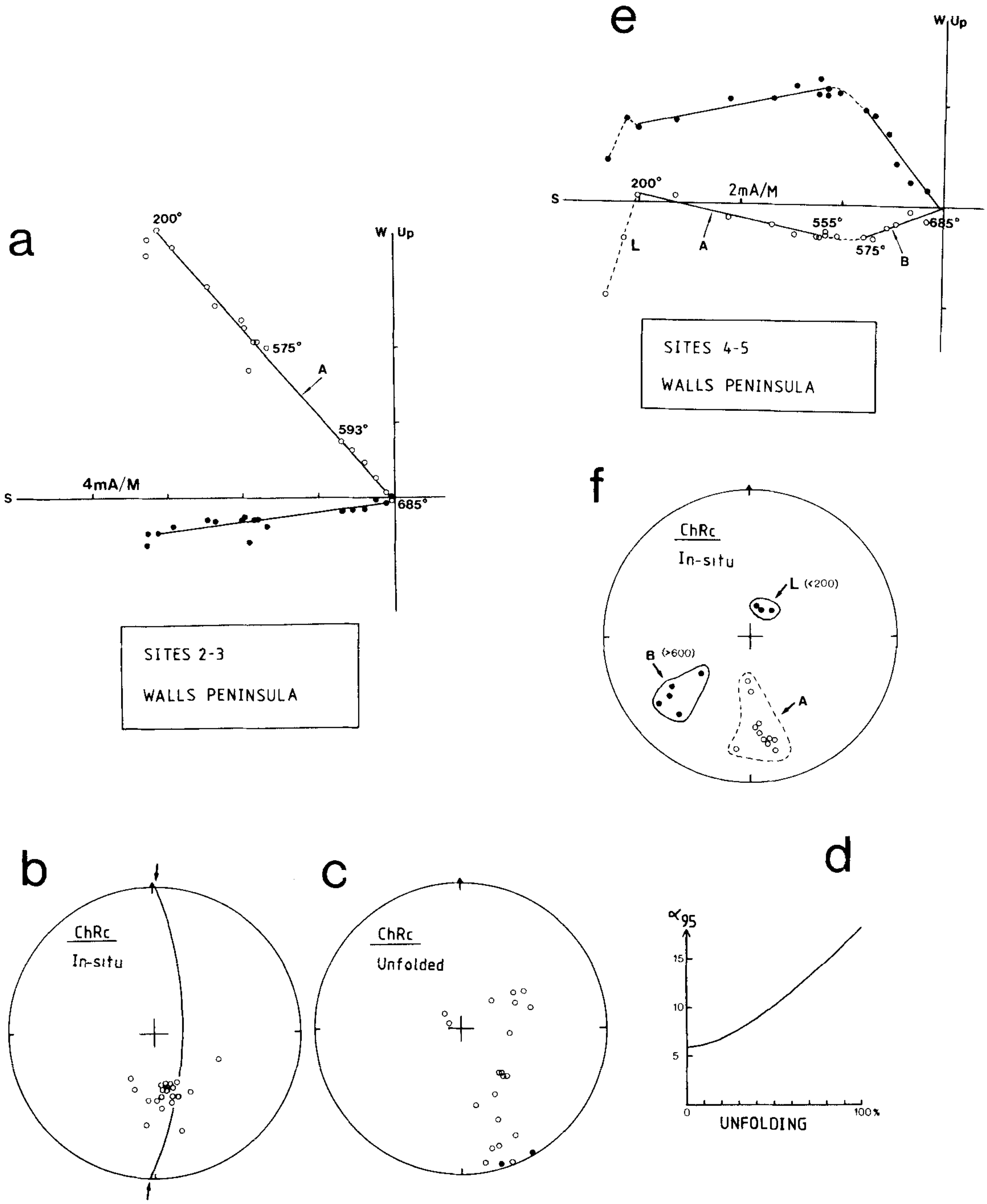


Figure 2. Thermal demagnetization examples of (a) red sandstone, Walls Peninsula, and (e) volcanics, Walls Peninsula. Distribution of characteristic remanence components from Sites 2 and 3 together with 4 and 5 are shown on stereographic projections in (b) and (f). (c) Tectonically corrected data from Sites 2 and 3 and the change in α_{95} associated with a stepwise unfolding is protrayed in (d). The fold test is negative at the 99 per cent confidence level. The great circle in (b) is a best fitted great circle for the distribution of poles to bedding from Sites 2 and 3. Throughout this paper, capital letters (*A*, *B*) with arrows on the orthogonal vector plots denote characteristic remanence components outlined in the text whereas *L* denotes low-blocking components. In equal angle stereoplots, positive (downward pointing) and negative (upward pointing) inclinations are shown as solid and open circles respectively. In orthogonal vector plots, solid and open symbols denote points in the horizontal and vertical plane, respectively.

a multiple origin and the high blocking part is somewhat steeper than the intermediate blocking part (Table 1). In the final statistics (Table 2), however, both parts are classified as *A*.

The magnetic signature of the mela-dolerites (Sites 7–9) is represented by both component *A* and *B*, the latter of dual polarity. Reverse polarity *B* components were observed at Site 7 (Fig. 3a and b), whereas Sites 8 and 9 (Fig. 3c and d) show a combination of both *A* and *B*. Component *A* always occupies the intermediate blocking spectra, but there are hardly any blocking contrasts between normal (Site 9) and reverse (Site 8) polarity *B* components.

Table 1. Sampling details and site-mean statistics.

