Geophys. J. Int. (1991) **105**, 467–473

The British Siluro-Devonian palaeofield, the Great Glen Fault and analytical methods in palaeomagnetism: comments on paper by K. M. Storetvedt *et al.*

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Accepted 1990 December 3. Received 1990 October 15; in original form 1990 July 19

SUMMARY

Late Silurian–early Devonian palaeomagnetic poles throughout the British Isles lie in a coherent group about 1°S and 314°E ($A_{95} = 9.6°$). The clustering of these poles, which are derived from 11 individual studies of Siluro-Devonian rocks of all the major tectonic elements of Britain, carries two important tectonic implications:

(1) the British sector of the Iapetus Ocean, recognizable from Ordovician poles, had closed by late Silurian times; and

(2) any postulated mega-shear, whether related to Acadian or Hercynian deformation, is below the limit of palaeomagnetic resolution.

The collective rejection of all Siluro-Devonian results by Storetvedt *et al.* (1990a,b) is demonstrated to be unfounded.

Key words: British Siluro-Devonian palaeofield, palaeomagnetism.

1 INTRODUCTION

Although the British Siluro-Devonian palaeofield has been a matter of some uncertainty, a recent contribution to this journal by Storetvedt *et al.* (1990a), in which all published Upper Silurian–Lower Devonian palaeomagnetic data from the British Isles were rejected, arouses concern. An objective documentation of Siluro-Devonian data is therefore required, and in this account we discuss the palaeomagnetic reliability of the British Siluro-Devonian poles. They are assessed through consideration of the classical palaeomagnetic stability tests, together with data-analytical techniques used in the derivation of the palaeopoles. We also outline demonstrable errors in the analysis of palaeomagnetic data presented by Storetvedt *et al.* (1990a).

2 THE BRITISH SILURO-DEVONIAN PALAEOFIELD

Apparent polar wander (APW) paths for Southern Britain (E Avalonia) and Scotland (southern margin of Laurentia) are characterized by a Siluro-Devonian 'corner', where the two paths converge defining a common locus from Mid-Upper Palaeozoic time (Briden, Turnell & Watts 1984; Briden *et al.* 1988; Torsvik *et al.* 1990). The British 'corner' poles (Fig. 1a), which are mostly obtained from Lower Old Red Sandstone (ORS) lavas, have recently been suggested to be palaeomagnetically unreliable (Storetvedt *et al.* 1990a,b). Indeed, over three decades, Storetvedt and coworkers have questioned the authenticity of palaeomagnetic poles from the Lower ORS (Storetvedt 1967; Storetvedt & Halvorsen 1968; Torsvik, Løvlie & Storetvedt 1983; Storetvedt *et al.* 1990a,b). They argue that 'dual-polarity remagnetizations have established stable discordant directions of net magnetization at variance with the true palaeomagnetic field axis'.

We have therefore attempted an objective assessment of the palaeomagnetic reliability of the Siluro-Devonian 'corner' poles using the criteria suggested by Van der Voo (1988) (Table 1). However, we do not address the reliability of Ordovician and Early Silurian poles from Britain in this contribution (see Torsvik *et al.* 1990).

We observe that numerous Siluro-Devonian palaeomagnetic results define the 'corner' (Fig. 1a) with data being drawn from many different rocktypes (i.e. Anglo-Welsh cuvette sediments: Chamalaun & Creer 1964: Scottish Old Red Sandstone lavas: Embleton 1968; McMurry 1970; Sallomy & Piper 1973; Latham & Briden 1975; Kono 1979; Torsvik 1985: Somerset & Gloucestershire Silurian lavas: Piper 1975: Moine metasediments (uplift magnetizations): Watts 1982: Silurian–Devonian plutons: Briden 1970; Turnell 1985: Silurian–Devonian siltstones and sandstones: Smethurst & Briden 1988; Storhaug & Storetvedt 1985:

