A high southerly palaeolatitude for Southern Britain in Early Ordovician times: palaeomagnetic data from the Treffgarne Volcanic Formation SW Wales

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SUMMARY

A palaeomagnetic pole is reported from late Tremadoc–early Arenig volcanics of the Treffgarne Volcanic Formation, southwest Wales. This pole, located at N56°, E306° ($dp/dm = 9/10$), implies that Southern Britain was positioned at $c.\,60°$S during Early Ordovician times. These data are considered palaeomagnetically reliable based upon a positive intraformational conglomerate test. Comparison with palaeomagnetic results from the southern Laurentian margin suggests the intervening Iapetus Ocean to have reached a width of at least 5000 km at this time.

A partial magnetic overprint of Hercynian age is also identified (pole: S42°, E346°, $dp/dm = 5/9$) and is correlated with similar remagnetization features across southern and central Wales. Geological indicators of palaeotemperature in the south/central Welsh Basin most likely reflect a Hercynian thermochemical pulse.

Key words: Iapetus Ocean, Ordovician palaeomagnetism, Treffgarne Volcanics, Wales.

1 INTRODUCTION

Recent studies of Middle Ordovician rocks from Southern Britain (McCabe & Channell 1990; Trench & Torsvik 1991) suggest a greater latitudinal separation from the Northern British terranes than previously indicated by palaeomagnetic data (e.g. Briden, Morris & Piper 1973; Piper 1979). The Middle Ordovician data set across Britain now implies that the Iapetus Ocean had a latitudinal width of $c.\,30°$ at this time. The latter estimate concurs with faunal interpretations of oceanic separation (Cocks & Fortey 1982, 1990). However, no reliable palaeomagnetic results exist for Early Ordovician times, the time of maximum faunal diversity (McKerrow & Cocks 1976, 1986). The present study was therefore initiated in an attempt to remedy this point and describes a palaeomagnetic survey of the Early Ordovician Treffgarne Volcanic Formation, SW Dyfed, Wales.

2 GEOLOGICAL BACKGROUND AND PALAEOMAGNETIC SAMPLING

The Treffgarne Volcanic Formation (TVF) is of late Tremadoc to early Arenig age (Traynor 1988; Fortey & Owens 1987, 1990) and forms the local base of the Gwynedd Supergroup in the southern Welsh Basin (Woodcock 1990). The volcanics are most likely of volcanic arc affinity and have been tentatively correlated (Traynor 1988) with the Rhobell Volcanic Complex in the central part of the basin (Kokelaar 1979; Kokelaar et al. 1984).

The type section of the TVF is exposed at Treffgarne Gorge, approximately 8 km North of Haverfordwest, Dyfed (Fig. 1). The TVF comprises andesitic lavas, which are overlain by volcaniclastic and epiclastic sediments. A total of 15 palaeomagnetic sites were sampled within quarries along the A40 (Fig. 1). Sites 1–3 comprise coarse-grained sandstones and purple laminated mudstones. Sites 4–7 are from bedded volcaniclastic deposits. Site 7 embraces a boulder conglomerate containing clasts of the underlying andesites (Thomas & Cox 1924). Sites 8–15 represent andesite lavas.

The volcanics and sediments dip to the north/NNE at between 20° and 40° over the sample section. Within the volcanics, a finely spaced jointing and weak foliation is observed which broadly parallels bedding in the overlying sediments. However, whilst the attitude of the jointing varied substantially within each site, the remanence directions proved unaffected by these changes. Lava sites (8–15) were therefore structurally corrected using the
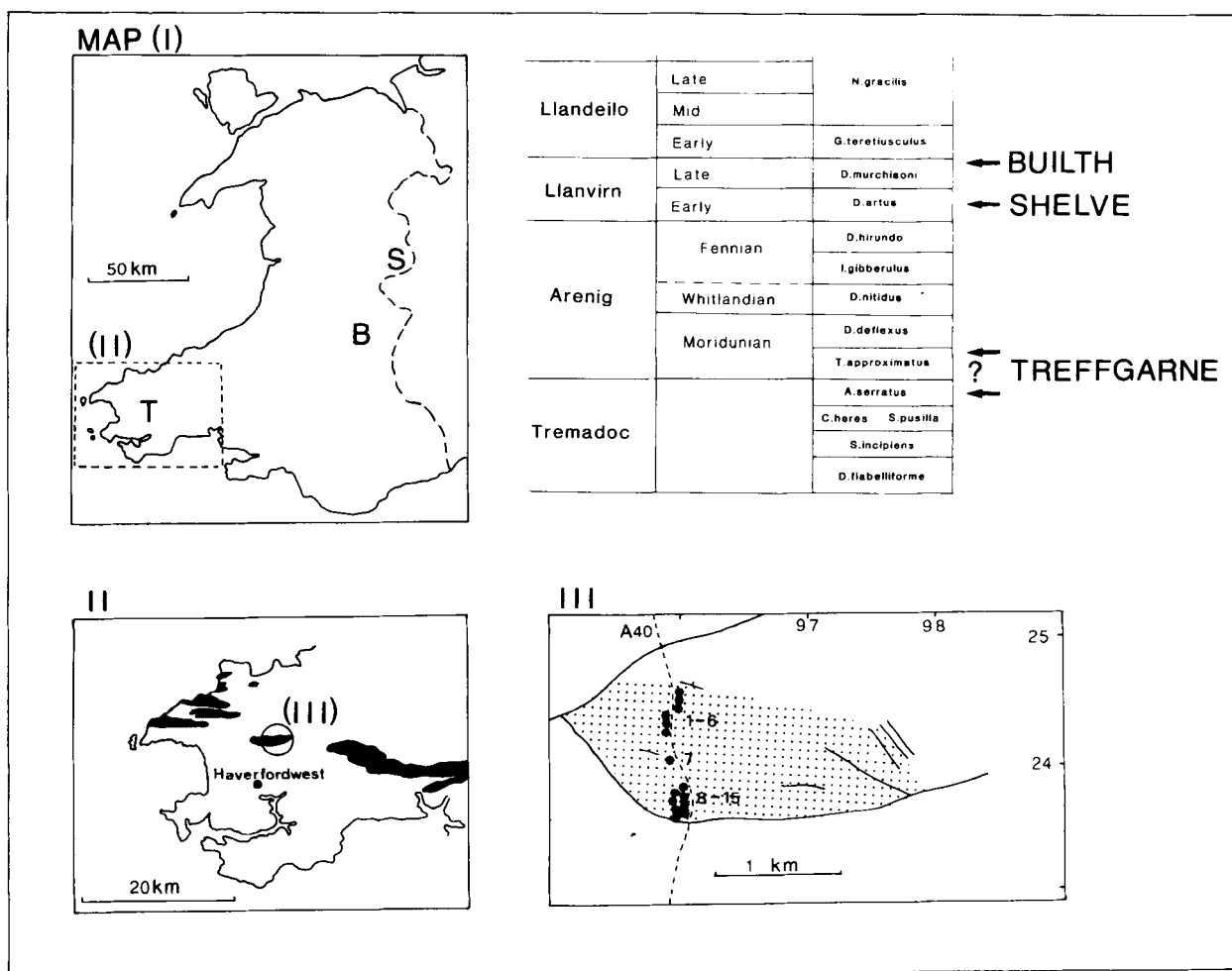
Figure 1. Location and stratigraphic position of the Treffgarne Volcanic Formation, SW Wales. Key to maps is as follows; Map (I) Ordovician Inliers referred to in the text, T—Treffgarne, B—Builth Wells, S—Shelve. Map (II), Tremadoc–Arenig outcrops in SW Dyfed, Treffgarne locality is encircled. Map (III) Treffgarne Volcanic Formation (shaded, after Traynor 1988) and palaeomagnetic sampling sites. Inset: relative Ordovician stratigraphy of volcanic inliers. Arenig stages from Fortey & Owens (1987).

average dip from the overlying beds. Northward tilting of the TVF occurred either during Acadian (Woodcock *et al.* 1988) or Hercynian deformation (Hancock, Dunne & Tringham 1981). Metamorphism is low-grade (anchizone) with palaeotemperatures in the order of 200°–300 °C (summarized by Oliver 1988).