Site	Rocktype	T_b	Dec	Inc	α_{95}	N	S_0	CDec	CInc	RGr.
Walls Peninsula:										
1	Grey Sandstone		—	—	—	—	—	—	—	—
2	Grey/Red Sandstone	H	168	−40	14	5	113/78	064	−48	A
3A	Grey/Red Sandstone	H	173	−54	61	3	096/47	039	−76	A
3B	Grey/Red Sandstone	H	—	—	—	—	—	—	—	—
3C	Grey/Red Sandstone	H	174	−42	9	6	162/30	147	−41	A
3D	Grey/Red Sandstone	H	166	−50	—	1	232/30	158	−22	A
3E	Grey/Red Sandstone	H	170	−44	27	2	225/39	159	−10	A
3F	Grey/Red Sandstone	H	163	−42	8	5	246/40	161	−2	A
4	Volcanics	I	172	−19	4	8	52/65	226	−62	A
		H	231	+24	12	5	52/65	210	+9	Br
5	Volcanics	H	184	−39	35	3	172/80[1]	134	−16	A
Plutonic Rocks:										
6	Red Granite	I	187	−22	18	4	—[2]			A
		H	182	−39	6	6	—[2]			A
7	Meladolerite	H	179	+10	5	7	—[2]			Br
8	Meladolerite	I	194	−36	37	2	—[2]			A
		H	197	+1	26	7	—[2]			Br
9	Meladolerite	I	167	−41	19	5	—[2]			A
		H	26	−1	19	5	—[2]			Bn
Esha Ness:										
10	Andesite	I	177	−51	11	6	005/40[3]	224	−37	A
		H	341	−50	5	7	005/40[3]	314	−20	C
11	Andesite	I	176	−39	19	5	126/40[4]	132	−60	A
		I	192	+26	25	4	126/40[4]	194	−11	Br
		H	001	−63	8	8	126/40[4]	019	−26	C
12	Volcanocl./Tuff	I	170	−49	8	6	024/2	172	−50	A
		H	334	−51	5	6	024/2	333	−50	C
13	Andesite	I	172	−53	7	8	155/86	101	−13	A
		H	333	−62	10	9	155/86	037	−5	C
14	Basalt	I	168	−25	8	9	341/15	175	−22	A
		H	198	−23	8	8	341/15	202	−14	A
15	Andesite	I	187	−17	17	9	204/16[5]	183	−12	A
		H	046	−51	12	9	204/16[5]	061	−43	C
16	Basalt	I	172	−17	12	6	195/22	168	−8	A
		H	184	+25	7	7	195/22	195	+27	Br
Eastern ORS:										
17	Red Sandstone	I	186	−28	17	4	352/15	193	−24	A
		I	185	−1	6	4	352/15	184	+3	Br
18	Red Sandstone	I	184	−1	30	3	073/25	186	−24	Br
19	Grey Sandstone	H	037	−3	15	7	002/20	035	−14	Bn
20	Red-Grey Sandstone	I	195	+2	20	6	003/66	186	+12	Br

T_b = Blocking temperature spectra (I = intermediate, H = High); Dec = declination; Inc = Inclination; α_{95} = 95 per cent confidence circle; N = Number of samples; S_0 = bedding/palaeo-horizontal; CDec = tectonically corrected declination; CInc = corrected inclination; RGr = Remanence group classification (cf. text); [1]Uncertain S_0; [2]Unknown tectonic correction; [3]S_0 measured in sand-horizon at top of flow; [4]S_0 measured at base of flow; [5]S_0 assumed to correspond to plane of flattened amygdales (gas-bubbles) and fine regular jointing.

2.2 Western ORS

Volcanic rocks from Esha Ness show a remanence pattern that is different when compared with that of the other areas, i.e. the presence of a remanence with near N declinations, and *steep* upward pointing inclinations (component *C*). Most sites show multi-component magnetization. From Site 10, a minor low blocking component is removed below 200 °C, a southerly and upward pointing component (*A*) is randomized in the intermediate temperature spectra (200–510 °C), and finally *C* is identified in the 510–570 °C range (Fig. 3e and f). Site 11 shows a multivectorial interplay of all the principal components *A*, *B* and *C* at the specimen level (Table 1). The Esha Ness basalts and andesites are dominated by titanium-poor magnetite, but the influence of haematite can be important. In the latter case component *C* is *absent* (Sites 14 and 16)—at Site 14 only component *A* is identified, whereas at Site 16 an intermediate blocking *A* component co-exists with the high-blocking *B* component (Fig. 4a and b).

2.3 Eastern ORS

Four sites, including grey and red sandstones, were tested from the Eastern Group. Unfortunately, remanence quality is not as good as in the rocks from the Central and Western ORS. Most samples are dominated by an intermediate component, chiefly identified in the 200–580 °C range (Fig.

Table 2. Overall palaeomagnetic data and fold tests.

	Dec	Inc	α_{95}	K1	CDec	CInc	α_{95}	K2	N
Component A									
Walls Peninsula	171	−41	7.8	51	147	−41	32.4	3.9	8
Plutonics	183	−35	14.4						4
Esha Ness	178	−35	12.4	21	172	−32	28	4.9	8
Eastern ORS	186	−28	17.4	28.7					4*
Mean	177	−37	5.7	31.5					21
		VGP: S50, E003 *dp*/*dm* = 4/7 (*In situ*)							
Component B									
Walls Peninsula	231	+24	12		210	+9	12		5*
Plutonics	(N) 026	−1	19						5*
	(R) 188	+6	45.1						2
	(C) 194	+4	22.6						3
Esha Ness	188	+26	15.9	247.3	194	+8	96.3	9.1	2
	198	+15	18.2	14.6					6
		[VGP: S20.6, E339.6 *dp*/*dm* = 10/19]#							
Eastern ORS	(N) 037	−3	15		035	−14	15		7*
	(R) 188	0	9.6	164.4	186	−3	29.1	18.9	3
	(C) 195	+1	17.8	27.7	193	+1	26.1	13.0	4
		[VGP: S27.9, E341 *dp*/*dm* = 9/18]#							
Mean	197	+9	12	17.1					10
		VGP: S24, E340 *dp*/*dm* = 6/12 (*In-situ*)							
Component C									
Esha Ness	355	−55	17.8	19.4	010	−36	42.4	4.2	5
		VGP: N10, E003 *dp*/*dm* = 20/27 (*In-situ*)							