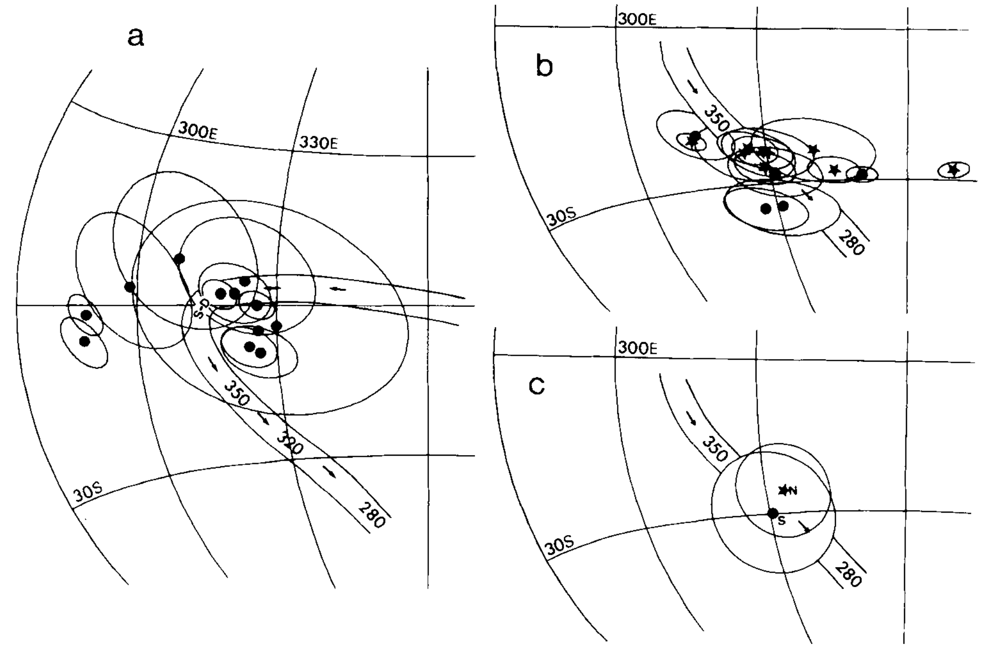

Figure 1. (a) Distribution of Siluro-Devonian poles (average age = 412 Myr) obtained from Siluro-Devonian rocks (Table 1). These poles are shown together with a postulated APWP for Southern Britain (Towsvik *et al.* 1990). Equal area projection. (b) Distribution of poles (**B** poles) argued by Storetvedt *et al.* (1990a) to represent the primary 'Mid-Palaeozoic' palaeofield (Table 2a,b) but by Torsvik *et al.* (1989a,b) to represent Lower Carboniferous overprints. Poles recorded in Upper Silurian and Devonian rocks north of the GGF (south of the GGF) are marked with solid (star) circles. (c) Comparison of mean values of **B** poles north (denoted N) and south (denoted S) of the GGF.

Lower Old Red Sandstone aged ignimbrites: Trench & Haughton 1990). Importantly, some of these results are of high data-quality (Table 1, Fig. 2a,b), demonstrating that the 'corner' poles are indeed reliable, and therefore that they truly represent the Upper Silurian–Lower Devonian palaeofield (Fig. 1a). In some of these studies, fold, conglomerate and contact tests, combined with magnetomineralogical and magnetostratigraphic evidence support a primary origin (Table 1, criterion 4). In rejecting all these studies, Storetvedt *et al.* (1990a,b) question the classical field tests and reliability criteria that have been developed in palaeomagnetism (e.g. Brunhes 1906; Graham 1949; Everitt & Clegg 1962; McElhinny 1964; McFadden & Jones 1981; Briden & Duff 1981; Van Der Voo 1988).

Storetvedt *et al.* (1990a) argue that the Silurian and Devonian palaeofields, which they refer to as the

Table 1. Compilation of some Siluro-Devonian rock units with pole positions conforming to the British Siluro-Devonian 'corner' (see text).