3 FIELD AND LABORATORY METHODS

Individual core samples were oriented using a magnetic compass. Bearings were later corrected for a local deviation of 7° west at the sampling site. Samples were treated using stepwise thermal demagnetization. The alternating-field method had earlier failed to achieve a satisfactory cleaning of directions (Almond 1971; described in Morris *et al.* 1973). The natural remanent magnetization (NRM) of samples was measured with a two-axis CCL superconducting magnetometer. Component analysis of demagnetization data was performed using least-squares line-fitting algorithms (Kent, Briden & Mardia 1983; Torsvik 1986), aided by inspection of orthogonal and stereographic projections.

4 ROCK MAGNETIC PROPERTIES

Thermomagnetic analyses

Thermomagnetic analyses reveal both magnetite/low-titanium titanomagnetite and haematite magnetic phases within the TVF (Fig. 2). Purple mudstones (site 3) are characterized by haematite (Fig. 2a), with secondary magnetite indicated on the cooling curve. Andesites are commonly dominated by paramagnetic phases (e.g. Fig. 2c) but yield some irreversible curves (Fig. 2b, d). In Figs 2(b) and (d), magnetite (580 °C) and haematite (670 °C) Curie points are identified during heating and cooling cycles. Increased saturation magnetization during cooling indicates additional magnetite formation through alteration of initially non-magnetic phases and/or reduction of haematite.

Isothermal remanence (IRM) experiments

IRM acquisition experiments concur with thermomagnetic analyses indicating the presence of both low-coercivity
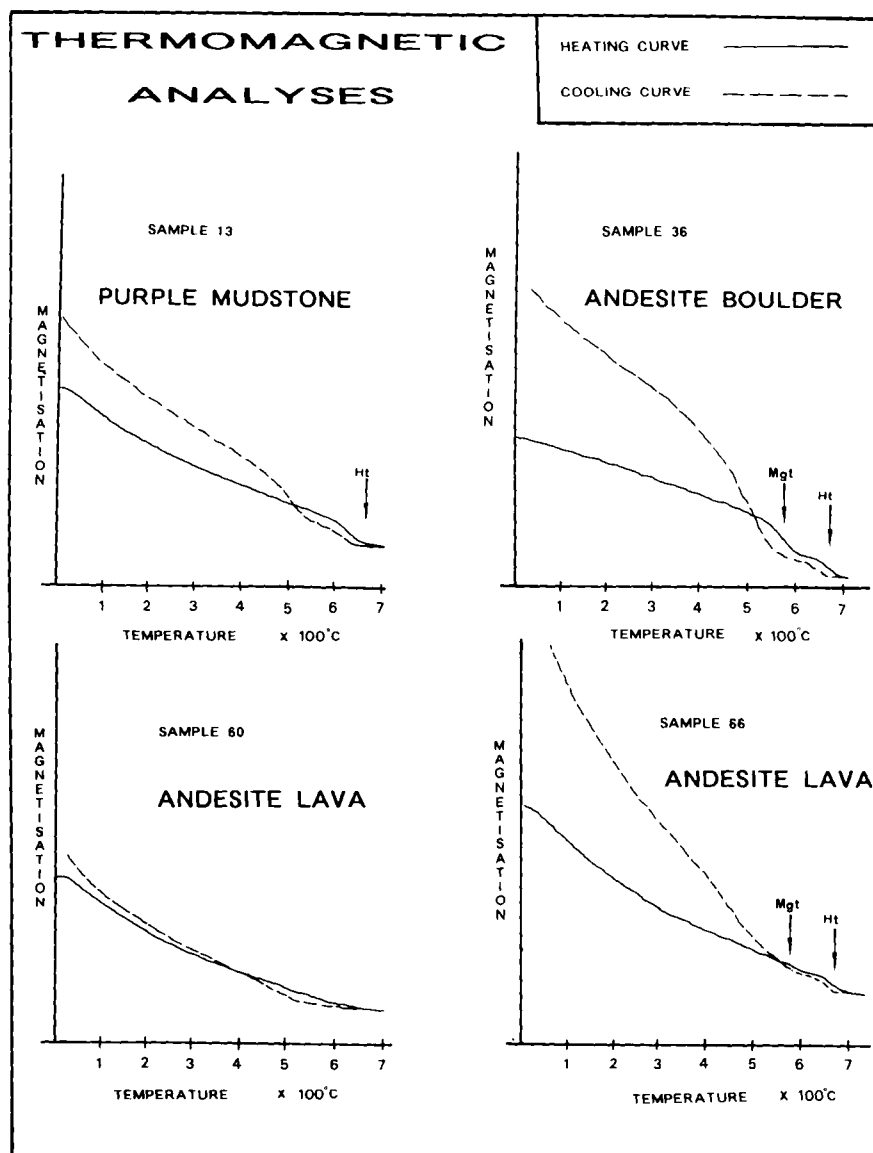
Figure 2. Saturation magnetization versus temperature curves for representative samples of the Treffgarne Volcanic Formation. (a) Purple mudstone, (b) Andesite boulder, (c) Andesite lava, (d) Andesite lava. Samples were heated in air. Curie temperatures of magnetite (Mgt) and haematite (Ht) are indicated when recognized during the heating cycle.

(magnetite) and high-coercivity (haematite) phases. Representative curves for the various TVF lithologies are shown in Fig. 3. These can be compared with thermal demagnetization from the same palaeomagnetic samples in Figs 4–6. The relative importance of magnetite and haematite correlates with the rock colour; i.e. red specimens are haematite-dominated, whilst green-grey specimens are magnetite-dominated.

Purple mudstones (specimen 13) indicate the presence of haematite, as inferred from the continuous increase of IRM up to the maxium available field of 300 mT. Andesites (specimen 69) and red-coloured volcaniclastics (specimen 34) show an interplay of both low- (magnetite) and high- (haematite) coercivity phases. Conversely, a second andesite (specimen 74) and a green-coloured volcaniclastic (specimen 20) show a magnetite, low-coercivity, dominated IRM signature, i.e close to saturation at 300 mT and minimum

remanence coercivities less than 50 mT [compare thermal demagnetization characteristics in Figs 4(a) and 5(a)].

5 THERMAL DEMAGNETIZATION EXPERIMENTS

Both sediments and volcanics of the TVF display composite NRMs'. Magnetization components were distinguished by their contrasting directions and unblocking spectra. Components are listed below in order of increasing laboratory unblocking temperatures. Typical examples of demagnetization data are presented in Figs 4–6.