N = Number of sites (*samples); (N)/(R)/(C) = normal-, reverse- and combined-polarity; K1/K2 = precision parameter before/after tectonic correction; VGP = virtual geomagnetic pole; dp/dm = semi-axis confidences; #Also plotted in Fig. 7a, i.e. west (w) and east (e) of the WBF/NF. Cf. Table for further legend.

5c), and with southerly declinations and shallow inclinations. The high-temperature component proved difficult to determine due to viscous directional behaviour (Fig. 4c), and only Site 19 samples provide a clear-cut definition of the high-blocking component (Fig. 4d). This haematite-bearing component is of normal polarity compared with the intermediate-blocking reverse directions observed in Sites 17, 18 and 20. We interpret these directions to represent component *B*, based on the dual-polarity structure and the directional similarity with component *B* from the Central and Western ORS. From Site 17, the *A* component was also identified, having lower blocking temperatures than the reverse *B* component. A fold test for the normal polarity *B* directions is negative at the 95 per cent confidence level. A combined fold test, based on both normal and reverse data, is also negative, but not statistically conclusive (Table 2).

3 REMANENCE ANALYSIS

Three principal remanence components, named *A*, *B* and *C* have been identified. In addition some samples show a low-blocking component ($T < 200\,^{\circ}\mathrm{C}$), most likely of Recent/Tertiary origin. Negative fold tests (95–99 per cent confidence level) point to a secondary origin of all components in sediments and lavas (Figs 2b–d; 5a and b; Table 2; see also below).

Component *A* is exclusively of reverse polarity, and is identified as a complete magnetic overprint, or it occupies the intermediate blocking spectra, when co-existing with component *B* and/or *C*.

Component *B* resembles a number of palaeomagnetic results from northern Britain (Orcadian Basin) and a recent palaeomagnetic result from the Esha Ness ignimbrites (Fig. 6). Some authors contend that the *B* components represent a primary Middle–Upper Devonian magnetization, but no field-stability tests have been presented as yet to sustain this argument. A conclusive fold test was not presented for the Esha Ness ignimbrites by Storetvedt & Torsvik (1985), but they concluded that *B* was primary in origin. However, in view of the negative fold test presented here and evidence presented elsewhere (Torsvik *et al.* 1989b, c), the *B* component should be considered to be secondary in origin. A fair antipodal dual-polarity structure of *B* ensures a satisfactory time-averaged pole.

The *C* component was found in basalts and andesites from Esha Ness, but not in the heamatite bearing ignimbrites (Storetvedt & Torsvik 1985). Similar magnetizations, however, have been reported from Esha Ness and the Walls Peninsula by Morris *et al.* (1973), but their palaeomagnetic findings were based on very *few* pilot specimens. It is noted that *C* is exclusively carried by magnetite, and at sites where heamatite predominates [ignimbrites tested by Storetvedt & Torsvik (1985) and Sites 14 and 16, this study], *C* is absent. This suggests that *A* and *B* formed partly via oxidation of magnetite which dominates the original magneto-mineralogy in andesites and basalts, implying a thermo-chemical (TCRM) origin for the secondary components. The *C* component, however, also fails a positive fold test. This is most effectively demonstrated from Sites 12 and 13 which embrace a monoclinal fold structure where the dips varies