Rock unit	Age*	Pole Lat	Pole Long	a95	Grading 1234567	Q#	Reference
Cheviout Combined	396	4	323	11	xxx xxx	6	Thorning, 1974
ORS Wales	398	3	298	13	x xx x	4	Chamalaun & Creer, 1964
Sarchlet ORS	400	-9	326	7	x x xxx	5	Storhaug & Storetvedt,1985
Garabal Hill	405	-5	326	24	x x x x	4	Briden, 1970
Comrie Complex	412	-6	287	6	xxx x	4	Turnell, 1985
Strahmore Lavas	415	2	318	3	xxxxxxx	7	Torsvik, 1985
G & L ignimbrites	416	-4	330	3	xxxxx x	6	Trench & Haughton, 1990
Arrochar Complex	418	-8	324	5	xxx x x	5	Briden, 1970
Salrock Formation	420	-2	288	4	xxxx x	5	Smethurst & Briden, 1988
Lorne Plateau	424	2	321	6	xxxxx x	6	Latham & Briden, 1975
S & G Lavas	430	8	309	14	xxxx xx	6	Piper, 1975

*Rock ages from original sources listed in the original palaeomagnetic studies, or revised & new ages listed in Thirlwall (1988)

#Grading and quality-factor (Q) from Van Der Voo (1988):
1=Well-determined age for the rocks and magnetization age is not demonstrably different from rock age
2=Sufficient number of samples (>25) and high enough precision (k>10 and a95<16°)
3=Demagnetization achieved and published in sufficient detail
4=Positive field-tests
5=Sufficient structural control, i.e. no suspicion exists about possible local rotations
6=Presence of reversals
7=Lack of similarity with younger palaeopoles

Abbreviations: S & G lavas = Somerset and Gloucester lavas.
G & L ignimbrites = Glenbervie and Lintrathen ignimbrites.
ORS = Old Red Sandstone.

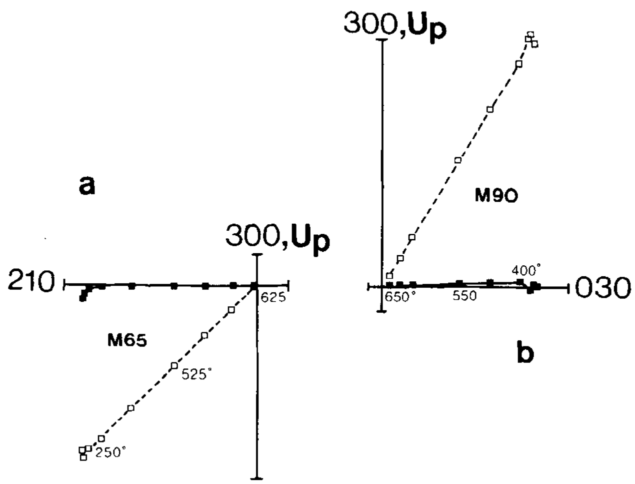

Figure 2. Examples of high-quality thermal demagnetization behaviour observed in the Lower ORS Strathmore Lavas, Midland Valley (from Torsvik 1985). (a) Arbuthnott Group, reverse polarity direction, (b) Crawton Group (flow 4), normal polarity direction. In orthogonal vector projections, points in the horizontal (vertical) plane are shown as closed (open) symbols. Note that the projection plane is optimized in both diagrams (030°–210°) to avoid distortion of the vertical projection.

'Mid-Palaeozoic' palaeofield, are essentially similar. We therefore undertook a reliability assessment of the relevant data (compiled by Storetvedt *et al.* 1990a) which is presented in Table 2(a). We also include the results of other studies yielding comparable directions (Table 2b).

