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A palaeomagnetic study of the Builth Wells–Llandrindod Wells Ordovician Inlier, Wales: palaeogeographic and structural implications

Allan Trench,[1,2] Trond H. Torsvik,[1,2] Mark A. Smethurst,[2] Nigel H. Woodcock[3] and Richard Metcalfe[4]

[1] *Department of Earth Sciences, University of Oxford,* OX1 3PR, *UK*
[2] *Norwegian Geological Survey, PB* 3006, *Lade N-*7002, *Trondheim, Norway*
[3] *Department of Earth Sciences, University of Cambridge,* CB2 3EQ, *UK*
[4] *Department of Earth Sciences, University of Leeds,* LS2 9JT, *UK*

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SUMMARY

Discrepancies exist in the Southern British Ordovician palaeomagnetic data set with individual studies indicating either high southerly or temperate southerly palaeolatitudes. Although previous palaeomagnetic investigations from the Builth inlier have delineated a three-component remanence structure, doubts have been raised concerning (i) the magnetization age of the supposed 'primary' component (P); (ii) the structural setting of the sampling area (Llanelwedd quarry) within a zone of strike–slip deformation; and (iii) whether detailed step-wise demagnetization has fully separated the various magnetization components.

In addressing these problems, we present new palaeomagnetic results as follows: (i) a positive palaeomagnetic conglomerate test establishing a pre-Late Llanvirn age for component (P); (ii) an enlarged geographic sampling embracing several tectonic domains indicating that *relative* rotations linked to strike–slip tectonism are minor within the Builth sampling area; and (iii) evidence that component (P) is uncontaminated by overprints at some sites suggesting the resulting palaeolatitude of 35°S to be representative for the Builth inlier.

We also present evidence for local syn-volcanic deformation within Llanvirn volcanics and for intrusion-related deformation of Llanvirn shales.

When the revised Llanvirn pole from the inlier (3°S, 4°E) is combined with other data from Southern Britain in a statistical spline analysis, a mean palaeolatitude of 44.5°S is calculated for Builth in Llanvirn times. A palaeoreconstruction for 468–474 Ma (*c.* Mid-Llanvirn) is presented utilizing this analysis.

Key words: palaeogeography, palaeomagnetism, Southern Britain.

1 INTRODUCTION

The Ordovician palaeopositions of Laurentia and Gondwana are now reasonably constrained to equatorial-tropical and high southerly latitudes respectively, based on palaeomagnetic data (reviews by Torsvik *et al.* 1990a; Bachtadse & Briden 1990). In addition, palaeomagnetic data from Baltica suggest it moved northward from *c.* 60°S to tropical southerly latitudes during Ordovician times (Torsvik *et al.* 1990b; Torsvik & Trench 1990). The latitudinal position of Southern Britain, however, is both enigmatic and contentious. This reflects a lack of palaeomagnetic studies which employ modern detailed demagnetization experiments in combination with appropriate field tests to constrain the relative age of magnetization.

Middle Ordovician palaeomagnetic data from Southern Britain imply either mid-southerly palaeolatitudes (Briden, Turnell & Watts 1984; Briden *et al.* 1988) or somewhat higher southerly latitudes (Piper *et al.* 1978; Thomas & Briden 1976; McCabe & Channell 1990a). The dissimilar palaeolatitudes imply competing Middle Ordovician palaeogeographic scenarios with Southern Britain either forming an independent microplate in mid-latitudes, or lying proximal to Armorica/Gondwana in high latitudes. We refer to Armorica here as comprising only continental Europe (*cf.* Van der Voo 1983) as we include Southern Britain in the Avalonian terrane (McKerrow 1988; Scotese & McKerrow 1990).

In order to constrain the position of Southern Britain within the framework of the Iapetus bordering continents, we have initiated palaeomagnetic studies at several key stratigraphic levels. The present account concerns volcanics and intrusions of Llanvirn–Llandeilo age from the Builth Wells–Llandrindod Wells Ordovician Inlier, Mid-Wales (Fig. 1).

In addition to the palaeogeographic enigmas, we aimed to elucidate whether strike–slip deformation of the Builth Wells inlier (Woodcock 1987) produced palaeomagnetically detectable block rotations. Rotations about vertical axes have been linked to strike–slip tectonism on scales ranging from entire terranes to isolated fault-blocks (reviewed by Beck 1989). In this respect, Trench (1988) and McCabe & Channell (1990a) noted that detailed palaeomagnetic analyses from the Builth inlier had been restricted to the fault-bounded Llanelwedd Quarry. We therefore aimed to test for the presence of relative tectonic rotation between proposed structural domains at the southern end of the Builth Wells inlier (Woodcock 1987).

Previous palaeomagnetic investigations of the inlier undertaken by Nesbitt (1967), Piper & Briden (1973) and Briden & Mullan (1984) resulted in the recognition of three magnetization components. Briden & Mullan (1984) dated these components as of Ordovician, Permo-Carboniferous and Recent age on the basis of an agglomerate test and through comparison with reference poles. McCabe & Channell (1990a) questioned the agglomerate test suggesting