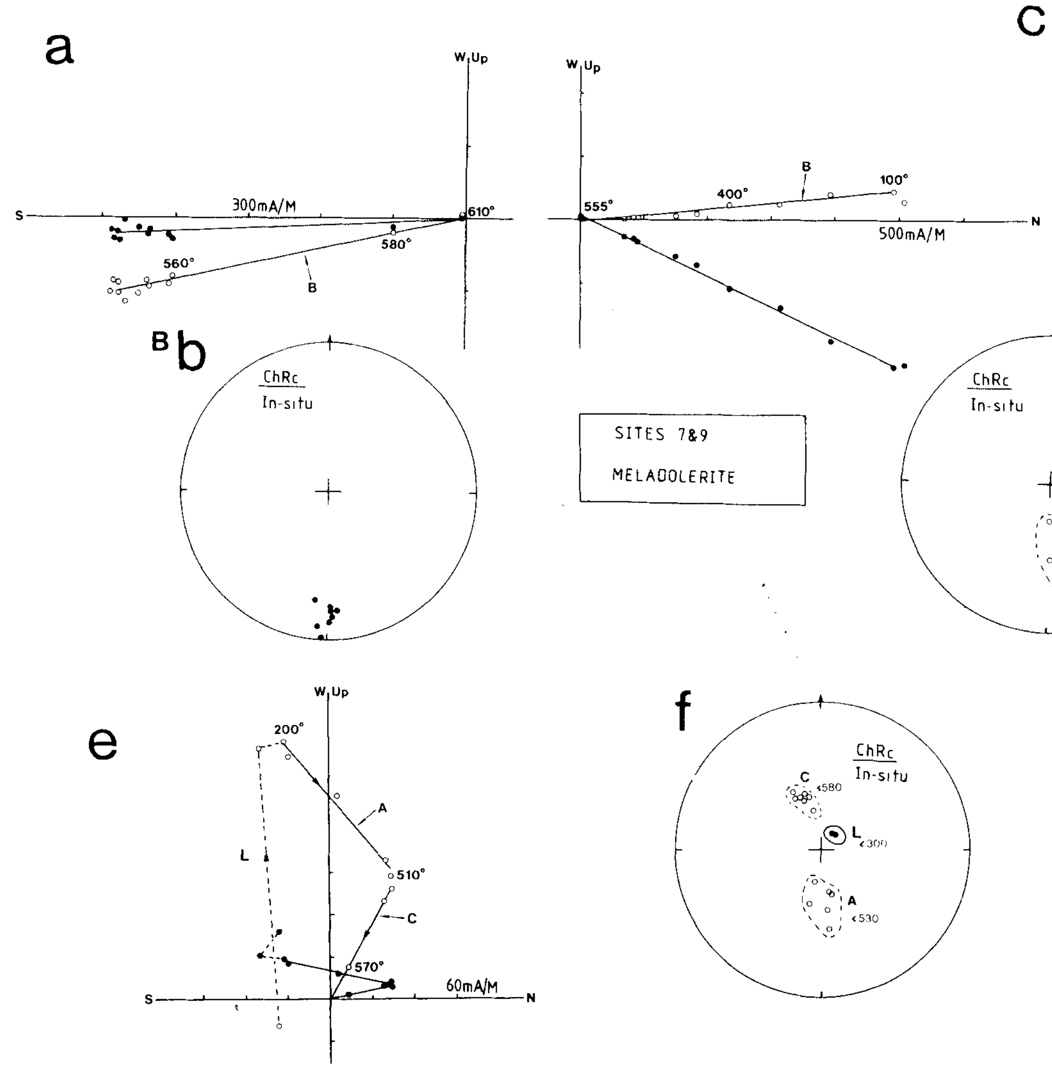


Figure 3. Examples of thermal demagnetization of samples from Sites 7(a), 9(c) and 10(e). The distribution of characteristic remanence components from these sites are illustrated in (b), (d) and (f).

from horizontal to vertical within 5 m (Fig. 5). The test is negative at the 99 per cent confidence level, and conversely no primary remanence is preserved in these lavas.

4 DISCUSSION

All the remanence components identified in sediments and lavas are post-fold and consequently post-*Middle Devonian* in origin. Judged from the thermal blocking spectra, when all three components co-exist at the sample level, and a suggested British Apparent Polar Wander Path (APWP), it is argued that component *A* is youngest, whereas *C* is the oldest acquired remanence (Fig. 7).

The near equatorial position of the British APWP was probably retained from Middle Silurian until Middle–Upper Devonian time (Torsvik *et al.* 1989c). The latitude of the palaeo-pole derived from *C* may indeed indicate a Devonian age, but it is noted that the pole longitude is somewhat anomalous (Fig. 7a). The discrepancy could relate to local tectonics, but a pure block rotation about a *local* vertical axis would not bring the *C* pole into complete agreement with any parts of the APWP. Thus, an inclined rotation is indicated, perhaps related to a hinge fault, the Melby Fault, or a flower structure associated with regional strike-slip faulting. The suggested inclined rotation of the Esha Ness Peninsula, however, must have taken place *prior* to acquisition of component *B*, since the latter can be matched throughout the Shetlands (Fig. 6). At the present time, however, we will not stress this issue since *C* has only been identified from a few localities, and may not necessarily represent a time-averaged pole position, i.e. a spot reading. Note that the inclined rotation path exemplified in Fig. 7a (IA) just represent an example of fitting the *C* pole onto the APWP.

Substantial post-Devonian strike-slip faulting along the GGF and its conceivable extension to Shetland, WBF, has been postulated from palaeomagnetic data (Storetvedt 1974, 1987; Van der Voo & Scotese 1981). On the assumption that the *A* component represented the genuine Devonian palaeo-field, Van der Voo & Scotese (1981) suggested a sinistral displacement in the order of 2000 km. It is substantiated, however, that *A* is secondary and originates from pervasive late Palaeozoic–early Mesozoic magnetic overprinting. The model proposed by Storetvedt (1974,