It becomes apparent that in assessing the 'Mid-Palaeozoic' palaeofield of Europe, Storetvedt *et al.* (1990a) lend support to palaeomagnetic data (shallow inclinations with declinations N–S or NNE–SSW) for which there are no reliable tests of remanence age (Storetvedt & Petersen 1972; Storetvedt & Carmichael 1979; Storetvedt & Torsvik 1983, 1985; Storetvedt & Meland 1985; Storetvedt & Otterå 1988), or for which the remanence proves to be secondary (e.g. Torsvik *et al.* 1989a; Storetvedt *et al.* 1990a) (*cf.* Table 2; criterion 4). We would argue that the poles reported in the latter studies (Table 2; Fig. 1b) represent *Carboniferous* (Hercynian, approximately 320 Ma) magnetizations since:

(1) they have all been shown to be magnetic overprints, or field tests are statistically inadequate (Table 2, criterion 4);

(2) they plot between well-dated Lower Carboniferous and Permian poles (Torsvik *et al.* 1990; Table 2, criterion 7); and

(3) some of the tested rocks, e.g. the Duncansby Volcanic Neck, are inadequately dated (see Rock 1988).

3 THE GREAT GLEN FAULT

The postulate of large-scale sinistral displacement (*c.* 600 km) along the Great Glen Fault (GGF) in Late Devonian time (Storetvedt 1987; Storetvedt & Otterå 1988; Storetvedt *et al.* 1990a) is based on a supposed declination discrepancy in 'Mid-Palaeozoic' magnetizations across the fault (Table 2a,b). A statistical analysis of this data set, however, proves poles north (mean: 25.5°S and 333.7°E, $A_{95} = 9.3$, $N = 9$) and south (mean: 29.9°S and 330.6°E, $A_{95} = 12.1$, $N = 5$) of the GGF to be indistinguishable at the 95 per cent confidence level (Fig. 1c). A 'declination smearing' is observed in the data set north of the GGF (Fig. 1b). If this smearing has a tectonic origin, however, it must be linked with subordinate fault movements to the north of the GGF rather than on the GGF itself.

Table 2. (a) Compilation of palaeomagnetic poles, considered by Storetvedt *et al.* (1990a) to represent the 'Mid-Palaeozoic' palaeofield of Europe. (b) Directionally comparable poles not listed by the authors.

Rock unit	Age*	Pole Lat	Pole Long	a95	Grading 1234567	Q#	Reference
(a)							
Foyers ORS[S]	Dm	-29	350	3	xxNx	3	Storetvedt et al. (1990a)
Caithness sst	Dm	-27	329	6	xxx xx	5	Storetvedt & Torsvik, 1983
John O'Groats sst	Dm	-24	325	10	x x x	3	Storetvedt&Carmichael,1979
Duncansby Neck	?	-24	329	6	x x	2	Storetvedt et al., 1978
Orkney Lavas	Dmu	-24	330	9	x x x	3	Storetvedt & Petersen,1972
Orkney dykes	?	-28	010	3	xx x	3	Storetvedt & Otterå,1988
Hoy ORS	Dmu	-23	326	6	x x x	3	Storetevdt & Meland,1985
Esha Ness	Dm	-21	314	3	xx xx	4	Storetvedt & Torsvik,1985
(b)							
Sarchlet II	400	-28	344	5	xxx xx	5	Storhaug & Storetvedt,1985
Shetland B	Dmu	-24	340	12	xxNxx	4	Torsvik et al., 1989b
Strathmore B[S]	415	-20	315	8	x x	2	Torsvik, 1985
Lintrathen D[S]	416	-35	327	8	x x	2	Trench & Haughton,1990
Claire Island I[S]	420	-35	331	11	xxNx	3	Smethurst & Briden,1988
Salrock Fm. I[S]	420	-28	331	9	xx x	3	Smethurst & Briden,1988

Legend as Table 1

[S]South of the Great Glen Fault

Note that failure to fulfill criterion 1 indicates either:
(1) rock-age not well-determined,
(2) magnetization proves secondary by field-tests, or,
(3) a co-existing component proves to be primary on field tests.