Component R

Component **R** is positively inclined *in situ* with generally northerly declinations. It contributes little to the total NRM
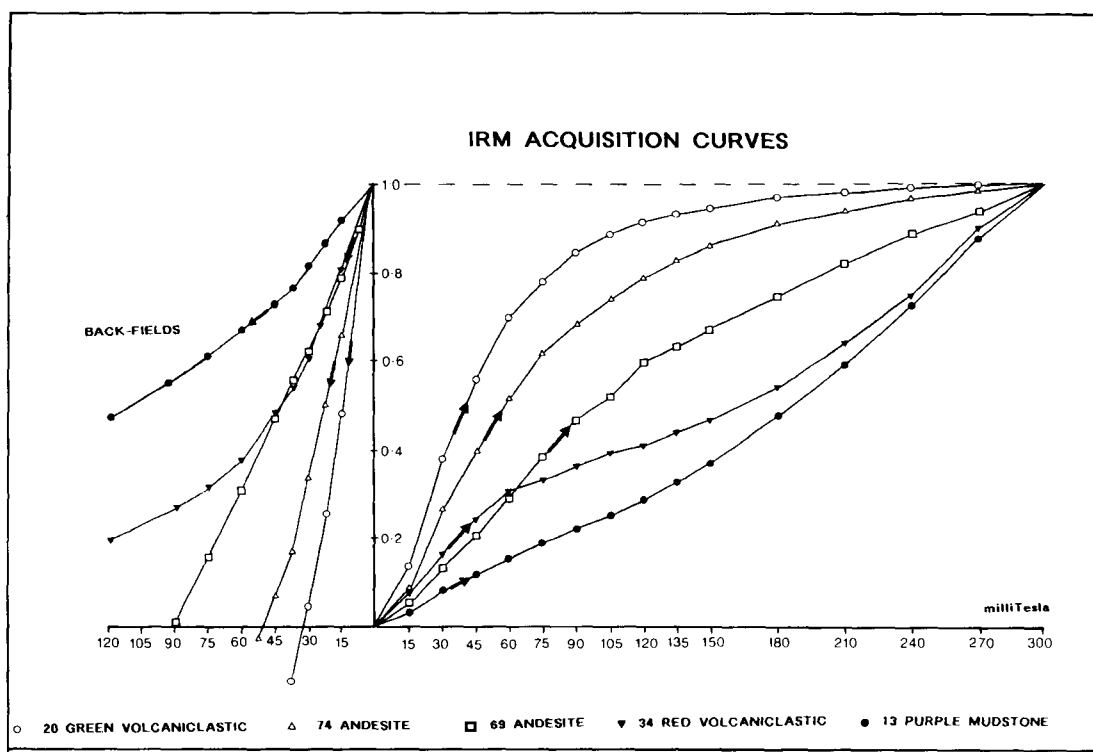
Figure 3. Isothermal remanent magnetization (IRM) acquisition curves for representative samples. Magnetization (Y) axis is normalized to the value at 300 mT. Minimum remanence coercive forces are indicated by the intersection of the back-field curves with the negative X axis.
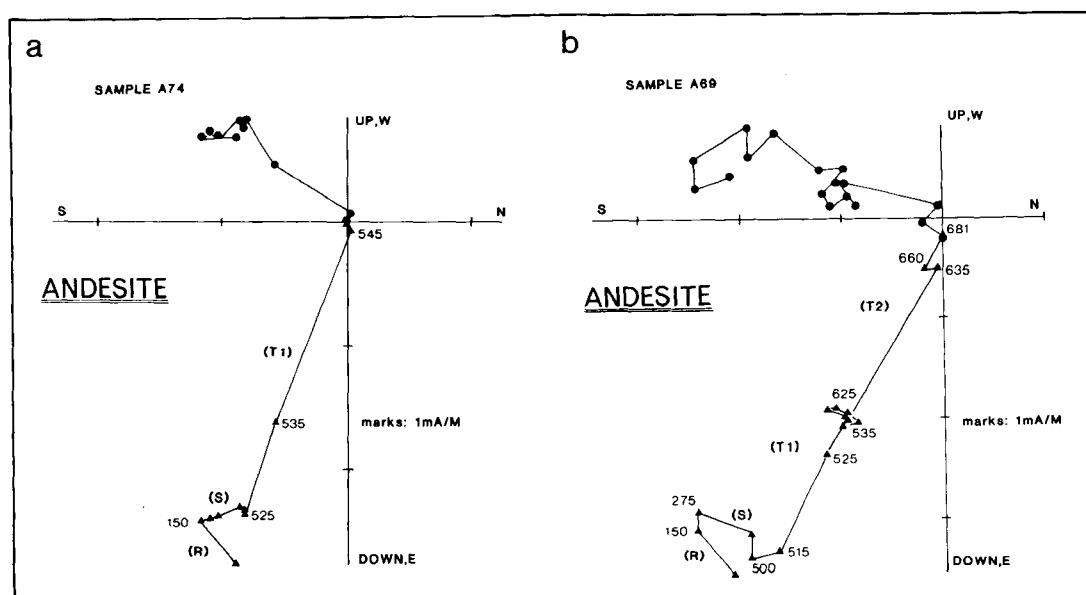

Figure 4. Orthogonal projections of typical demagnetization data from the Treffgarne Andesites (characteristic of sites 8–15). In the vector diagrams, circles (triangles) refer to projection in the horizontal (vertical) plane. Magnetization components are labelled on the vertical projection. Numbers next to data points refer to demagnetization temperatures. (a) Components **R**, **S**, and **T1**. Note that **T1** completely unblocks below the Curie temperature of magnetite. Component analyses: **S**, 150°–525 °C, Dec. 157°, Inc. +12°, M.A.D. (maximum angular deviation, Kirschvink 1980) = 16°. **T1**, 515°—origin, Dec. 222°, Inc. +64°; M.A.D. = 3.0° (b) Components **R**, **S**, **T1** and **T2**. Note the separate unblocking temperatures in **T1** and **T2** but their similar directions. Component analyses: **S**, insufficiently defined; **T**, 515°–681 °C, Dec. 208°, Inc. 58° (comprised of **T1**, 515° – 575 °C, Dec. 227°, Inc. 58°, M.A.D. = 13.0° and **T2**, 600°–681 °C, Dec. 204°, Inc. 60°, M.A.D. = 8.5°). All components are quoted in *in situ* coordinates.
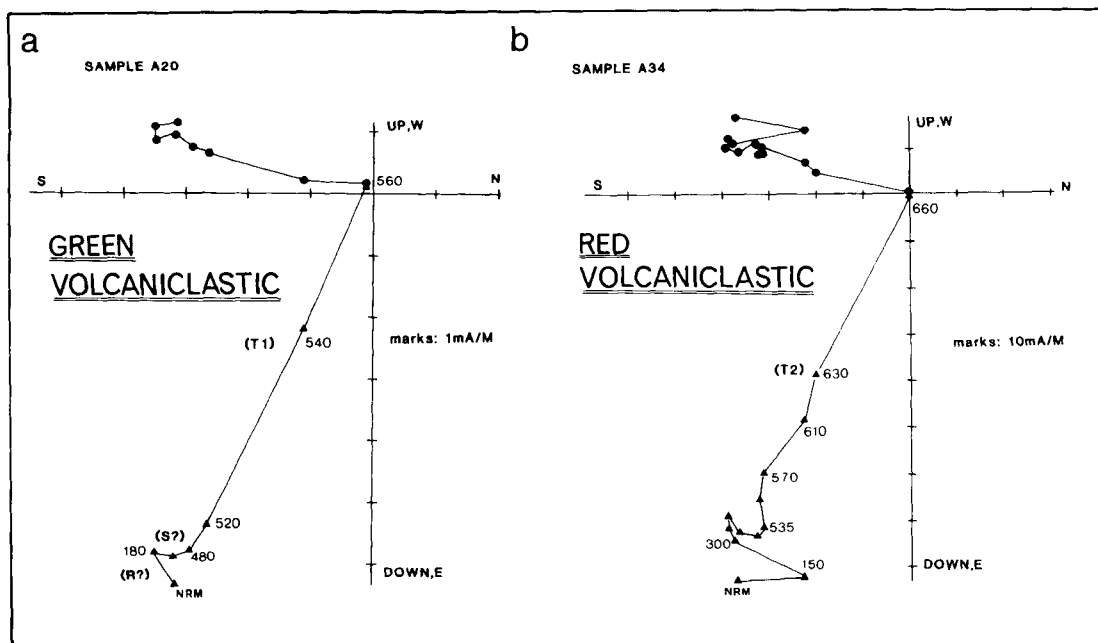
Figure 5. Typical orthogonal projections from the Treffgarne Bedded Volcaniclastics (characteristic of sites 4–6). Labelling of projections is as Fig. 4. Note that in (a), T1 is completely unblocked by 560 °C, whereas in (b), T2 is unblocked up to 660 °C. T1 and T2 have similar directions in each case. Component analyses: T1, 480°–560 °C, Dec. 193°, Inc. 64°, M.A.D. = 1.9°; T2, 570°–660 °C, Dec. 197°, Inc. 64°, M.A.D. = 4.6°. All component directions are in *in situ* coordinates.