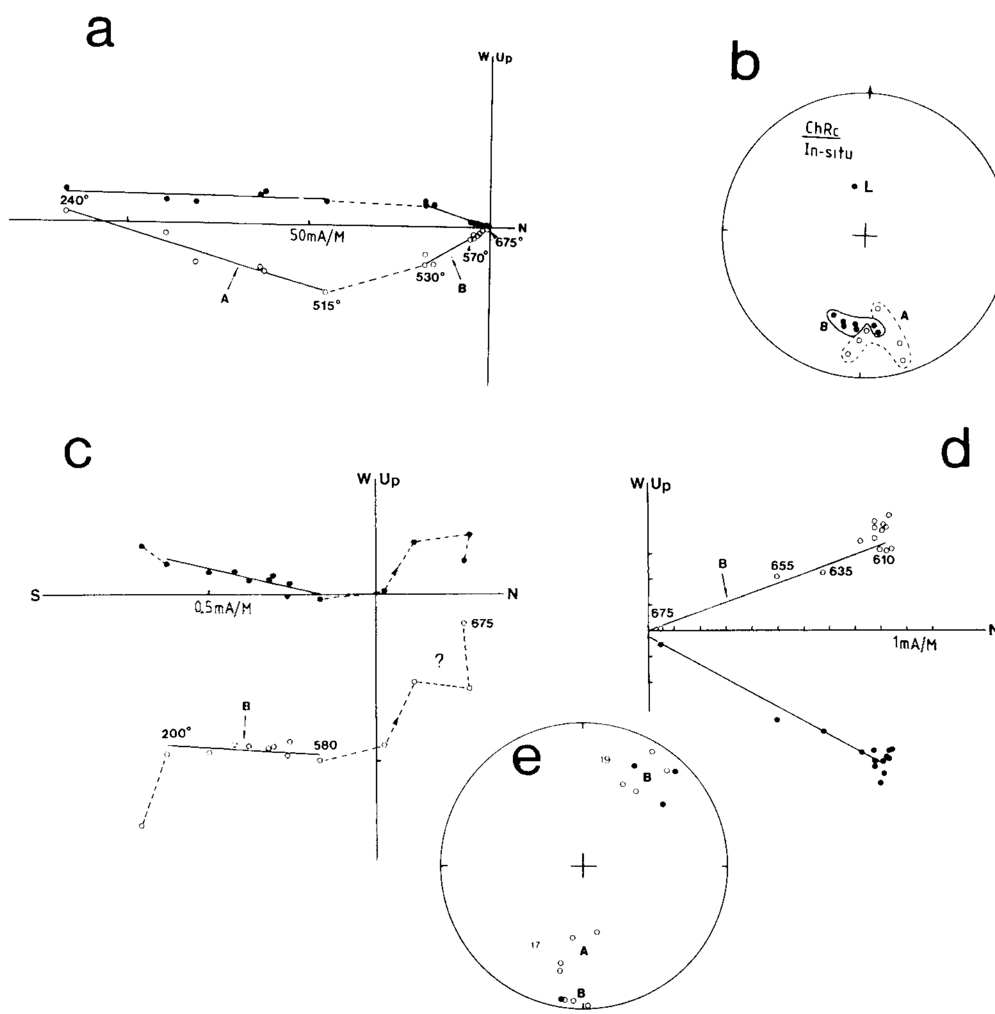


Figure 4. Examples of thermal demagnetization from Sites 16(a), 17(c) and 19(d), together with stereoplots showing the distribution of characteristic remanence components.

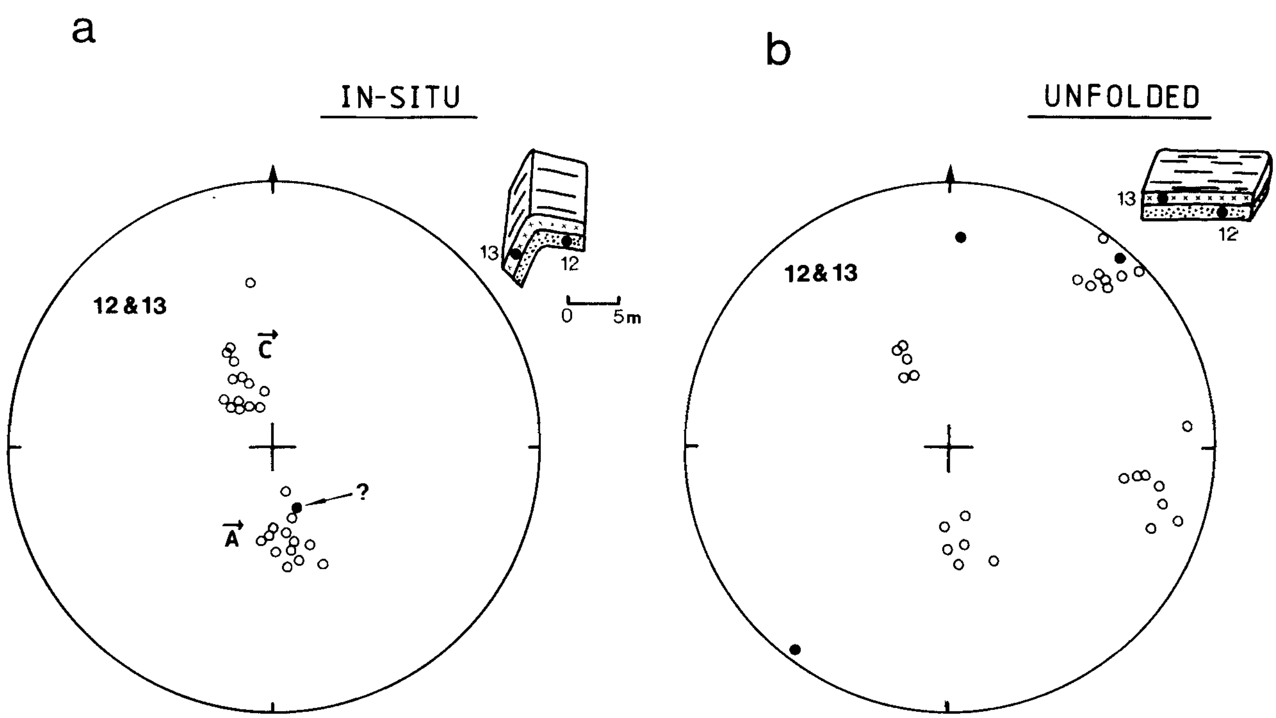


Figure 5. Characteristic remanence components from Sites 12 and 13, shown *in situ* (a) and tectonically corrected co-ordinates (b). These sites embrace a small monoclinal fold structure (see inset figures with sampling position of the sites), and the fold test is negative at the 99 per cent confidence level for the *A* and *C* components (cf. text).