For criteria 4, entries marked **N** denote a statistically negative fold-test.

Also note that as Storetvedt et al. (1990) argue for rotations linked with the Great Glen Fault (Table 2a), then if correct, the quality-factor (Q) for each of these entries should be Q-1 (as no study would satisfy criterion 5).

*Dm=Middle Devonian; Du=Upper Devonian

4 ANALYTICAL METHODS IN PALAEOMAGNETISM

4.1 The Lower and Upper ORS, Western Midland Valley

In a recent contribution, Torsvik *et al.* (1989b) presented palaeomagnetic data from the Lower and Upper ORS of the Western Midland Valley, Scotland. Within the data, they argue for the presence of two components, termed **A** and **B** (Fig. 3a). Both components failed fold and conglomerate tests, and hence they were both inferred to be secondary and post-tectonic. The **A** components conformed to directional results from local Permo-Carboniferous dykes, whereas the **B** components were directionally similar to data from the subhorizontal overlying lavas of Lower Carboniferous age (Fig. 3b). From the Kinghorn area (Eastern Midland Valley), the Lower Carboniferous lava directions are shown to be primary as stratigraphically linked reversals are identified (Wilson & Everitt 1963; Torsvik *et al.* 1989b).

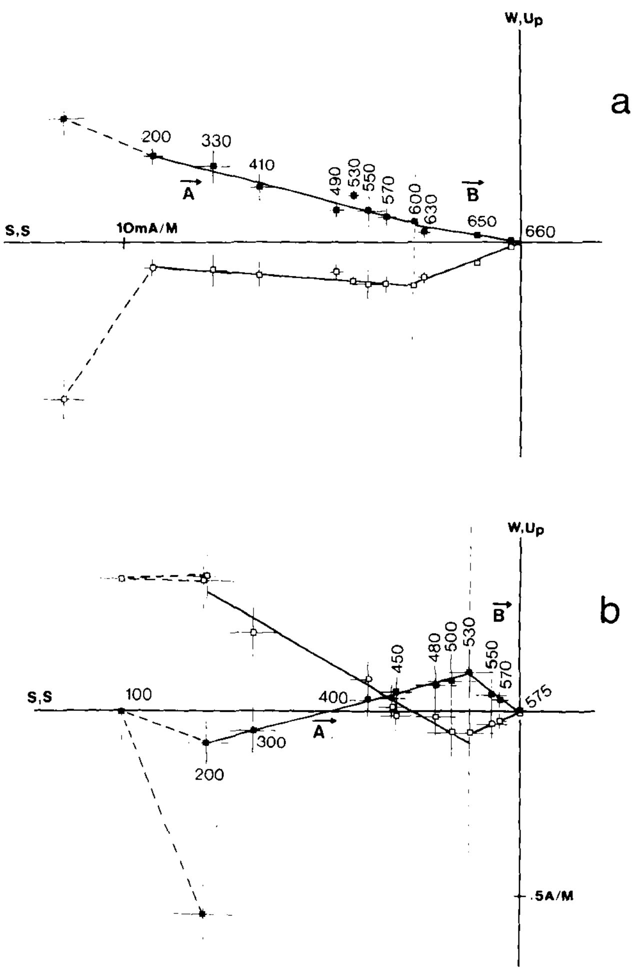

Figure 3. (a) Example of thermal demagnetization behaviour for a sample from the Lower ORS, Western Midland Valley. Components **A** and **B** [originally referred to as **IB** and **HB** by Torsvik *et al.* (1989b)] are labelled. (b) Example of demagnetization behaviour for the overlying Lower Carboniferous Lavas. The a_{95} (Briden & Arthur 1981) measurement error is included for each demagnetization step. Fitted lines are calculated from least-square analysis. N–S projection planes.

A relatively clear-cut magnetic history was therefore envisaged with:

(1) complete magnetic overprinting of the Lower/Upper ORS in Lower Carboniferous times (component **B**), followed by;

(2) partial overprinting of Lower Carboniferous lavas and ORS sediments associated with Permo-Carboniferous dyke activity (component **A**).