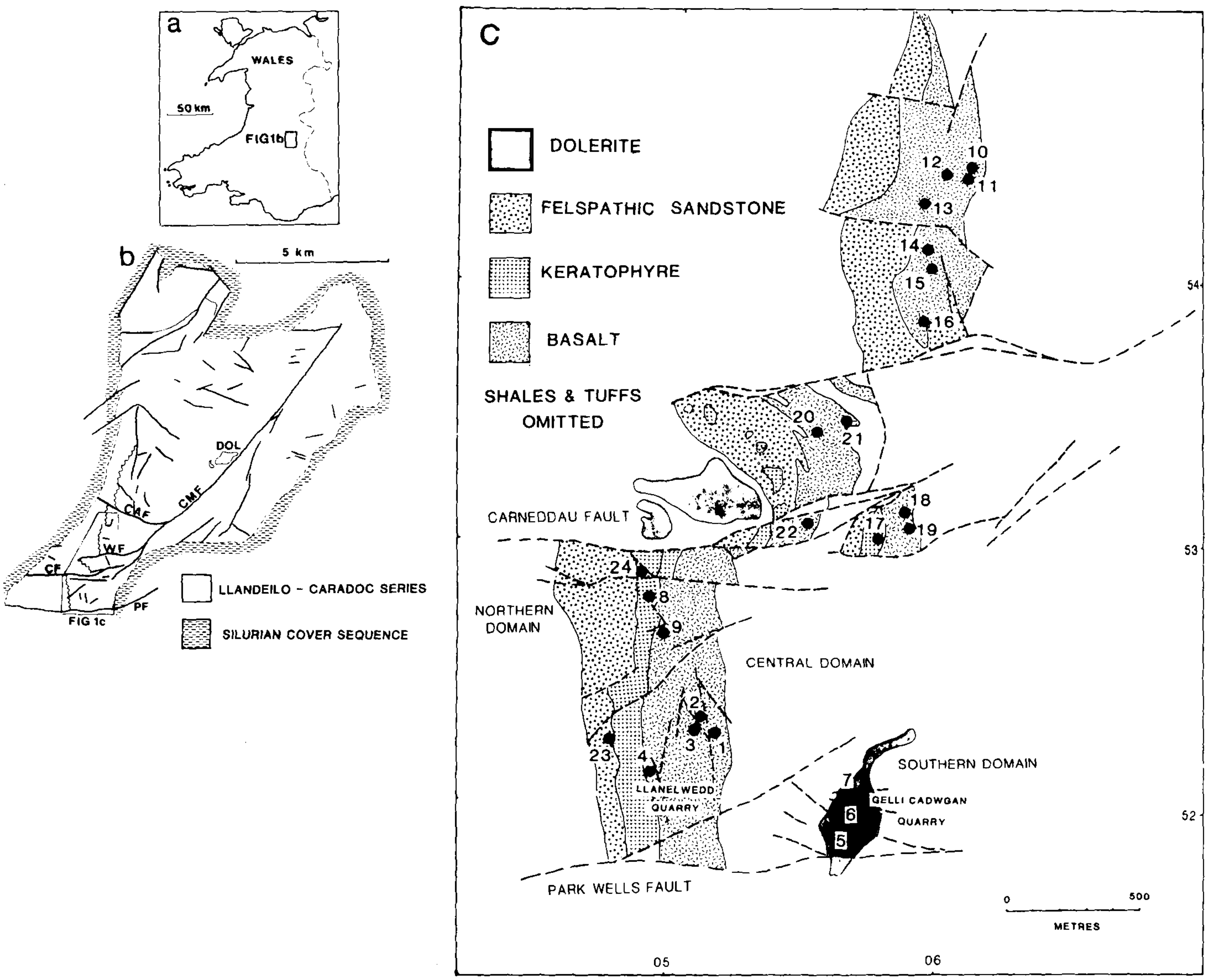

Figure 1. Location of palaeomagnetic sampling sites reported in this study. (a) Position of the Builth inlier, Mid-Wales. (b) Main structural elements of the Builth inlier. Labels are as follows; PF—Park Wells Fault, CF—Carneddau Fault, CAF—Cwmamliw Fault, WF—WernTo Fault, CMF—Cwm Mawr Fault, DOL—Blaenkerry Dolerite (Sites 25–28). Rocks of the Llanvirn series are unshaded. (c) Detailed geology of the Llanelwedd area (southern end of the inlier). Palaeomagnetic sampling sites are numbered.

it to contain some non-randomly dispersed directions. Subsequently, however, these authors present new evidence suggesting the test to be reliable (McCabe & Channell 1990b), but doubt that magnetization components have been properly isolated in previous studies of the inlier. In order to address these uncertainties, this study presents the results of a more extensive sampling of the inlier including a conglomerate test and two local fold tests.

2 GEOLOGICAL BACKGROUND

Llanvirn–Llandeilo rocks crop out over approximately 70 square kilometres of the Builth Wells–Llandrindod Wells inlier, Wales (Fig. 1b). Llanvirn volcanics and sediments are overlain by shales now thought to be entirely Llandeilo in age (Sheldon 1987). Dolerites and andesites form local, mainly concordant, intrusions which were emplaced over a considerable time period during the Mid-Ordovician (Jones & Pugh 1948; Piper & Briden 1973). The Ordovician rocks are overlain with weak angular unconformity by patchy Upper Llandovery sandstones followed by Wenlock mudstones and then Upper Silurian sedimentary rocks. Major steep faults striking mostly NE and E affect the Ordovician inlier as do local, open, NE-trending folds. The predominant dip of the Ordovician rocks is to the west however. No cleavage is developed. Some of the faults do not appear to cut the sub-Silurian unconformity (e.g. CAF and CF on Fig. 1b), and an important phase of movement on them must be pre-Llandovery (Jones & Pugh 1941). These faults show dextral strike–slip displacements of hundreds of metres or more, inferred to be of Ashgill age (Woodcock 1987). Some NE-striking faults in the northwest corner of the inlier have been reactivated in post-Silurian time as part of late Caledonian displacements along the Pontesford lineament.

The area was mapped in detail by Jones & Pugh (1941, 1946, 1948, 1949) and is covered by a 1:25 000 solid geological special sheet (Institute of Geological Sciences 1977).

Palaeomagnetic sampling was concentrated on the southern end of the inlier where the structural domains are most clearly defined, and the intradomain faults are exposed in quarry sections [Fig. 1(c), detailed in Woodcock (1987)].

3 FIELD AND LABORATORY METHODS

Individual core samples were oriented using both magnetic and sun compasses. Sun compass observations indicate a local magnetic deviation of 7° west for Builth Wells. Sites were recorded on 1:10 000 topographic sheets or detailed quarry plans (Fig. 1c). Sampling embraced spilites and keratophyres of the Llanelwedd volcanics (late Llanvirn) and dolerites which intrude Llanvirn shales at Gelli Cadwgan and Blaenkerry (Fig. 1b, c). All samples were treated by thermal demagnetization (typically 15 steps) which provides better component separation than the alternating-field method in these rocks as previously found by Briden & Mullan (1984). Magnetic moments were measured with a two-axis CCL superconducting magnetometer. Magnetic fabrics were measured using a Minisep anisotropy delineator calibrated against a Kappabridge (KLY-2). Isothermal remanent magnetizations (IRM) were imparted with a Molspin pulse magnetizer. Component analysis of demagnetization data was performed using least-squares line-fitting algorithms (Kent, Briden & Mardia 1983; Torsvik 1986) aided by visual inspection of orthogonal and stereographic projections.

4 THERMAL DEMAGNETIZATION ANALYSIS

Demagnetization experiments identify three magnetization components distinguished by their contrasting directions and unblocking temperature spectra. For clarity, we adopt the component nomenclature (**R**, **S**, **P**) used by Briden & Mullan (1984). These authors suggest the components to be of Recent, Secondary, and Primary origin respectively. The three components have discrete (non-overlapping) thermal stability in most samples, but overlap of unblocking spectra occurs at some sites. The relative contribution of each component to the total NRM varies between different lithologies.

Representative demagnetization data are shown in Fig. 2. Component site-mean data are listed in Table 1. Generally, the keratophyres display intensities of 20–60 $mA\,m^{-1}$, and the dolerites and spilitic basalts $<10\,mA\,m^{-1}$

Component R (low blocking temperatures)

Maximum unblocking temperatures approach 350 °C in the spilitic basalts but are generally less than 200 °C within the dolerites. This component is poorly developed or absent in the keratophyres. Component **R** is downwardly directed *in situ* with generally northward declinations (Fig. 2a, b) close to the Earth's present field. We interpret **R** as a viscous remanent magnetization (VRM) of Recent age and therefore do not discuss it further (see Briden & Mullan 1984).

Component S (intermediate blocking temperatures)

S generally unblocks between 250° and 470 °C (Fig. 2a, b) although a few samples display a wider range of 200°–500 °C. Unblocking temperatures occasionally overlap with **R**. Component **S** is most prominent in the spilitic basalts (e.g. Fig. 2a) and is only sporadically developed in the dolerites and keratophyres (Fig. 2b, c, d). The **S** component is southerly directed with subhorizontal to shallow–moderate negative inclination *in situ*.

Component P (high blocking temperatures)

Component **P** unblocks betweeen 350° and 580 °C for all lithologies (Fig. 2a–d). In some cases, however, most notably for the dolerites and keratophyres, **P** unblocks over a fairly discrete range between 480° and 580 °C.