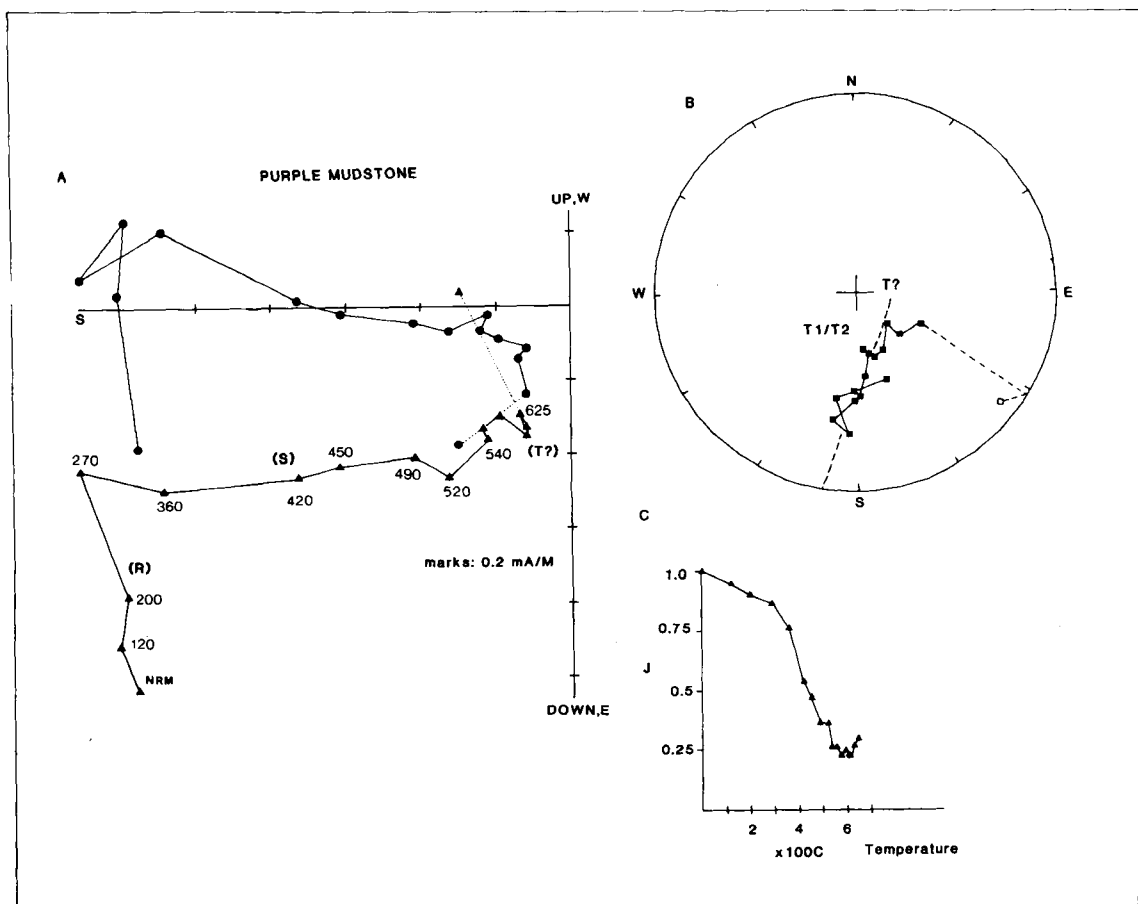**Figure 6.** An example of demagnetization data from epiclastic mudstones at Treffgarne (characteristic of sites 2 and 3). Site 1 (medium–coarse purple sandstone) did not yield a consistent magnetization behaviour. (a) Orthogonal projection. Labelling as Fig. 4. (b) Equal-angle projection. Closed (open) squares refer to projection in the lower (upper) hemisphere. (c) Normalized NRM intensity/temperature decay curve.

Table 1. Component S site-mean directions and statistics. Columns are as follows: SITE, number of palaeomagnetic sampling site; n, number of palaeomagnetic samples yielding the component at the site; IN SITU, Dec. Inc., declination and inclination of site-mean remanence vector quoted in geographic coordinates; k, a95%, Fisher precision parameter and cone of 95 per cent confidence, TILT CORRECTED, Dec. Inc., declination and inclination of mean remanence vector quoted after correction for strike and dip at the site. For overall statistics, *n* becomes the number of palaeomagnetic sites.

| SITE | n | IN SITU | | k | a95% | TILT CORRECTED | |
		Dec.	Inc.			Dec.	Inc.
2	13	191	1	126.7	3.7	191	20
3	6	182	7	25.4	13.6	181	27
4	8	189	-8	27.3	10.8	190	29
6	3	194	-15	(20.2)	(28.2)	194	20
8	3	168	-15	(17.8)	(22.4)	168	15
9	3	205	-11	(10.8)	(29.3)	206	18
10	6	173	-25	9.7	22.6	174	5
11	8	168	-2	14.2	15.2	166	27
12	4	205	-14	8.7	33.2	205	15
13	7	187	-6	35.7	10.2	187	25
15	3	195	-6	19.2	25.3	196	25

Overall Mean (11 sites)

| In Situ | | | | | | PALAEOPOLE | | |
						Lat	Long	dp/dm
11		187	-9	27.8	8.8	42S	346E	4.5/9

Structurally Corrected
| 11 | | 187 | 21 | 31.2 | 8.3 | | | |

Table 2. Component T site-mean directions and statistics. SITE, n, Dec. Inc. k, a95% as Table 1. (T1/T2) denotes whether the T component unblocks over the magnetite (Mgt <580 °C), haematite (Ht >580 °C) or both magnetite and haematite (Mgt/Ht) unblocking temperature ranges.

| SITE | n | IN SITU | | k | a95% | TILT CORRECTED | | (T1/T2) |
		Dec.	Inc.			Dec.	Inc.	
4	13	199	65	127.4	3.7	334	75	Mgt
5	16	193	59	128.6	3.3	37	86	Mgt
6	10	207	52	67.0	5.9	263	83	Ht
8	16	235	61	138.0	3.2	301	66	Mgt
9	12	231	60	122.4	3.9	298	68	Mgt/Ht
10	14	221	56	55.5	5.4	281	71	Mgt/Ht
11	11	222	60	240.0	3.0	296	72	Mgt
12	6	217	62	30.8	12.3	301	75	Mgt/Ht
14	12	231	54	123.4	3.9	284	65	Mgt/Ht
15	17	215	63	69.0	4.3	305	75	Mgt/Ht

Overall Mean (10 Sites).