The high-temperature component (**B**) identified in the Lower and Upper Devonian rocks of the Western Midland Valley is difficult to estimate due to viscous behaviour at temperatures exceeding 570°–600 °C (Torsvik *et al.* 1989b). Indeed, these rocks were sampled twice and remeasured on a two-axis Squid, since in the original study of these rocks (Lyse 1987), remanence measurement with a spinner magnetometer (Digico) proved difficult at high temperatures.

The raw data for sample L283 [Fig. 4(a)—*in situ* coordinates], unfortunately not originally reported with lines connecting the order of demagnetization steps and the associated a_{95} (Briden & Arthur 1981), demonstrate the irregular directional behaviour at high temperatures. Sample L283 displays the characteristic demagnetization behaviour, and was therefore published as an example by Torsvik *et al.* (1989b). In L283, a line above 570 °C was origin-anchored (Fig. 4a). This component ($D = 222.5$, $I = 28.1$), was calculated by a least-square algorithm (Torsvik 1986), but we note that the maximum angular deviation (MAD) is high at 16.4° (Kirschvink 1980). A few samples show considerably better data-quality than L283, however, as portrayed in Fig. 3(a). In this case, the high-temperature component **B** ($D = 189°$, $I = +21°$, $MAD = 4.3°$), resident in haematite, is clearly identified above 600 °C, after removing the Permo-Carboniferous **A** component ($D = 194°$, $I = -4°$, $MAD = 3.9°$) in the 200°–600 °C range. We feel that this latter example justifies the original analysis of sample L283 (Fig. 4a).

In an attempt to argue for the presence of Mid-Palaeozoic flatlying magentization vectors, Storetvedt *et al.* (1990a) ignore the above analysis and offer a reinterpretation based upon one published example (L283) and using an improper analytical procedure (see below).

In modern palaeomagnetic studies, orthogonal vector projections, otherwise referred to as Zijderveld diagrams (Zijderveld 1967), are routinely used for presentation of stepwise demagnetization data. In these diagrams, it is implicit that breakpoints between linear segments on the horizontal and vertical projections must lie on a common perpendicular to the horizontal axis. We note that diagrams presented by Storetvedt *et al.* (1990a) do not satisfy this requirement [reproduced in Fig. 4(b) and see below].

4.2 Reinterpretation offered by Storetvedt *et al.* (1990a)

Reinterpretation of published data has many pitfalls, and unfortunately the true sequence of demagnetization steps (Fig. 4a) differs from that indicated by Storetvedt *et al.* (1990a) in their fig. 10(b). [Fig. 10(b) of Storetvedt *et al.* (1990a) is reproduced as Fig. 4(b) here.] Additionally, all diagrammatic demagnetization results published by Torsvik *et al.* (1989b) were reported in *in situ* coordinates. As the