Components **P** and **S** overlap in a minority of samples. At site 11, demagnetization trajectories are curved between 200° and 520 °C, and do not directly approach the origin (Fig. 3a). No stable endpoint is observed in stereographic projection (Fig. 3b) and satisfactory line-fitting was not possible. Similar behaviour was observed in some specimens from site 20 (spilitic basalt) and 25–28 (Blaenkerry dolerite). Except for the above behaviour, component **P**

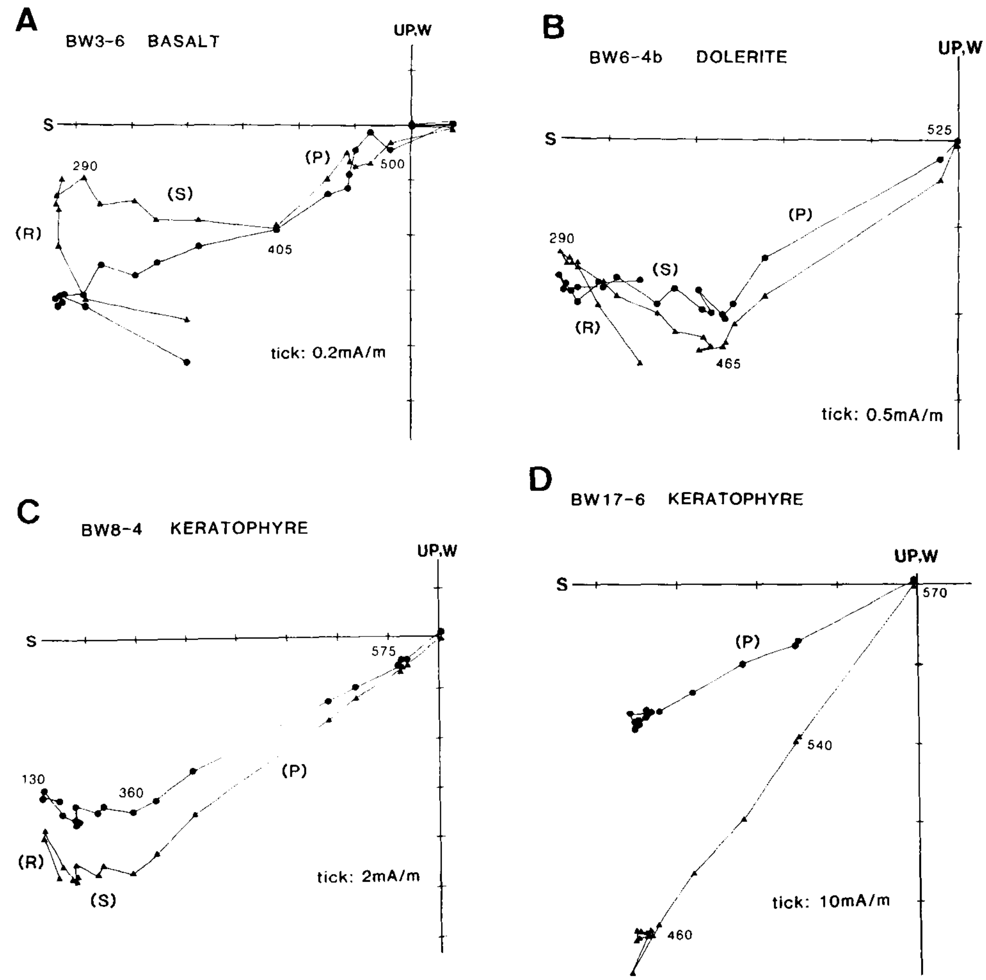

Figure 2. Representative orthogonal projections from the Builth Wells–Llandrindod Wells Ordovician Inlier. Interpreted components of NRM are labelled. In the projections, circles (triangles) represent points in the horizontal (vertical) plane. Respective lithologies are indicated. (a, b, c) Three component demagnetization with little inference between components. (d) Single component (P) demagnetization.

appears adequately resolved from **S** during demagnetization experiments where it unblocks as a linear vector and often forms the dominant component (Fig. 2c, d). We therefore find little evidence to corroborate the proposal of McCabe & Channell (1990b) that **P** is artificially shallow due to contamination by **S**.

5 MAGNETIC FABRICS, IRM ACQUISITION AND THERMOMAGNETIC ANALYSES

Anisotropy of magnetic susceptibility was determined for samples from each site. Most sites, however, proved either isotropic (i.e. gave no systematic orientation of the principal susceptibility axes), or displayed weakly developed prolate or oblate planar fabrics which did not obviously correlate with structural parameters (e.g. bedding, fault/joint orientation). The magnetic fabrics may therefore reflect local volcanic flow-related processes during emplacement.

Thermomagnetic analyses were performed on specimens of spilitic basalt, dolerite and keratophyre. Unfortunately, the paramagnetic contribution is dominant. A keratophyre example (Fig. 4e) shows a single Curie temperature approaching 560 °C. Irreversible curves suggest formation of additional magnetite through thermochemical alteration of initially non-magnetic phases.

IRM curves saturate in fields of 0.4–0.6 T for keratophyre, dolerite and basalt specimens (Figs. 4a–d). Coercivities of remanence are in the range 50–60 mT.

The IRM experiments, along with thermomagnetic analysis and thermal demagnetization studies indicate almost pure magnetite as the principal remanence carrier, most likely in a pseudo-single or single-domain state.

6 CONSTRAINTS ON MAGNETIZATION AGES

Conglomerate test

A basal conglomerate of late Llanvirn age unconformably overlies the Llanelwedd volcanics in the south of the Builth inlier (Site 23; Fig. 1c). Furthermore, the conglomerate clasts lithologically match the underlying keratophyres (Jones & Pugh 1946, 1949). Eight samples (nine specimens) were recovered from five conglomerate clasts. Demagnetization reveals single-component magnetizations which prove directionally consistent *within* individual clasts but which are randomized between clasts (Fig. 5a). Thermal

Table 1. Site-mean statistical details of components (P) and (S). Lithology Code: B—spilitic basalts, D—dolerite, K—keratophyre. No—number of samples collected at site, N—number of samples yielding specific component. k—Fisher (1953) precision parameter. a95%—cone of 95 per cent confidence about the mean direction. Site-mean statistics are quoted '*in situ*' after correction for '*local*' measured dip or for appropriate dip of the Llandeilo series which overlies the Llanvirn volcanics with '*unconformity*'.

COMPONENT P

SITE & LITHOLOGY		N/No	k	a95%	In situ Dec	In situ Inc	Local Correction Dec	Local Correction Inc	Unconformity Correction Dec	Unconformity Correction Inc
BW2	B	0/5	--	----	---	---	---	---	---	---
BW3	B	7/7	51.3	8.5	139	39	178	53	169	42
BW4	B	5/7	20.9	17.2	121	36	156	61	152	50
BW5	D	7/7	90.3	6.4	134	36	175	56	163	43
BW6	D	7/7	350.3	3.2	145	36	184	48	171	37
BW7	D	5/5	33.4	13.4	119	26	168	71	140	43
BW8	K	6/6	644.8	2.6	151	32	169	39	170	42
BW9	B	3/4	235.6	8.1	101	62	217	68	173	86
BW10	B	0/8	--	----	---	---	---	---	---	---
BW11	B	OVERLAPPING STABILITY SPECTRA					(see text)			
BW12	B	6/6	22.5	14.4	133	44	171	64	169	58
BW13	B	6/6	53.8	9.2	125	51	192	63	173	67
BW14	B	5/6(**)	399.7	3.8	308	19	306	-9	---	---
BW15	B	6/6	57.4	8.9	156	35	186	38	180	40
BW16	B	6/6	149.5	5.5	137	36	172	50	164	50
BW17	K	6/6	311.1	3.8	160	52	210	43	201	63
BW18	B	4/7	15.0	24.5	135	49	191	61	183	62
BW19	B	7/7	34.2	10.5	165	41	188	35	192	53
BW20	B	5/6	16.7	19.3	171	30	192	35	189	41
BW21	B	5/6	20.8	17.2	138	45	183	54	163	67
BW22	B	6/6	66.7	8.3	118	40	145	54	123	67
BW24	K	7/7	197.0	4.3	159	42	(186	46)^	186	46
DOLERITE FOLD TEST										
BW25	D	8/8	58.2	7.3	141	59	196	83		
BW26	D	9/9	32.1	9.2	135	66	260	85		
BW27	D	6/6	111.2	6.4	126	52	122	26		
BW28	D	9/9	169.2	4.0	127	50	128	32		

(**) Anomalous site, not used in overall statistics.
(^) Correction for sandstones stratigraphically (3m) above site rather than easterly dipping keratophyre foliation.