In Situ
| 10 | 217 | 60 | 99.2 | 4.9 |

| Structurally Corrected | | | | | PALAEOPOLE | | |
					Lat	Long	dp/dm
10	79.1	5.5	298	75	56N	306E	9/10

of the volcanics\volcaniclastics (Figs 4 and 5) but is prominent within the epiclastic sediments (Fig. 6). Unblocking temperatures do not exceed 250 °C. We interpret component R as a viscous remanence of Recent origin and therefore do not discuss it further at length.

Component S

S unblocks between temperatures of 200°–500 °C within the volcanics\volcaniclastics where it forms only a minor constituent of the total NRM (Figs 4 and 5). In the sediments however, S is unblocked between 200° and 630+ °C and predominates the NRM (Fig. 6). S has a southerly declination and subhorizontal inclination *in situ* (Table 1).

Component T

Component T forms the dominant magnetization component of the TVF residing in both magnetite and haematite remanence phases. The portions of component T covering the magnetite (<580 °C) and haematite (>580 °C) unblocking temperature ranges are referred to as T1 and T2 respectively. T1 and T2 have the same direction within the volcanics\volcaniclastics (compare Figs 4a, b, 5a, b). *In situ*, the components have S–SW declinations and moderate-steep downward inclinations (Figs 4 and 5, Table 2). In the sediments, neither T1 or T2 is adequately resolved, although there is evidence for a steeply directed component above the blocking temperatures of component S (Fig. 6).

6 PALAEOMAGNETIC CONGLOMERATE TEST (SITE 7)

A horizon of boulder conglomerate overlies the Treffgarne andesites (GR 95902400) containing clasts derived from the

underlying lavas (Thomas & Cox 1924). To facilitate a palaeomagnetic conglomerate test, several samples were drilled from each of five boulders within this conglomerate. Demagnetization experiments reveal a composite NRM (Fig. 7). Due to the comparable magnetization structure (see below), we use the component nomenclature adopted for the remainder of the TVF. Component directions from the conglomerate (Site 7) are listed in Table 3.

Component R

Low blocking temperature components (<200 °C) are poorly developed within the conglomerate (Fig. 7), indicating the high magnetic stability of the volcanic clasts. Such behaviour is consistent with derivation of the boulders from the underlying volcanics (*cf*. Fig. 4). No components were sufficiently defined to allow calculation of meaningful directions.

Component S

Boulders #1 and #2 (Fig. 7c, d) display more distributed unblocking temperature spectra than the remaining boulders allowing a component of southerly declination and shallow negative inclination, S, to be recognized between 200° and 500 °C. The S component has an identical direction in each clast (Table 3) and therefore fails the conglomerate test.

Component T1

The NRM of each boulder is dominated by a magnetization component, T1, unblocking in the 510°–560 °C temperature range. Although the T1 directions are similar *within* each boulder, they are dispersed *between* boulders (see stereonet
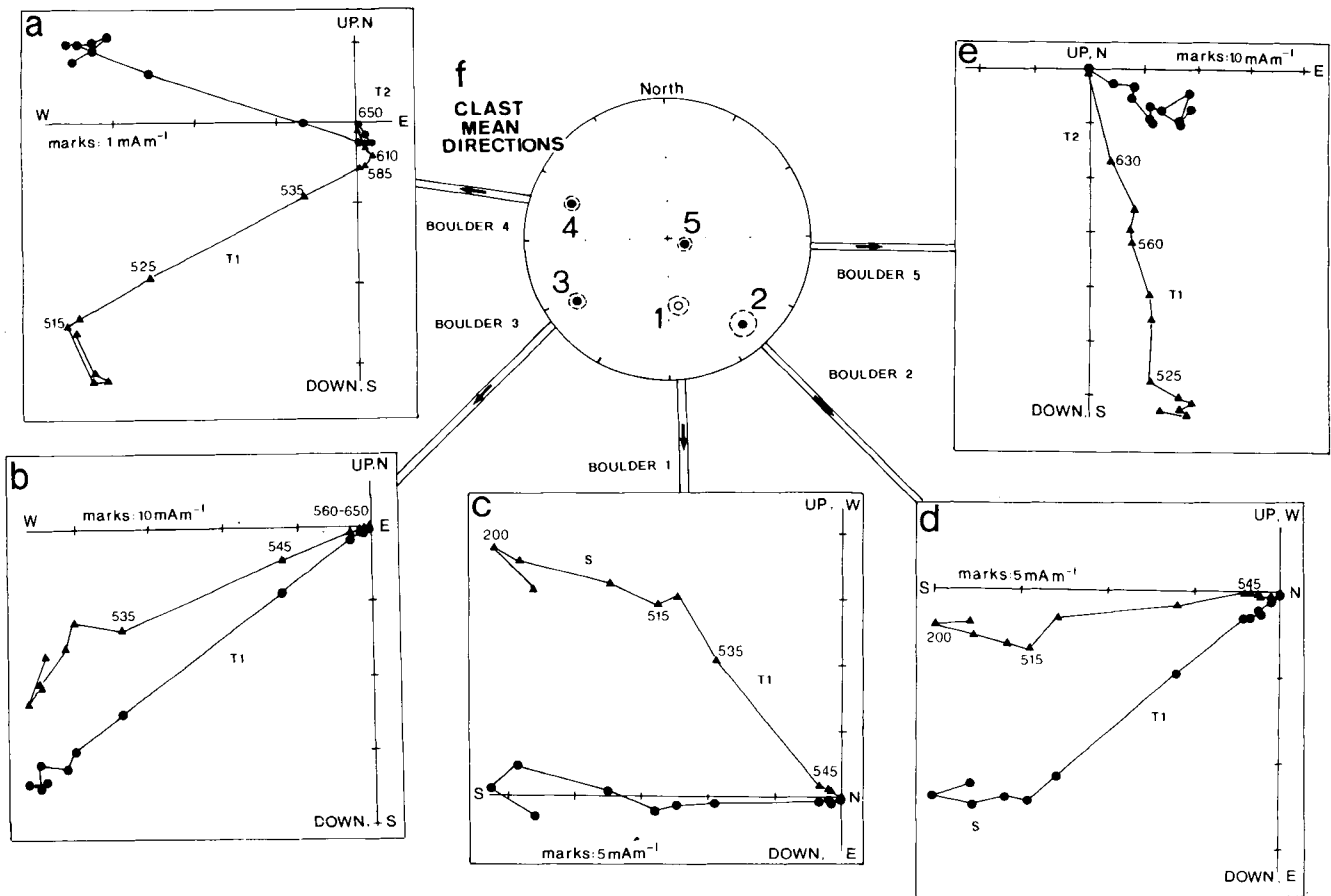
Figure 7. Results of the palaeomagnetic conglomerate test (Site 7). Typical orthogonal projections are presented from each of the five boulders. Labelling is as Fig. 4. Projections are as follows: (a) Boulder #4. Components T1 and T2 are labelled. (b) Boulder #3. T1 (c) Boulder #1. S and T1. (d) Boulder #2. S and T1. (e) Boulder #5. T1 and T2. (f) Equal-angle projection of mean directions of component T1 from each boulder. 95 per cent confidence circles are indicated for each boulder.

in Fig. 7, Table 3). This indicates a positive stability test ($N = 5$, $R = 2.8$, $Ro = 3.5$, Watson 1956) and implies that T1 was acquired prior to deposition of the intraformational conglomerate. T1 is therefore considered as a primary magnetization which blocked during initial cooling of the Treffgarne lavas.