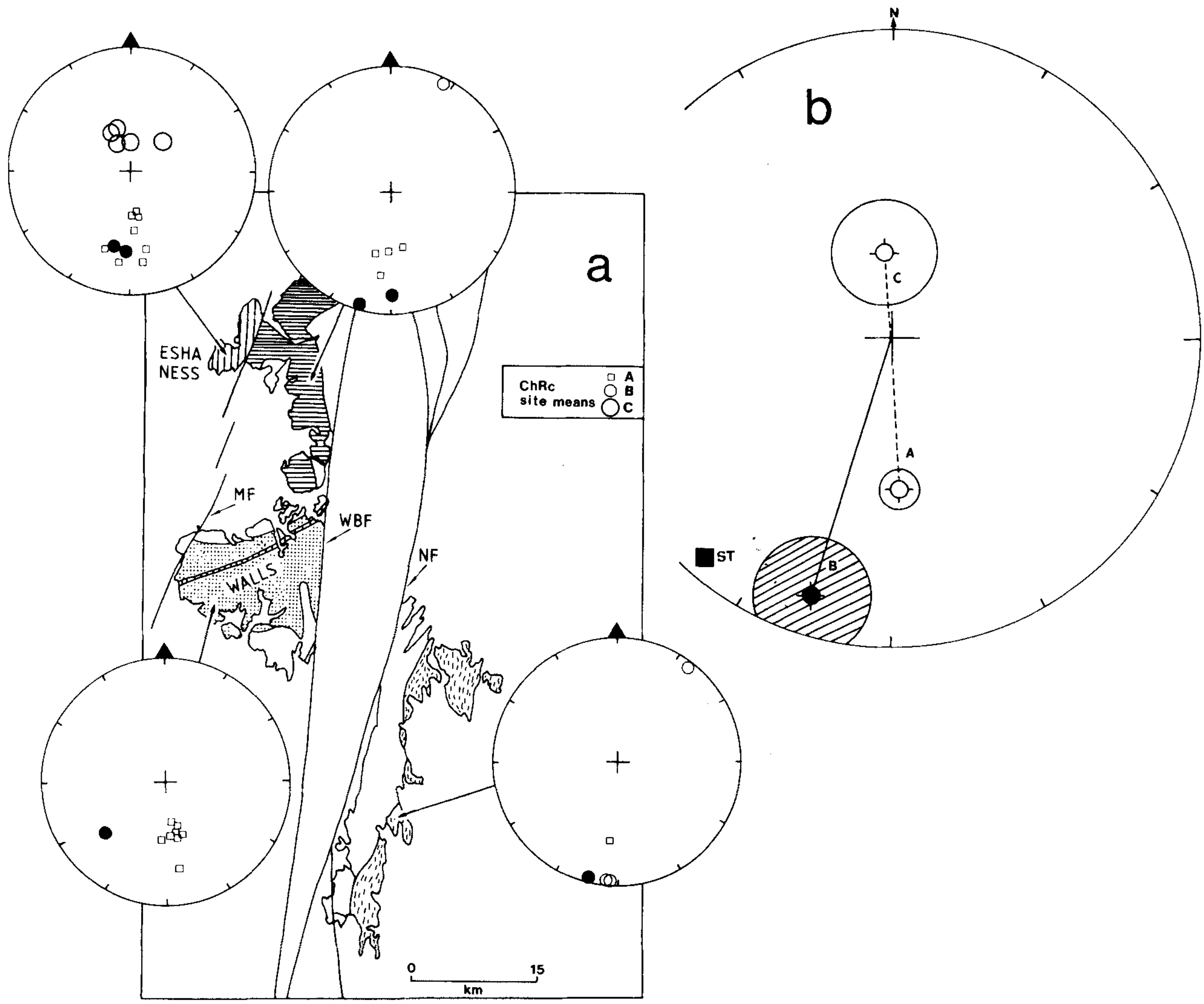
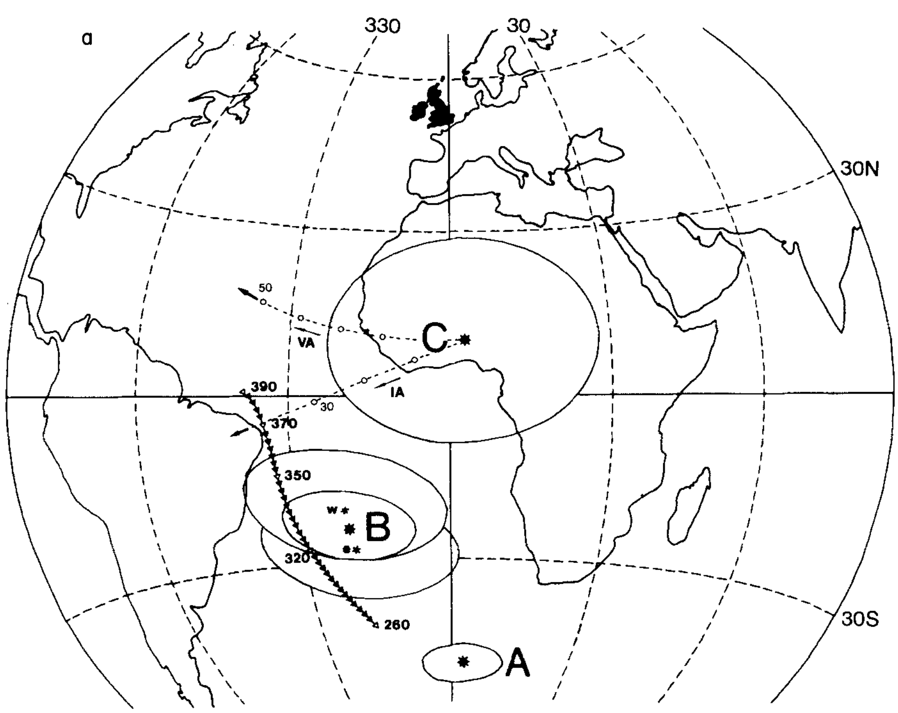


Figure 6. The distribution of site-mean directions from Esha Ness, Walls Peninsula sandstone, plutonic rocks and Eastern ORS (a). In (b) is shown the overall mean directions (Table 2) for components *A*, *B* and *C*, together with a recent palaeomagnetic result from the Esha Ness ignimbrites (ST—Storetvedt & Torsvik 1985).