CONGLOMERATE TEST

		(no. of clasts)			(Resultant vector)		
BW23	KC	5/5	1.5	114.9	(271)	(6)	R = 2.20

COMPONENT S

SITE	N/No	k	a95%	In situ Dec	In situ Inc
BW2	4/5	46.7	13.6	184	-6
BW3	1/7	----	----	164	-12
BW4	2/7	58.9	33.2	198	-31
BW5	1/7	----	----	190	-30
BW6	6/7	38.9	10.9	181	-30
BW7	0/5	----	----	---	---
BW8	5/6	60.1	9.9	208	-41
BW9	0/4	----	----	---	---
BW10	4/8	57.9	12.2	173	-13
BW11	OVERLAPPING STABILITY SPECTRA				
BW12	0/6	----	----	---	---
BW13	6/6	70.7	8.0	183	-4
BW14	0/6	----	----	---	---
BW15	0/6	----	----	---	---
BW16	0/6	----	----	---	---
BW17	0/6	----	----	---	---
BW18	2/7	40.6	40.3	179	-9
BW19	3/7	213.7	8.5	185	-15
BW20	5/6	252.7	4.8	184	-14
BW21	1/6	----	----	206	-3
BW22	6/6	83.2	7.4	183	-13
BW24	0/7	----	----	---	---
BW25	8/8	6.8	22.9	184	-1
BW26	5/9	14.9	20.9	187	2
BW27	5/6	12.3	22.8	174	-5
BW28	4/9	6.7	38.5	175	5

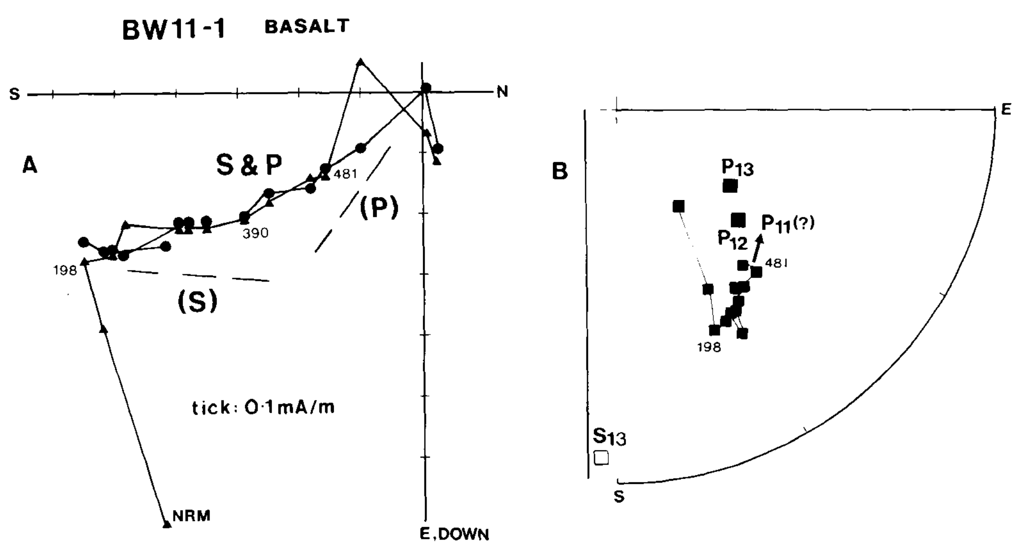

Figure 3. Overlapping stability spectra of components (S) and (P) at Site 11. (a) Orthogonal projection symbols as Fig. 2. The approximate 'uncontaminated' vertical projections of (S) and (P) are 'dashed'. (b) Stereographic projection of demagnetization data from sample BW11-1 showing that no stable endpoint is reached. P11?; true 'uncontaminated' P direction for Site 11. P12 and P13 are '*in situ*' site-mean directions from Sites 12 and 13 within the same fault-block. S13 is the Site 13 mean (S) direction.

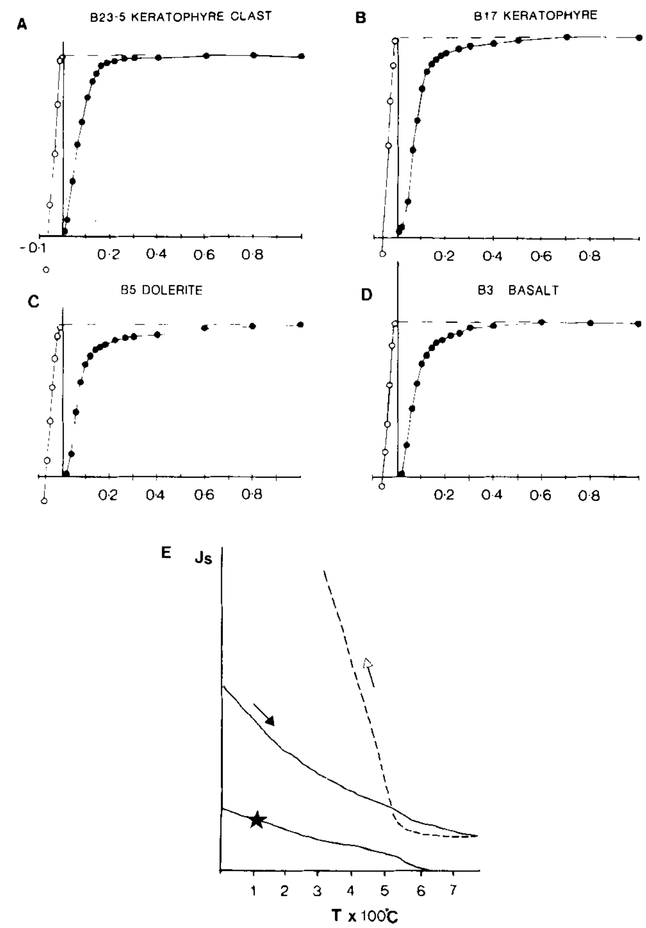

Figure 4. (a–d) IRM acquisition determinations (closed circles) for representative samples (intensity of remanence; *y* axis, magnetizing field; *x* axis). Approximate saturation level is 'dashed' for each sample. Open circles represent 'back-field' measurements to determine remanence coercive force. (e) Saturation magnetization versus temperature curve for a sample of keratophyre. Heating (cooling) curve is depicted by a solid (dashed) line. Samples were heated in air. 'Starred' heating curve is corrected for paramagnetic contribution. Magnetization scale is arbitrary.

unblocking spectra are similar to those of the underlying keratophyre in which component **P** is the predominant component (*cf.* Figs 2d, 5b–d). The site mean statistics for the conglomerate (Table 1, Site BW23) are not significant at 95 per cent confidence (Watson 1956) indicating a positive conglomerate test. Component **P** therefore pre-dates deposition of the conglomerate which is of late Llanvirn age.

Local fold tests

Two fold tests are described from a keratophyre (Sites 8 and 24) and a dolerite (Sites 25–28) which are locally deformed. Unfortunately, doubts exist on the origin of this folding. In the case of keratophyre, syn-volcanic or flow folding has been suggested to explain changes in the attitude of its foliation (Furnes 1978) whereas the dolerite may have deformed surrounding sediments during intrusion (Jones & Pugh 1946).

Only if these hypotheses prove incorrect therefore, could a primary magnetization pass the fold test. In the absence of other field tests, a negative test would remain ambiguous in that either remagnetization or flow-folding/intrusion processes would explain the data.

Thermal demagnetization of the keratophyre revealed components **R**, **S** and **P** at Site 8 but only component **P** at Site 24. A fold test was therefore only possible for component **P**. Stepwise unfolding (Fig. 6) indicates optimum clustering at 30 per cent unfolding with *in situ* statistics better grouped than fully corrected. Given the conglomerate test evidence for a primary origin of **P**, we interpret this to indicate a syn-volcanic origin for folding.

Components **S** and **P** from the Blaenkerry dolerite fail the fold test at the 95 per cent confidence level McElhinny (1964) suggesting that they were acquired after the deformation of the surrounding sediments (Fig. 7, only component **P** is shown). Once again, given the independent evidence for the primary nature of **P**, we interpret this to indicate intrusion-related deformation (see Jones & Pugh 1946).