Component T2

In boulder #4, a further component, T2, is recognized as a linear segment above the maximum unblocking temperature of magnetite (Fig. 7a). T2 therefore resides within a haematite remanence phase. Within #4, T2 has a steep downward inclination and southeasterly declination *in situ* (Table 3). In boulder #5, a component unblocked above 580 °C has a similar direction to T1 in the clast (Fig. 7e, Table 3). Remaining boulders do not show distinct components above 580 °C as only a small percentage of the total NRM remains.

The existence of T2 is confirmed by the smeared distribution of T1 directions from each clast (Fig. 8). This implies a partial blocking temperature overlap between T1 and T2. The best-fit least-square intersection of great circles fitted to T1 components from each boulder is moderate– steeply downward (*in-situ,* dec. 141°, inc. 51°; corrected,

dec. 96°, inc. 65°), similar to T2 in boulder #4 (Table 3). The directional difference between the T2 great-circle intersection in the conglomerate and T2 in the lavas/volcaniclastics is enigmatic (*cf.* Tables 1 and 3). There is a considerable uncertainty on the best-fit great-circle intersection however as three of the five planes are steeply inclined, and have similar strike directions (#1, #2, #5). Nevertheless, the convergence of the great circles signifies that T2 post-dates conglomerate deposition.

7 DISCUSSION OF PALAEOMAGNETIC RESULTS

Remanence ages

Site-mean component directions from the TVF are shown in Fig. 9 and listed in Tables 1 and 2. A schematic magnetization history is illustrated in Fig. 10 and is recounted below.

Component T1 is identified as a 'primary' magnetization based on a positive conglomerate test (Fig. 10a). Given the directional similarity with T1, component T2 in the TVF is also inferred to be Early Ordovician, but is suggested to be post-depositional in origin (negative conglomerate test, Fig. 8). As T2 unblocks above 580 °C, it is linked to

Table 3. Statistical details of components identified within the conglomerate (Site 7). Columns are as follows: CLAST no., number of the sampled boulder/clast (1–5). n, number of samples yielding the particular component in the clast. Dec., Inc., a95% and k as for Tables 1 and 2. Components S and T1 are listed in geographic coordinates. Component T2 is listed in both geographic and tectonic coordinates. M.A.D.—maximum angular deviation on best-fit intersection great circle.

COMPONENT S (conglomerate)

CLAST No.	n	IN SITU Dec.	Inc.	a95%	k
1	5	193	-6	12.4	39.3
2	7	186	-13	12.4	24.6

COMPONENT T1 (conglomerate).

CLAST No.	n	IN SITU Dec.	Inc.	a95%	k
1	8	172	-39	6.6	71.8
2	9	140	13	6.5	63.6
3	9	236	15	4.1	162.2
4	9	291	19	4.0	163.5
5	5	134	74	9.9	61.1

COMPONENT T2 (conglomerate).

CLAST No.	n	IN SITU Dec.	Inc.	a95%	k	TILT CORRECTED Dec.	Inc.
4	6	153	57	12.9	27.8	89	72
5	5	105	76	4.4	308.0	33	58

"Best-Fit" Intersection of Five Great Circles.

			M.A.D.		
5	141	51	21.8	96	65

Tremadoc–Arenig haematization *after* deposition of the intraformational volcanic conglomerate (Fig. 10b).

The conglomerate test results therefore indicate that component T site-means require structural correction for the present dip of the TVF. Following untilting, the overall-mean T direction in WNW directed with steep positive inclination ($N = 10$, dec. 298°, inc. +75°, $a_{95} = 5.5$, $k = 79$; Fig. 9a) corresponding to an Early Ordovician (Tremadoc–Arenig) palaeopole at N56° E306° (Fig. 11).

Component S is identified as a magnetic overprint based upon a negative conglomerate test [clasts means from boulders #1 and #2 are shown in Fig. 9(b) and listed in Table 3]. A comparison of the *in situ* S palaeopole with the Southern British APWP suggests a post-tectonic origin in Permo-Carboniferous times (Fig. 11). Component S is therefore linked to orogenic-fluid migration following northerly directed Hercynian thrusting at c. 290 Ma (Fig. 10d).

Tectonic implications of the Early Ordovician magnetization

The identification of a primary magnetization (component T1) from the Early Ordovician of Southern Britain has important palaeogeographic consequences. The mean inclination of 75° indicates that Treffgarne occupied a high southerly palaeolatitude of 61° (±9°) in Early Ordovician times. When compared with Ordovician palaeomagnetic data from Scotland and Laurentia (c. 15°S, Torsvik *et al.* 1990a), the combined data imply that the British sector of
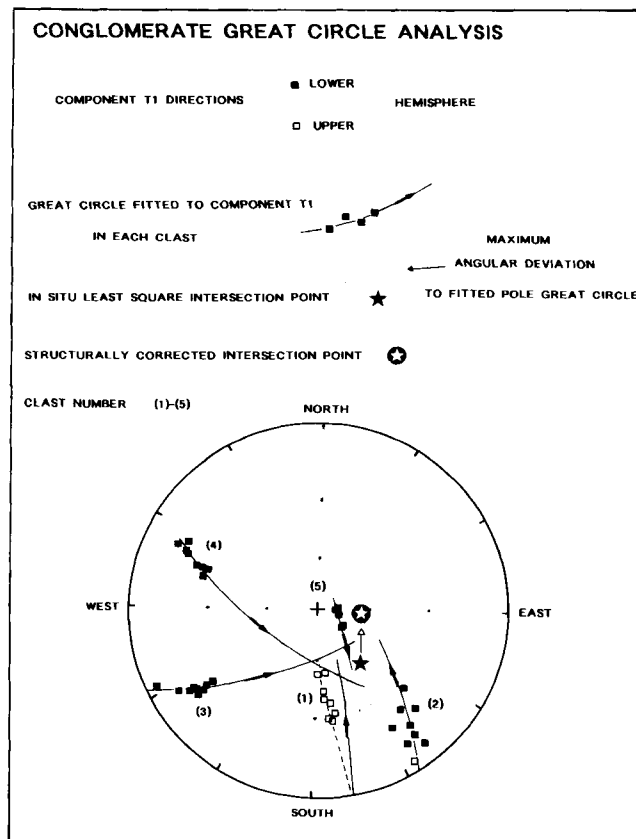

Figure 8. Great circle analysis of conglomerate data (site 7). Equal angle projection. Great circles are fitted to the T1 component directions from each clast. The 'smearing' of T1 directions implies that there is an overlap of unblocking spectra between components T1 and T2 in the conglomerate. Note that any similar overlap in the remainder of the TVF (between T1 and T2) would not bias the mean pole as T1 and T2 have similar directions in all other sites.

the Iapetus Ocean covered some 45° (5000 km) of palaeolatitude in Tremadoc–Arenig times (Fig. 12a, b).