1988) relies on the assumption that the *B* component is the true Middle–Upper Devonian palaeofield. In Storetvedt's (1987) latest model, the GGF underwent at least 600 km sinistral displacement in late Devonian times followed by a later dextral phase in Permian times. In this model, a pre-Middle Devonian fit of palaeomagnetic data across the GGF (see e.g. Briden, Turnell & Watts 1984 and Fig. 7b) and radiometric age data is ignored (Rock 1988). For reasons given elsewhere (Torsvik *et al.* 1989b, c) and demonstrated in this study, the *B* component is also secondary, and therefore not necessarily representative of the Middle–Upper Devonian palaeofield. It can also be demonstrated that component *B* can be matched across the WBF/NF at Shetland (Fig. 6; Table 2) and the GGF, thus invalidating the model of Storetvedt (1987), independently of the nature and origin of this remanence.

Late Caledonian (Devonian) deformation and remagnetization is widespread in western and central Norway (Torsvik *et al.* 1986, 1987, 1988, 1989a). The nature and origin of this deformation, however, is controversial—some argue that folding, faulting and anchizone to lower greenschist facies metamorphic features have a purely syn-kinematic extensional origin (Hossack 1984; Norton 1986), whereas others favour a post-depositional compressional event (Svalbardian/Solundian) in Upper Devonian time (Vogt 1928; Sturt 1983; Roberts 1983; Torsvik *et al.* 1987, 1988, 1989a). A combination of Lower–Middle Devonian syn-depositional extensional deformation and Upper Devonian post-depositional compressional deformation is perhaps also applicable. The Devonian geology of the Shetlands, and most notably the Walls Peninsula Formation (Central Group) shows striking similarities to that of western Norway. Fold trends and metamorphic grades are compatible, and in order to explain the structural features and similarities together with the presence of calc-alkaline lavas cut by a batholitic complex (Central Shetland), a late Devonian collision zone has been postulated along the Møre Trøndelag Fault Zone (Central Norway) and its conceivable extension into the GGF/WBF system (Torsvik *et al.* 1989a). We consider that the *C* components relate to this Upper Devonian deformation and magnetic overprinting, compatible with remagnetization features observed throughout



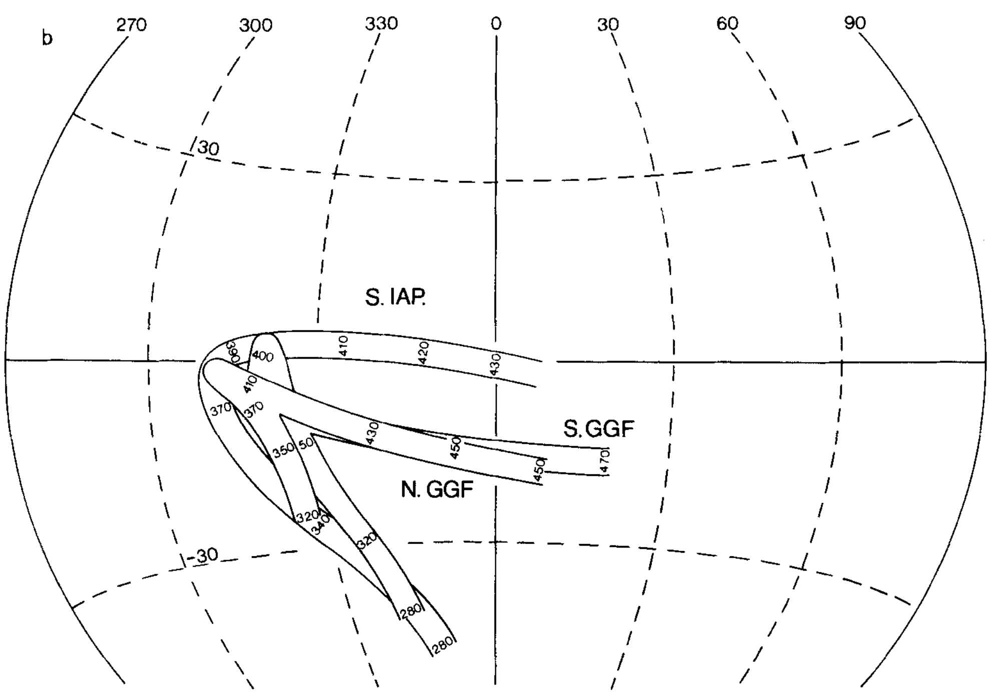


Figure 7. (a) Virtual geomagnetic poles (*A–C*) obtained in the present study (equal area projection). Small stars marked *w* and *e* represent mean poles from west and east of the Walls Boundary Fault–Nesting Fault). Note the overlapping *dp*/*dm* confidence circles. Mean poles are displayed together with a smoothed APWP detailed in Torsvik *et al.* (1989c). The APWP is derived from Lower Devonian to Permian rocks from northern Britain, i.e. North of the Iapetus Suture. The *C* pole is somewhat anomalous, and two possible explanations are portrayed. The first explanation involves rotation about a *local* vertical axes (VA) plotted in 10° steps (up to 50°). The second interpretation entails a rotation (IA) about an inclined axis. The latter rotation path is based on a tentative euler pole rotating the *in situ* pole position into correspondence with the Upper Devonian palaeofield (360–370 Ma). Note that an inclined rotation is required to bring the *C* pole onto the given APWP (cf. text). (b) Comparison of Ordovician to Permian APWPs including data for South and North of the Great Glen Fault and southern Britain, south of the Iapetus Suture (Torsvik *et al.* 1989c). Note the close similarity between the paths north (N.GGF) and south (S.GGF) of the Great Glen Fault, suggesting that any displacement along the GGF is below the resolution power of palaeomagnetic studies.