Summary of field tests

Component S

Component **S** fails the agglomerate test of Briden & Mullan (1984), the dolerite fold test, and always displays the lower thermal stability range when coexisting with component **P**. The *in situ* remanence declination/inclination (184/−13, Fig. 8a, Table 1) corresponds to a pole at 44°S, 351°E close to Permo-Carboniferous results from Southern Britain (Fig. 8b). In agreement with Briden & Mullan (1984), we therefore suggest that component **S** is a Permo-Carboniferous overprint (*c.* 290 Ma).

Post-emplacement low-grade regional metamorphic temperature estimates for the Llanvirn volcanics and shales are of the order of 200 °C (Metcalfe 1990). These temperatures cannot be accounted for solely through Ordovician burial as Llandeilo–Ashgill stratigraphic thicknesses only total *c.* 2 km (Williams *et al.* 1972; Smith & George 1961). Furthermore, the Llandovery–Ludlow sequence which unconformably overlies the Builth Inlier has also experienced palaeotemperatures of 190°–300 °C (Conodont alteration index 4; Aldridge 1986). The geological evidence therefore suggests a post-Silurian event caused the regional metamorphic assemblage observed in the Builth volcanics. We note that a palaeotemperature of 250 °C, when sustained for a 10 Ma period, may produce laboratory unblocking temperatures of approximately 400 °C in a magnetite assemblage (Pullaiah *et al.* 1975). Should such an event have imparted component **S**, then a Permo-Carboniferous origin linked to a period of heating coincident with Hercynian deformation (south of the inlier) is indicated. A partly thermochemical origin is likely however, as a purely thermal overprint would not produce overlapping unblocking spectra (Fig. 3).

Component P

The above field tests for component **P**, when combined with the previously performed agglomerate test, are schematically illustrated in Fig. 9. The stratigraphic levels of the positive conglomerate/agglomerate tests confirm that the

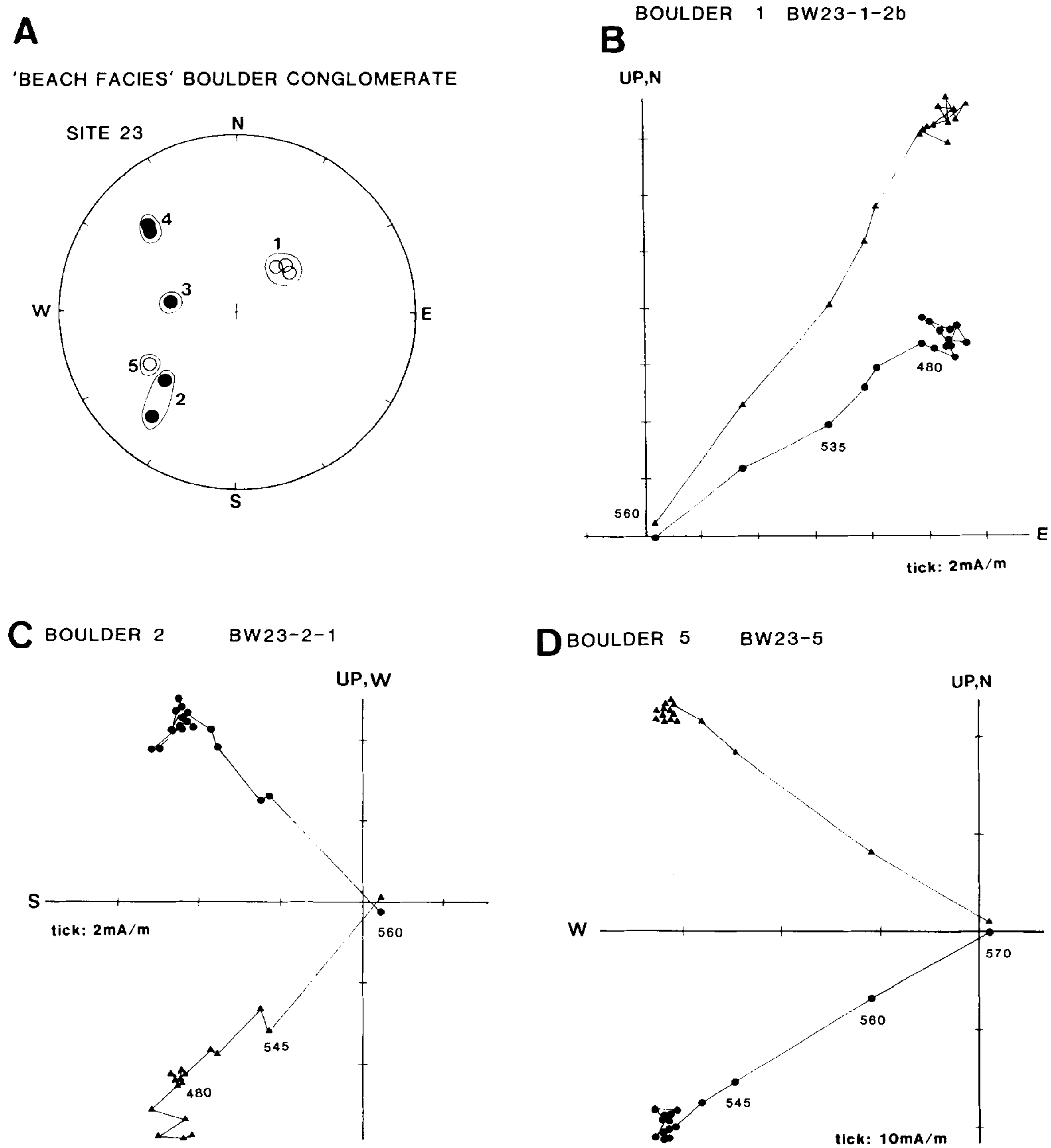

Figure 5. Positive conglomerate test on Keratophyre boulders from the Newmead Sandstone Conglomerate. (a) Stereographic projection. Open (closed) circles refer to projection on the upper (lower) hemisphere. Directions from the same clast are enclosed. (b, c, d) Orthogonal projections of clast demagnetization data showing randomly oriented single components. Symbols as Fig. 2.

keratophyre and dolerite 'folds' must relate to flow-folding and intrusion-related deformation respectively.

In analysing component **P** therefore, we must account for the local dip at the sites, but it is desirable to avoid the effects of syn-volcanic tectonism leading to erroneous structural corrections. This can be achieved as the strata above and below the late Llanvirn unconformity have equivalent westward dips (Jones & Pugh 1948). In addition to the bedding at the site therefore, measurements were made immediately above the late Llanvirn unconformity (Felspathic Sandstones, Fig. 1c).

In fact, either a 'local' or 'unconformity' correction to component **P** site-means makes scant difference (Fig. 10b, c, Table 2) giving overall directions of *Dec.* 182, *Inc.* +53 and *Dec.* 171, *Inc.* +54, respectively. As the latter correction is independent of possible syn-volcanic effects, we have used the 'unconformity' correction to calculate a mean south pole at 3°S, 4°E. Component **P** data from sites 25–28 (Blaenkerry Dolerite) were excluded however as no reliable structural correction could be determined.