Using palaeomagnetic data to reconstruct the former west Gondwanan margin (e.g. Van der Voo 1988; Bachtadse & Briden 1990) suggests that Southern Britain lay in the vicinity of Mauritania (Fig. 12a, b). This reconstruction assumes that Avalonia formed a peri-Gondwanan terrane since Late PreCambrian times (Scotese & McKerrow 1990; McKerrow 1988). Taken at face value, the mean declination of component T at Treffgarne (298°) implies that the North English margin of Avalonia faced Gondwana rather than the Iapetus Ocean (Fig. 12a). We advise caution in reconstructing Southern Britain (East Avalonia) in this manner however as: (i) there is a high uncertainty on the mean Treffgarne declination due to the high inclination of site-means (±22° see Beck 1980); (ii) the survey area may have been subjected to local rotation and therefore the declination may not be applicable outside the immediate vicinity: in this context, thrusting of the Ordovician sequence has been described approximately 500–800 m from Treffgarne Gorge (e.g. Thomas & Cox 1924); and (iii) reconstruction using the Treffgarne declination implies that East and West Avalonia were not contiguous in Early Ordovician times (Fig. 12a). The possible effects of rotation about a local vertical axis on the T pole are shown in Fig. 11.
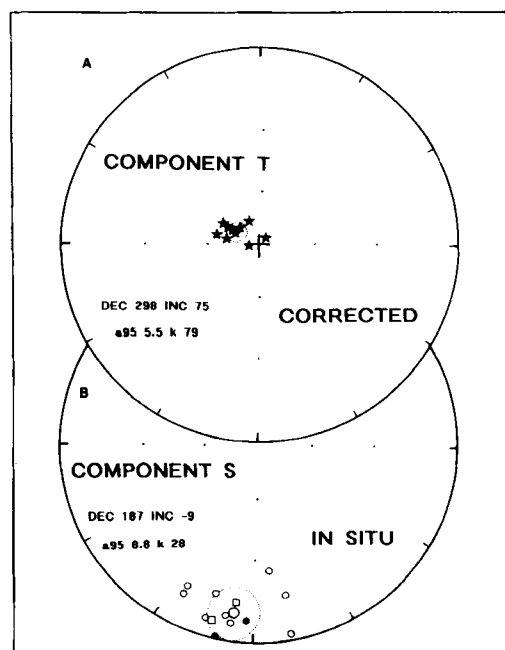
Figure 9. (a) Component **T** site-mean directions following structural correction. Stars indicate projections on the lower hemisphere. The cone of 95 per cent confidence about the mean direction is dotted. (b) Component **S** site-mean directions plotted in *in situ* coordinates. Open (solid) circles refer to the upper (lower) hemisphere. Clast mean directions from site 7 (component **S**, boulders #1 and #2) are plotted as open squares but were not included in the statistical analysis. The overall mean direction is shown as a large open circle. 95 per cent confidence limit about the mean is dotted.

A reconstruction which adopts a preferred orientation for East Avalonia to maintain the facing of the postulated Iapetus margin in Southern Britain is shown in Fig. 12(b) (see also Torsvik & Trench 1991).

Hercynian remagnetization effects

Component **S** is interpreted as a partial remagnetization of Hercynian age. In the present study, the sediments of the TVF are preferentially remagnetized when compared to the volcanic facies (*cf*. Figs 4, 5 and 6), suggesting a possible link of local remagnetization with the permeability of the host rock.

On a wider scale, **S** can be correlated with several magnetic overprints recognized elsewhere in Wales. For example, Devonian red beds 15 km to the southwest of Treffgarne have been completely remagnetized in Hercynian times, possibly during thrust deformation (McClelland & McCaig 1989). Furthermore, partial overprints similar to component **S** occur within the Builth Wells and Shelve Ordovician Inliers in mid-Wales (Fig. 1, Briden & Mullan 1984; Trench *et al.* 1991; McCabe & Channell 1990). Similarly, the magnetic direction (*in situ*) of the Cader Idris Basalts (Thomas & Briden 1976) plots close to a Hercynian field and may therefore represent an overprint magnetization.

The recognition of 'Hercynian' (Permo-Carboniferous) and not 'Acadian' (Early Devonian) or 'Shelvian' (Late Ordovician) partial magnetic overprints at Treffgarne, Builth and Shelve bears on the tectonothermal history of the Welsh Basin. If remagnetization did occur during the earlier orogenies, then it has been completely masked by the Hercynian record. Maximum palaeotemperatures across southern and central Wales determined by a variety of methods (e.g. Robinson, Nicholls & Thomas 1980; Aldridge 1986; Oliver 1988; Metcalfe 1990) therefore most likely record Hercynian thermal enhancement. Acadian remagnetization is more likely to be identified in the northern Welsh Basin where deformation is more penetrative and metamorphism locally reaches greenschist facies (Coward & Siddans 1979).

8 CONCLUDING REMARKS

Palaeomagnetic data from sediments and volcanics of the Early Ordovician Treffgarne Volcanic Formation indicate a composite magnetization history. Three remanence components of geological significance have been identified using thermal demagnetization experiments. A viscous remanence of Recent origin is also recognized. Components are characterized as follows.

(i) Component **T1**: a primary remanence acquired during Early Ordovician lava extrusion and volcaniclastic deposition. **T1** generally unblocks between temperatures of $500°$ and $560 °C$. Rock magnetic observations suggest a low-Ti magnetite remanence carrier. **T1** is randomly directed between clasts of an intraformational conglomerate indicating a primary origin.

(ii) Component **T2**: a post-depositional remanence related to haematization in Early Ordovician times. **T2** unblocks at temperatures between $570°$ and $650 °C$ indicating a haematite remanence phase. When **T1** and **T2** coexist within the volcanics, the components display identical magnetization directions. However, in the conglomerate, **T2** is not randomized between individual clasts. **T2** is therefore attributed to post-depositional haematite growth during Early Ordovician low-temperature alteration.

(iii) Component **S**: a partial magnetic overprint of Hercynian (Permo-Carboniferous) age. **S** unblocks between temperatures of $200°-500 °C$ in the volcanics and $200°-630+ °C$ within the sediments. The component fails the intraformational conglomerate test implying a secondary origin. The '*in situ*' pole position for **S** (S42°, E346°, $dp/dm = 5/9$) lies on the Late Carboniferous–Early Permian segment of the British apparent polar wander path. We relate remagnetization to orogenic-fluid migration north of the Hercynian Front in SW Wales.

The identification of a reliable Tremadoc–Arenig magnetization (**T**) from the Treffgarne Volcanics has important tectonic implications. The resulting palaeopole (N56°, E306°, $dp/dm = 9/10$) and palaeolatitude (61°S) indicates a peri-Gondwanan position for Southern Britain in Early Ordovician times. When compared with Ordovician palaeomagnetic data from Scotland and the Laurentian margin (15°S), the combined data indicate an Iapetus Ocean covering some 45° of palaeolatitude.