central and western Norway. The *C* component is post-fold in origin which may suggest considerable burial of the ORS, with the *C* component produced during uplift.

The age and origin of the *B* component is debatable, though it does in fact match some syn- and post-fold magnetizations derived from the deformed ORS of western Norway, e.g. Kvamshesten (Torsvik *et al.* 1986). In a recent review of European palaeomagnetic results most *B* components reported from the British Isles were assigned a Carboniferous (~320 Ma) age (Torsvik *et al.* 1989c). This was based on the fact that they plot between well-dated Lower Carboniferous and Permian poles on the APWP (see also Torsvik *et al.* 1989b), and that *no* field test has been presented in the literature to prove a primary origin. From Shetland, it is tempting to relate *B* to the period of extensive late to post-orogenic plutonism in Central Shetland. The *C* component is only found in lavas west of the MF, and within Central Shetland this *C* component is nearly obliterated. This is also the case for the Eastern ORS, but this may relate to magnetic stability contrasts between sediments, Eastern ORS, and lavas on Esha Ness. Seen in relation to the suggested APWP (Fig. 7), an upper Lower Carboniferous age is preferred for component *B*, an age-estimate which compares with the youngest K/Ar age obtained from the Central Shetland plutonics (334 Ma; Miller & Flinn 1966). Relating component *B* with the plutonic activity implies that *B* found in mela-dolerites could be primary, since no independent remanence stability testing is available. *B* has a dual-polarity structure in these dolerites, and the lack of differences in the thermal blocking spectra between normal and reverse field-directions *may* support a primary origin of the remanence.

The *A* component compares well with other reported remagnetization features from NW Scotland, and a Permian/early Mesozoic age has been deduced for this overprint. Similarly, in the Appalachians of North America, Permian overprinting is now known to be far-reaching (see, e.g. Irving & Strong 1984; Kent & Opdyke 1985). A Permian age is partly indicated from an inspection of existing APWPs, but also as a result of the consistent reverse, and presumably Kiaman polarity. However, not all the reported *A* components from Northern Britain show reverse polarity (e.g. Storetvedt & Carmichael 1979; Torsvik 1984), and some could be early Mesozoic in origin. The late Palaeozoic–early Mesozoic was a period of extension and widespread intrusion of dykes and sills, and the initiation of the Viking Graben, North Sea, probably during the early Triassic (Ziegler 1982; Coward 1986; Beach, Bird & Gibbs 1987). In western and central Norway late Palaeozoic–Mesozoic remagnetization is widespread. Such remagnetization features are mainly restricted to the vicinity of major Caledonian fault zones, which were reactivated as normal faults or strike–slip faults during Permian to early Cretaceous times (Torsvik *et al.* 1988, 1989a; Grønlie & Torsvik 1989). A structural linkage in NW Scotland and Shetland, however, is not so clear-cut, but it is tempting to suggest a similar explanation. Shetland is cut by numerous faults and crush zones considered to relate to post-Devonian movements or reactivation along the WBF, and uranium enrichment in granites from Shetland and Scotland, often caused by martitization of magnetite, is well known to be associated with hydrothermal fluids penetrating these faults and crush zones (Simpson, Plant & Cope 1976; Tweedie 1979). The *A* component is therefore tentatively considered as having originated via late Caledonian faulting and hydrothermal activity producing thermochemical magnetic resetting.

5 CONCLUSIONS

The magnetic structure of the ORS and plutonic rocks from Shetland is dominated by three major remanence components which can be proved to be secondary in lavas and sediments. In conclusion we propose that:

(i) *C* correlates with Upper Devonian compressional tectonism which affected vast tracts of the ORS in the North Atlantic area,

(ii) *B* may have originated via extensive geothermal disturbance caused by plutonic activity and/or reflecting the cooling-uplift history in early–mid Carboniferous time,

(iii) *A* is most likely Permian–Early Triassic in age and relates to extensional fault reactivation and hydrothermal activity guided by older Caledonian structures,

(iv) the GGF system has *not* been the site of post-Devonian mega-shearing, but was an important structural controlling element during the Late Palaeozoic and Mesozoic with displacements in the order of tens of kilometers (Flinn 1977; Rogers 1987).

Viewed in relation to the various proposals of mega-shearing along the GGF, Rock (1988) remarks that the palaeomagnetic technique appears unusually subjective. This, however, relates to the failure to recognize extensive magnetic overprinting and resetting. It must be stressed that APWPs should not be used as permanent frames of reference (Van der Voo 1988), and proposals of mega-shearing on the GGF can be considered as essentially artifacts owing to comparisons of palaeomagnetic poles with *different ages*.

We are of the opinion, however, that the precise timing of and the detailed mechanism for the origin of the various palaeomagnetic components, identified in northern Britain, are still not adequately resolved. Hence, additional palaeomagnetic studies should be initiated in order to shed more light on these issues.

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