7 STRUCTURAL CONSIDERATIONS AND STRIKE-SLIP ROTATIONS

Rotations can be considered on a number of different scales. First, the sampling has been designed to determine internal

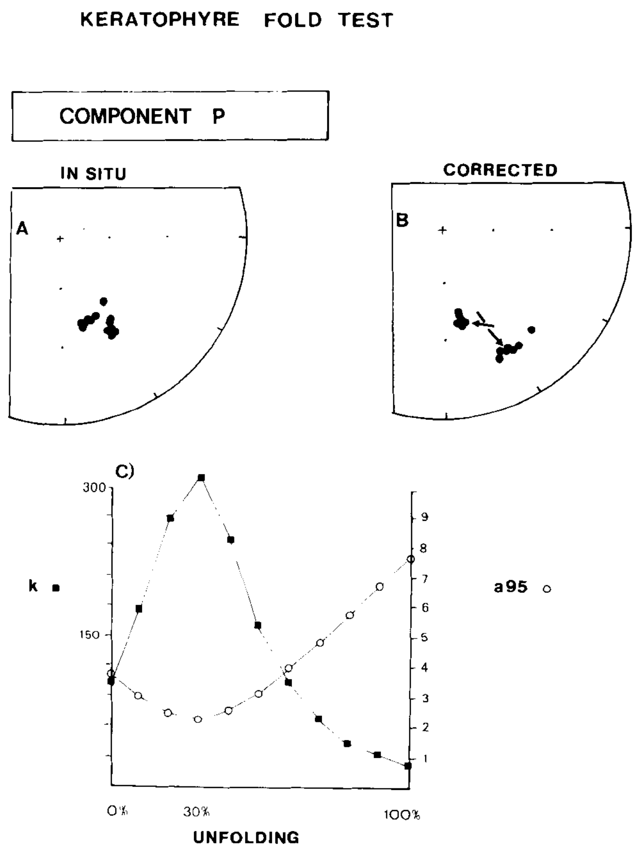

Figure 6. *In situ* (a) and structurally corrected (b) component (P) directions from the Keratophyre at sites 8 and 24. Structural correction is for local 'folding' of the keratophyre foliation. (c) Variation of Fisher (1953) statistical parameters with incremental tilt correction. Squares (open circles) depict precision parameter (α_{95}).

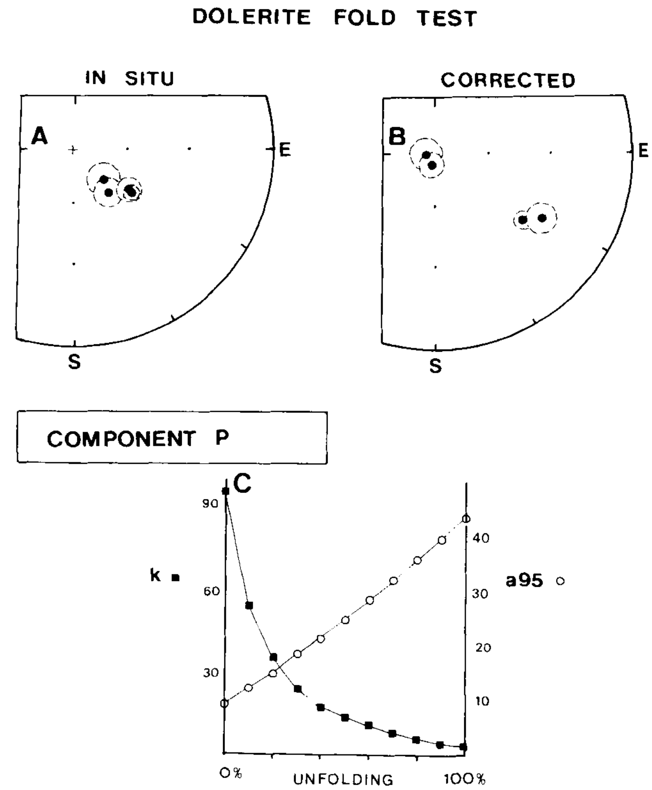

Figure 7. (a) *In situ* and (b) structurally corrected (P) component site-mean directions and cones of 95 per cent confidence from the Blaenkerry dolerite. (c) Variation of Fisher (1953) statistical parameters with incremental tilt correction. Squares (open circles) depict precision parameter (α_{95}). Structural correction is performed using bedding from surrounding sediments.

structural rotations within the Builth inlier (Figs 1c, 11). Second, a directional comparison can be made between component **P** from Builth and near contemporaneous results from the Shelve inlier (McCabe & Channell 1990; Trench & Torsvik 1990). Third, we can consider the overall rotation of Southern Britain as deduced from palaeomagnetic data for Ordovician–Devonian times.

Component **P** site-level declinations are shown in Fig. 11 after 'local' structural correction. We note that no relative block rotations are fully resolved above the 95 per cent confidence limits. This observation significantly reinforces the structural reliability of the mean pole and invalidates criticism of the Builth data as drawn from a single rotated block (Trench 1988; McCabe & Channell 1990a).

Some scatter within the site-level data probably has a structural origin however. For example, spilites within an extensional duplex (Site 22, Fig. 11a) may have undergone anticlockwise rotation associated with duplex shunting (Woodcock & Fischer 1986) along the dextral Carneddau fault [see figs 3 and 9 of Woodcock & Fischer (1986)].

Comparison of the magnetization directions from Builth Wells (171/+54, $\alpha_{95} = 7°$) with results from the Shelve inlier (116/+68, $\alpha_{95} = 5°$; Stapeley volcanics, McCabe & Channell 1990a, 119/+52, $\alpha_{95} = 9°$; Shelve intrusions, Trench & Torsvik 1990) reveals a significant rotation. However, a kinematic interpretation is hampered by the difficulties in establishing a Mid-Ordovician reference direction. As the Builth sampling sites (Fig. 1b, c) fall within a broad zone of distributed shear bounded by dextral faults (i.e. Cwmamliw Fault, Wern-To Fault, Carneddau Fault, Park Wells Fault), clockwise rotation of all the Builth domains with respect to Shelve could be explained by the rotation between these faults (Fig. 11b). However, the Shelve inlier has itself been subjected to strike–slip tectonism (Lynas 1988), and cannot be considered as unrotated. For the present, we note that the kinematic model of Fig. 11(b) can be tested by an extended palaeomagnetic sampling.

Despite the above complications, all Ordovician poles plot east of their Silurian and Devonian counterparts (Fig. 8b). This indicates counterclockwise rotation of Southern Britain from Ordovician to Early Devonian times (Briden *et al.* 1984; Torsvik *et al.* 1990a).

8 THE INCLINATION DISCREPANCY BETWEEN THE BUILTH AND SHELVE ORDOVICIAN INLIERS

A significant inclination difference is evident between palaeomagnetic results from volcanics of the Builth and Shelve inliers. The Builth and Shelve volcanics yield palaeolatitudes of 34°–35°S (Briden & Mullan 1984, this study) and 51°S respectively (McCabe & Channell 1990a). Structural correction of dual polarity data from the Shelve