Likewise, the recognition of partial magnetic overprints of Hercynian age across southern and central Wales sheds light
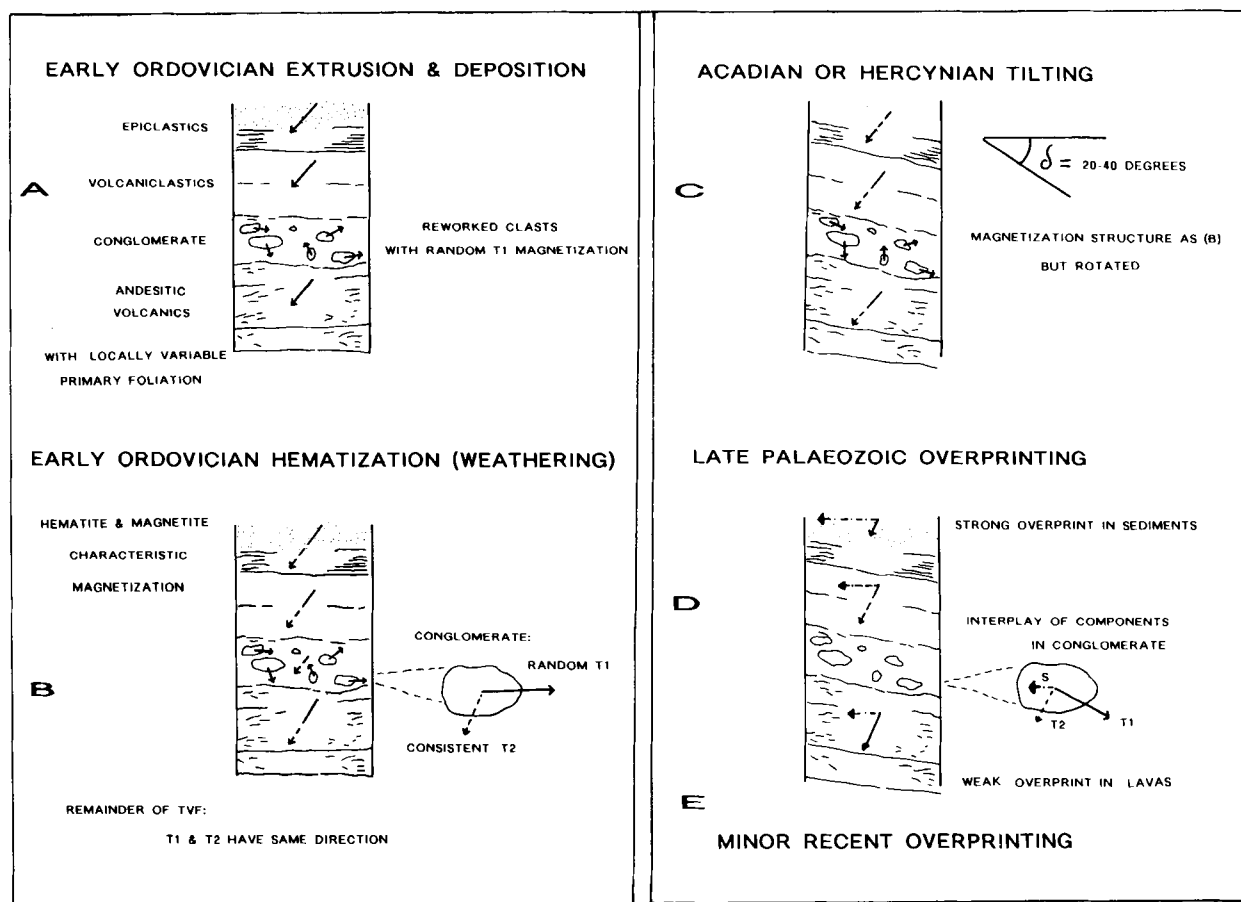
Figure 10. A tentative magnetic and tectonic history for the Treffgarne Volcanic Formation. (A) Extrusion and deposition of the TVF and initial magnetization **T1**. During deposition, reworked boulders (site 7) maintain a stable **T1** magnetization which is randomized. (b) Haematization of the TVF shortly after deposition **T1** (magnetite) and **T2** (haematite) remanences have similar directions in all sites except the conglomerate where T1 is random. (C) Acadian or Hercynian tilting of the TVF. The magnetization structure is unchanged but all components are rotated. (D) Post-tectonic overprinting (component S) preferentially affects the sedimentary facies of the TVF. Component S is detectable, but weak, in the volcanic/volcaniclastic facies. (E) Minor Recent overprinting occurs inducing component **R**.
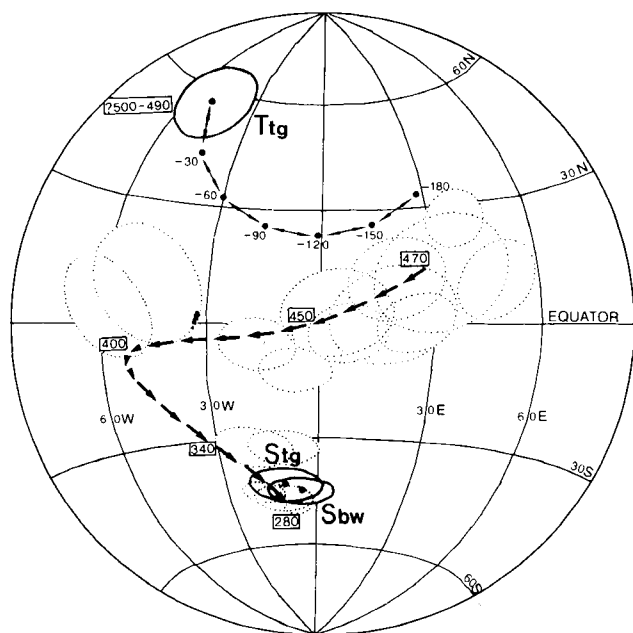
on the tectonothermal history of the Welsh Basin. Geological indicators of palaeotemperature (e.g. Metcalfe 1990) most likely reflect a Hercynian thermal pulse in the southern/central Welsh Basin.

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Figure 11. Comparison of the Treffgarne poles to a reference Palaeozoic APWP for Southern Britain (after Trench & Torsvik 1991). Labelling is as follows: Ttg—structurally corrected **T** direction from Treffgarne; Stg—*in situ* component S direction from Treffgarne; Sbw—Hercynian overprint direction from the Builth Wells Ordovician Inlier, Mid-Wales (Trench *et al.* 1991). Semi-axes of 95 per cent confidence about these poles are shaded. Numbers within boxes indicate approximate ages in millions of years. Single-headed arrows denote the locus of APW. Confidence limits on poles included in the path are dotted. Double-headed arrows indicate the possible effect of local rotation about a vertical axis on the Treffgarne **T** pole. Counter-clockwise rotations at 30° intervals are shown.
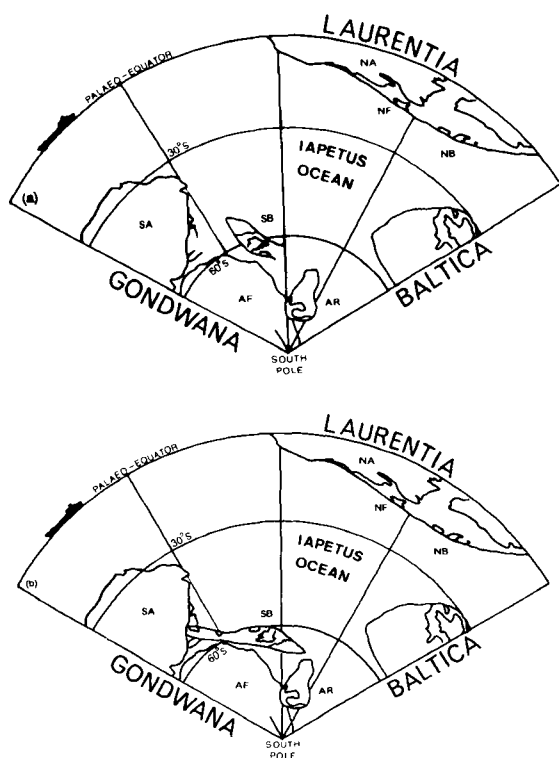
Figure 12. (a) The Iapetus Ocean in Early Ordovician times. The major Iapetus-bordering continents of Laurentia, Gondwana and Baltica are labelled. Constituent geographic codes are as follows; SB—Southern Britain, NB—Northern Britain, AR—Armorica, AF—Africa, SA—South America, NF—Newfoundland, NA—North America. Schmidt projection. Longitudes (arbitrary) are shown at 30° grid intervals. Reconstruction poles; Southern Britain (Treffgarne pole), Gondwana (34°N, 7°E; African coordinates, Van der Voo 1988), Laurentia and Northern Britain combined (Bullard, Everitt & Smith 1965 fit, 13°S, 29°E; European coordinates, Torsvik *et al.* 1990a), Baltica (31°N, 86°E; combined path X and Y, Torsvik *et al.* 1990b), Armorica (30°N, 334°E; Torsvik *et al.* 1990a). (b) Reconstruction as for Fig. 12(a) but with Avalonia positioned in latitude using the Treffgarne inclination and given a preferred orientation to maintain the facing of the apparent Iapetus margin in Southern Britain.

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