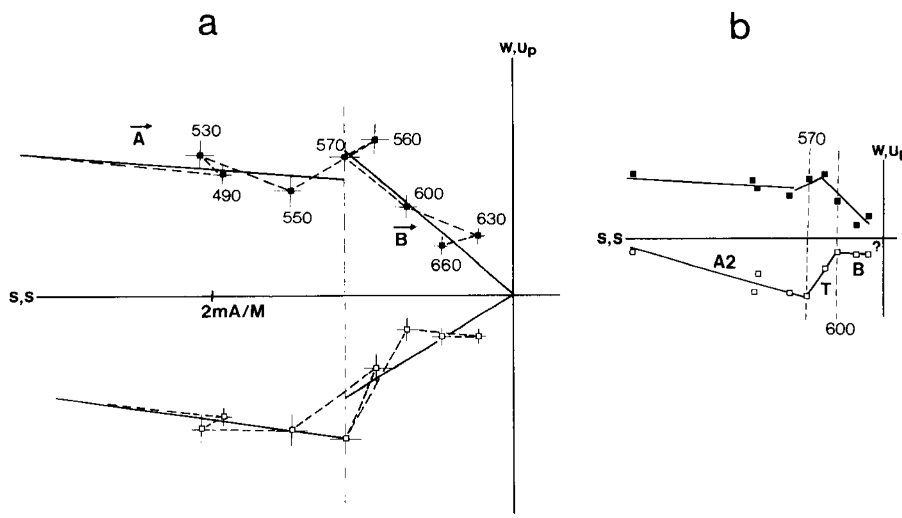

Figure 4. (a) Thermal demagnetization of sample L283 from the Lower ORS, Western Midland Valley, Data reproduced from Torsvik *et al.* (1989b), but now shown with error confidences and lines connecting the sequence of demagnetization order. (b) Reinterpretation offered by Storetvedt *et al.* (1990a) or (a). Note that their 'linear' segments or components do not have common breakpoints in the horizontal and vertical plane. In addition their reinterpretation must include a fourth high-temperature component, since the vertical part of their component **B** is not decaying toward the origin of the diagram. N–S project planes.

regional bedding for site 18 (sample L283 in Fig. 4a,b) is 320°/52°NE [see fig. 1(c) of Torsvik *et al.* (1989b)], the shallow SW directed **B** component advocated by Storetvedt *et al.* (1990a; Fig. 4b) would dip approximately 50° downwards if it was corrected for bedding.

The new interpretation offered by Storetvedt *et al.* (1990a) (Fig. 4b) of the original component **B** (Fig. 4a), divides it into two new components plus an unresolved component above 660° (?). In this interpretation, the unblocking temperatures of the horizontal (550°–560 °C), and vertical segments (570°–600 °C) of their **T** component differ, and indeed none of their new components, named **A2**, **T** and **B**, has breakpoints which correspond in both horizontal and vertical projections (Fig. 4b). We are confident that computer program failure, incidentally designed by one of us for the Department of Geophysics, University of Bergen (Torsvik 1986), cannot explain this extraordinary analysis. Indeed, figs 4(d) and (e), and 5(a) and (b) of Storetvedt *et al.* (1990a) show a similarly erratic procedure, leaving us to conclude that their analytical procedure is inadequate. We suspect that Storetvedt *et al.* (1990a) have calculated remanence components either from apparent directional stability in stereoplots, or by vector subtraction between two arbitrary selected demagnetization steps. The latter is indicated from the analysis of the **A1** component (fig. 6a–f, p. 157), all of which are defined between only two data points (NRM and 100 °C). We therefore do not consider that the **A1** component of Storetvedt *et al.* (1990a) can be reliably attributed to 'Alpine shear motions' on the Great Glen Fault as they suggest.

5 CONCLUDING REMARKS

Late Silurian and Lower Devonian palaeopoles from throughout the British Isles, both north and south of the Iapetus suture, are found to be palaeomagnetically reliable. The poles define a coherent grouping about 1°S and 314°E ($A_{95} = 9.3°$). The reasonable consistency between these pole positions implies that the Iapetus Ocean was essentially closed in Britain by Late Silurian time, and that no subsequent mega-shearing causing resolvable palaeomagnetic discrepancies occurred during either the Acadian or Hercynian orogenies (compare with Storetvedt 1987).

The collective rejection of all late Silurian–early Devonian palaeomagnetic results by Storetvedt *et al.* (1990a,b) is completely inconsistent with any reasonable method of data selection. We suggest that the criticism regarding 'incomplete and superficial remanence analyses' directed at other workers by Storetvedt *et al.* (1990a, p.161) most appropriately applies to their own data analyses.

ACKNOWLEDGMENTS

NAVF, NERC and NGU are thanked for monetary support. Dr E. McClelland reviewed a preliminary version of the manuscript. We thank an anonymous reviewer for useful comments. Norwegian Lithosphere Project no. 117.

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