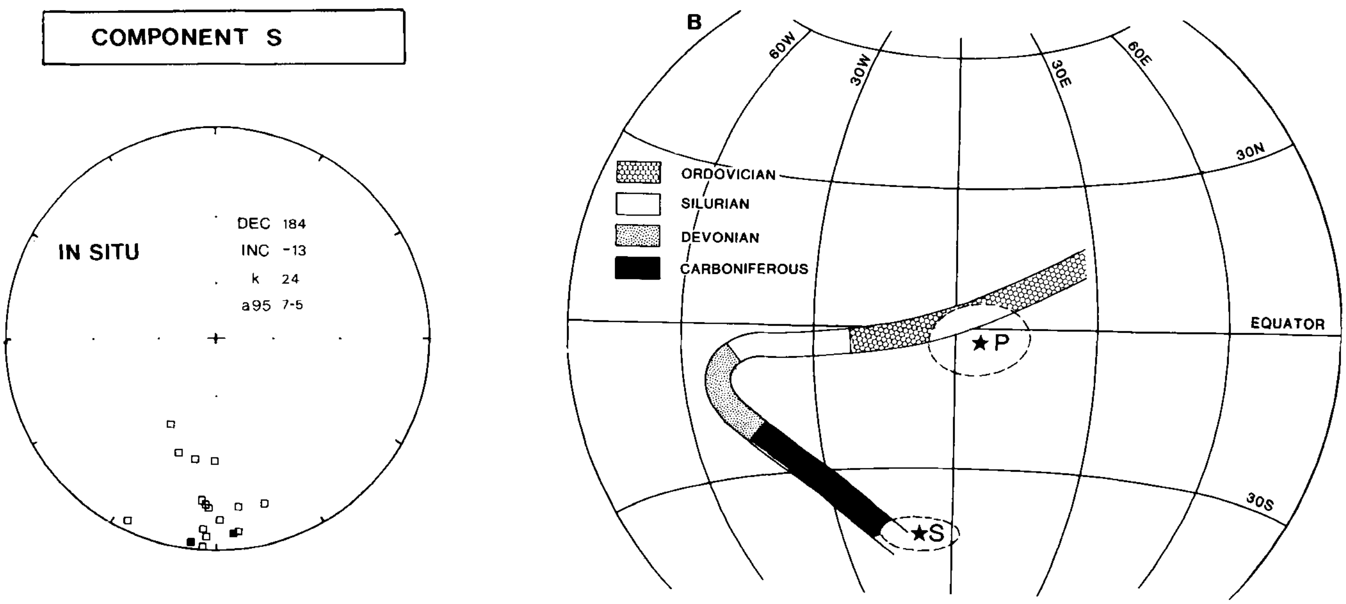

Figure 8. (a) Stereographic projection of component (S) site-mean directions plotted in '*in situ*' coordinates. Open (closed) symbols refer to projections on the upper (lower) hemisphere. (b) Palaeomagnetic pole positions for component (P) (unconformity correction) and component (S) plotted on a smoothed apparent polar wander path for Southern Britain. Approximate age segments of the Southern British path are indicated.

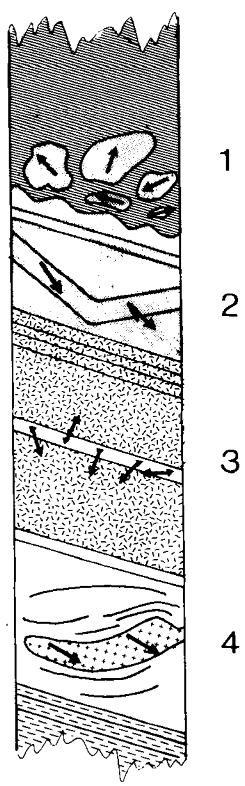

Figure 9. Schematic illustration of component (P) palaeomagnetic field tests related to stratigraphy. Field tests are numbered as follows: (1) positive conglomerate test, keratophyre boulders; (2) late-syn- to post-folding acquisition with respect to a stratigraphically constrained local structure deforming the keratophyre foliation; (3) positive agglomerate test (Briden & Mullan 1984; McCabe & Channell 1990b); (4) negative 'fold' test from the Blaenkerry Dolerite.

intrusions produces a mean palaeolatitude of 32°S (Trench & Torsvik 1990). The origin of the inclination disparity in the volcanic data is enigmatic. Opposing viewpoints have been forwarded as follows.

(i) Trench & Torsvik (1990) observed that reversely magnetized sites from the Shelve intrusions (Piper 1978) were significantly steeper than their normal polarity counterparts following structural correction. As McCabe & Channell (1990a) had obtained only reversely polarized sites from the Stapeley lavas, Trench & Torsvik (1990) argued for a bias towards steep inclinations in the Stapeley lava data.

(ii) McCabe & Channell (1990b) suggested that component (P) has yet to be completely isolated from the Builth inlier. They suggest that contamination by the shallower (S) component may have resulted in an artificially low mean inclination for the Builth inlier. In the present study, overlap of components (S) and (P) has been observed at site 11 (Fig. 3), which was excluded from further analysis. McCabe & Channell (1990a) further contended that the asymmetry in the Shelve intrusion data might be the result of Ordovician APW.

A conciliatory explanation involving parts of (i) and (ii) can be developed when the relative ages of the Shelve and Builth volcanics are considered. Although both suites were erupted during Llanvirn times, the former date from the *D. artus* Zone (Early Llanvirn, Williams *et al.* 1972) whereas the latter occur late within the *D. murchisoni* Zone (Late Llanvirn, Williams *et al.* 1972; IGS 1977). Part of the inclination discrepancy may therefore reflect the northward drift of Southern Britain over this time period (Trench, Torsvik & McKerrow 1991).

In conclusion therefore, it is possible that despite the above uncertainties, the palaeomagnetic inclinations from both the Builth and Shelve inliers are reliable. This scenario

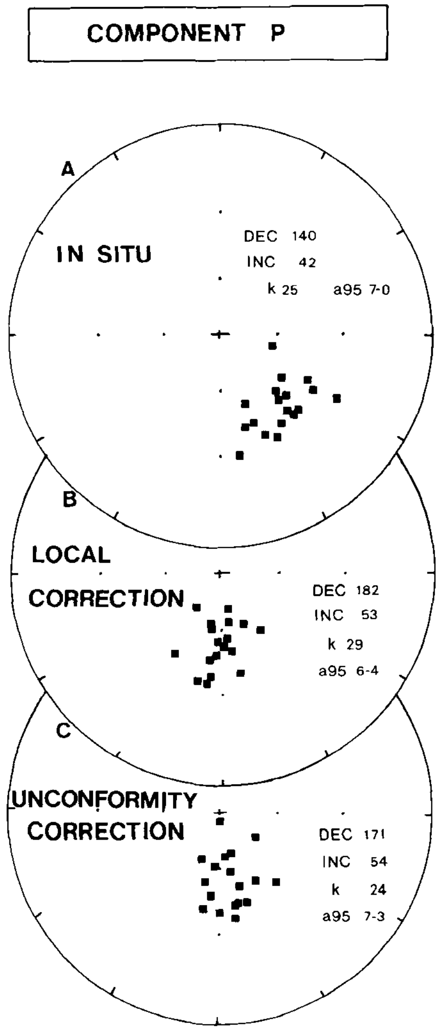

Figure 10. Stereographic projections showing site mean component (P) directions (a) *in situ*, (b) corrected for 'locally' determined dips (site 24 corrected for dip of sandstones immediately overlying the site rather than the keratophyre foliation) and (c) corrected for appropriate dips of the Llandeilo series unconformably overlying the respective sites. All sites plot in the lower hemisphere.

Table 2. Palaeomagnetic pole positions and overall statistics for components (P) and (S). N—number of palaeomagnetic sites used in calculation, Dec—mean declination, Inc—mean inclination, a95%—apical half angle of cone of 95 per cent confidence about mean direction, Lat & Long—latitude and longitude of pole position, dp & dm—semiaxes of the oval of 95 per cent confidence about the pole position.

	N	DEC	INC	k	a95%	Lat	Long(E)	dp	dm
COMPONENT P.									
'In situ'	18	140	42	25	7.0	-6	32	5	9
'Local' Correction	18	182	53	29	6.4	-4	355	6	9
'Unconformity' Correction	18	171	54	24	7.3	-3	4	7	10
COMPONENT S.									
'In Situ'	17	184	-13	24	7.5	-44	351	4	8

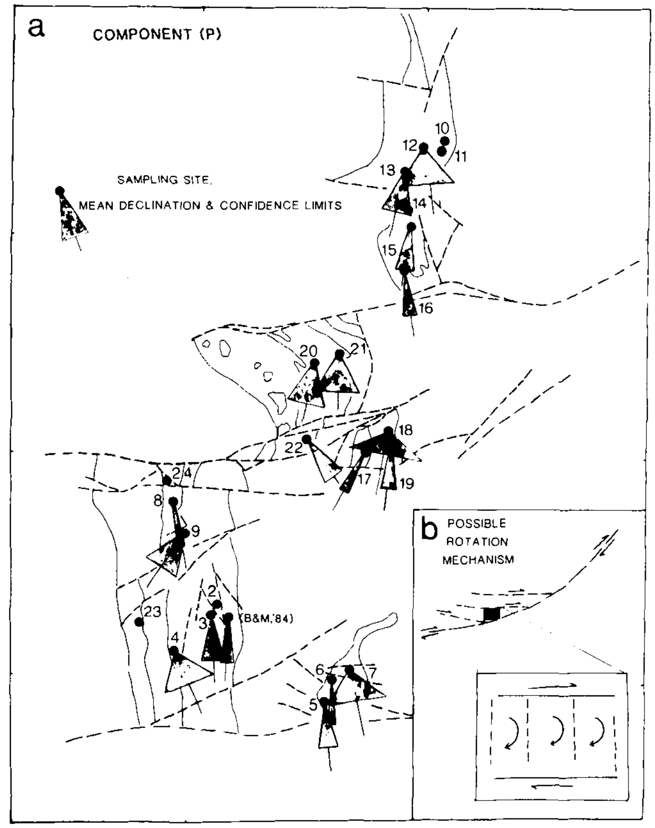

Figure 11. (a) Palaeomagnetic declinations and associated 95 per cent confidence limits for component (P) following 'local' structural correction. Geological base map and scale is as Fig. 1(c). Confidence limits calculated using the method of Beck (1980). Previous results of Briden & Mullan (1984, 49 samples) are shown within Llanelwedd Quarry. (b) Inset: postulated structural model to explain clockwise rotation of structural domains between E–W-trending dextral splay faults.

envisages the volcanics and intrusions of each inlier to temporally record the northward drift of Southern Britain during Ordovician times. That is, the Shelve volcanics (51°S), were magnetized prior to the reversely magnetized Shelve intrusions (45°S), the Builth volcanics and intrusions (35°S), and finally, the normally magnetized Shelve intrusions (26°S).

9 PALAEOGEOGRAPHIC IMPLICATIONS

The component **P** inclination of 54° yields a palaeolatitude of 34.5°S which compares favourably with a previous estimate of 35°S (Briden & Mullan 1984) based upon more limited sampling of the inlier. To facilitate comparison with other palaeocontinents, the Builth data were combined with other reliable palaeomagnetic results from Southern Britain to compute a time-calibrated apparent polar wander path (Fig. 8b). At present, the trend of the path is better constrained than its absolute time-calibration, however, given the likelihood that unrestored local rotations may have affected some poles (e.g. Builth inlier versus Shelve inlier).

In the updated Southern British APWP, Mid-Ordovician poles from the Shelve volcanics (McCabe & Channell

1990a), Shelve intrusions (Trench & Torsvik 1990), structurally reinterpreted and recalculated data from the Carrock Fell Gabbro, Binsey and High Ireby volcanics (Harris & Dagger 1987; Trench & Torsvik 1991), the Borrowdale volcanics (Faller, Briden & Morris 1977) and Tramore volcanics (Deutsch 1980) were incorporated. Data from only two studies were omitted from the APWP analysis. We consider that the results from the North Wales intrusions (Thomas & Briden 1976) record either an anomalous field (as originally proposed), or represent unresolved multicomponents. Data from minor intrusions in NW England (Piper *et al.* 1978) are based on inadequate demagnetization experiments given that a high proportion of NRM persists following 'demagnetization'.

Palaeomagnetic poles were attributed magnetic ages depending on available stratigraphic constraints in each case. Component **P** was assigned a magnetic age of 468 Ma, equivalent to the Llanvirn–Llandeilo boundary on the time-scale of Harland *et al.* (1982). Spherical spline analysis of these data yields a model palaeolatitude of 44.5°S for Builth Wells at 468 Ma corresponding to a pole at 12°N, 23°E. The difference between the measured and model palaeolatitude for Builth is difficult to explain and may indicate the resolution power to be expected of Palaeozoic palaeomagnetic studies.

A plate reconstruction using the 468–474 Ma APWP pole for Southern Britain is given in Fig. 12. Other continents have been positioned using time-equivalent mean palaeomagnetic poles as follows; Laurentia and Northern Britain (combined pole, 22°S, 19°E, Torsvik *et al.* 1990, 1991), Baltica (21°N, 32°E, Torsvik *et al.* 1991, combined path X and Y), Armorica (33°N, 345°E, Torsvik *et al.* 1990a), Gondwana (34°N, 7°E, Van der Voo 1988). We note the following points.

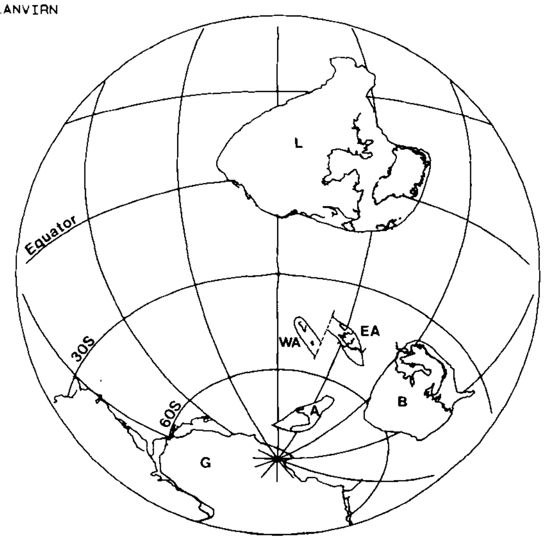

Figure 12. Palaeogeographic reconstruction for Llanvirn times. Continents are positioned using mean poles from time-calibrated APWP's listed in Torsvik *et al.* (1990) and Bachtadse & Briden (1990). The new pole from the Builth Wells Ordovician Inlier (this contribution) has been incorporated in the calculation of a mean 468 Ma pole for Southern Britain. L—Laurentia, WA—Western Avalonia, EA—Eastern Avalonia (Southern Britain), B—Baltica, G—Gondwana.

(1) Southern Britain was latitudinally separate from both Armorica and from the North African margin of Gondwana by Mid-Ordovician times.

(2) Baltica and Southern Britain both lay in mid-southerly latitudes. This scenario envisages the intervening Tornquist Sea to close by the continental scale rotation of Baltica.

(3) Mid-Ordovician separation across the British sector of Iapetus (*c.* 30° of latitude) is greater than previously estimated using APWP analyses (see Briden *et al.* 1984, 1988; Torsvik *et al.* 1990).

The Early Ordovician (Tremadoc–Arenig) palaeoposition of Southern Britain remains unconstrained by palaeomagnetic data. This needs to be rectified before the exact peri-Gondwanide origin of Southern Britain in Cambro-Ordovician times (McKerrow 1988) can be located.

10 CONCLUSIONS

Llanvirn volcanics and comagmatic dolerite intrusions of the Llandrindod Wells–Builth Wells inlier, Wales, display a multivectorial NRM. Three components are identified by their contrasting unblocking temperature spectra. Overlap of stability spectra occurs in a minority of the samples studied. Component **P** pre-dates the deposition of latest Llanvirn sediments as evidenced by a positive conglomerate test. Component **S** is interpreted as an overprint of Permo-Carboniferous age. Component **R** forms a viscous remanence of Recent age.

A comparison of Llanvirn palaeomagnetic results from the Builth and Shelve inliers indicates a significant discrepancy in both declination and inclination. The inclination discrepancy may be reduced if northward drift of Southern Britain during Llanvirn times is considered (Shelve 51°S, early Llanvirn; Builth 35°S, late Llanvirn). The declination discrepancy most likely has a predominantly structural origin (Fig. 11b), although a slight rotation during Llanvirn times might be expected from the Southern British apparent polar wander path (Fig. 8b).

Comparison of all reliable Middle Ordovician poles from Southern Britain with coeval poles from other palaeocontinents produces the reconstruction in Fig. 12.

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