Palaeogeographic significance of mid-Silurian palaeomagnetic results from southern Britain—major revision of the apparent polar wander path for eastern Avalonia

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SUMMARY

Early Wenlock (c. 430 Ma) lavas from the East Mendips Inlier, Southern Briain, are characterized by either single-component magnetizations (Type 1) or a more complex system of three magnetization components (Type 2) during stepwise thermal demagnetization. The type of demagnetization behaviour is related to changes in magnetic petrology within the lava pile. The lower and intermediate unblocking temperature components of Type 2 represent magnetic overprints of Tertiary/Recent and Hercynian (mid-Carboniferous) origin respectively. The primary nature of the high unblocking temperature magnetization component, Types 1 and 2 (Dec = 095°C, Inc = −24°, α_{95} = 8.8°), is demonstrated by positive agglomerate tests. Conversely, an overlying Upper Old Red Sandstone sequence did not provide primary magnetizations; the magnetic signature is governed by syn-tectonic Hercynian remagnetizations.

The primary Silurian data demonstrate that the East Mendips Inlier experienced considerable clockwise rotation, probably of the order of 80°, prior to partial remagnetization during Hercynian deformation and folding. The Silurian palaeopole (VGP: 13°N, 271°E, dp/dm = 5/9) cannot therefore be used for apparent polar wander path construction. Nevertheless, the palaeolatitude estimate (13° ± 5S) suggests that southern Britain (eastern Avalonia) was at comparable mid-Silurian latitudes to Baltica and northern Britain (10–20°S). Both the Iapetus Ocean and Tornquist Sea therefore, which separated southern Britain from Laurentia and Baltica respectively in Ordovician times, were closed by Wenlock time.

As Ordovician and Silurian palaeomagnetic data from Baltica and Eastern Avalonia now record a comparable northwards translation from high southerly to near-equatorial latitudes during this time, we postulate pre-Wenlock collision of these blocks to form BALONIA (Baltica + eastern Avalonia). A new apparent polar wander path for eastern Avalonia constructed on the basis of this palaeogeographic model is presented.

Key words: apparent polar wander, palaeogeography, palaeomagnetism, Silurian, southern Britain.
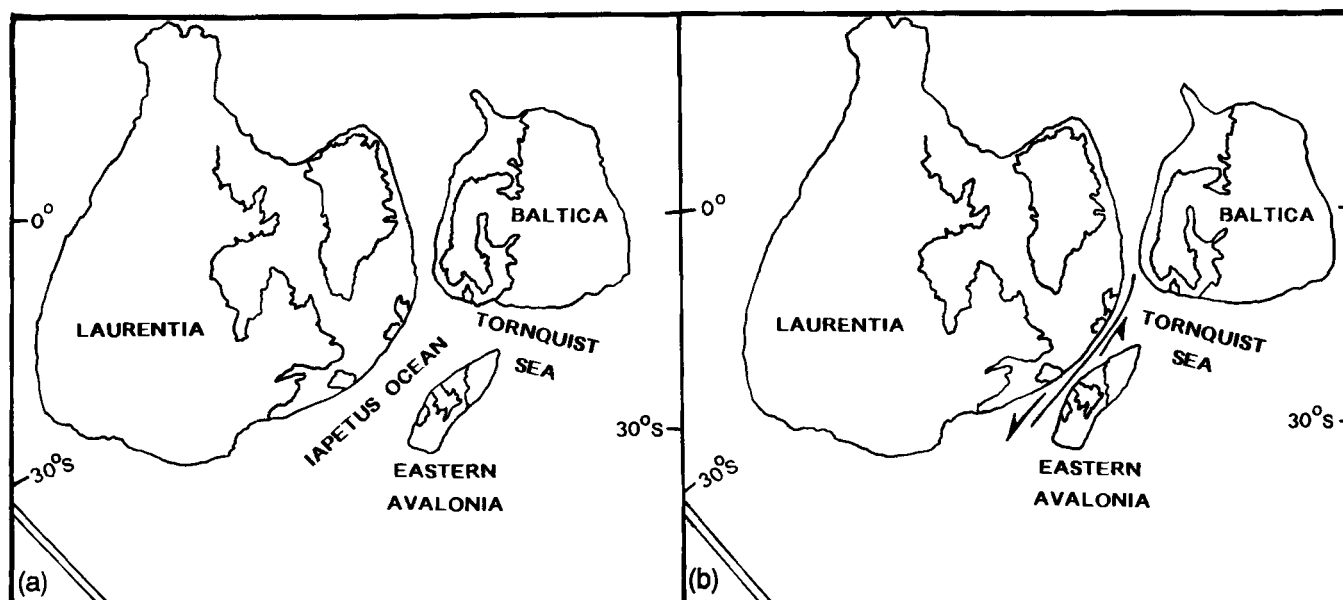
INTRODUCTION

Early palaeozoic palaeomagnetic data from southern Britain (Eastern Avalonia) demonstrate a peri-Gondwanan linkage for this block in early Ordovician times (Torsvik & Trench

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1991; Trench *et al.* 1992a) and a convergence with northern Britain by early Devonian times (Torsvik, Trench & Smethurst 1991a; Torsvik *et al.* 1991; Channell, McCabe & Woodcock 1992). In this scenario, southern Britain formed part of a three-plate Caledonian framework (e.g. Soper & Hutton 1984), separated from the palaeo-continents of Baltica and Laurentia by the Tornquist Sea and Iapetus Ocean respectively. Early–Middle Ordovician palaeomagnetic data from southern Britain and Baltica also indicate

Figure 1. Wenlock to Ludlow (mid-Silurian) continental reconstruction for the Iapetus Ocean and Tornquist Sea bordering continents based upon *existing* palaeomagnetic data. Note that while the positions of Baltica and Laurentia are reasonably established, the position of southern Britain (Eastern Avalonia) relies on a single palaeomagnetic result (Piper 1975). In (a), a vestige of the Iapetus Ocean is shown across Britain. In (b), a 'closed' Iapetus Ocean is shown (given the uncertainty in palaeolongitude) but this requires large scale post-mid-Silurian sinistral strike–slip tectonism. Note that both palaeogeographies indicate significant oceanic separation between Eastern Avalonia and Baltica across the Tornquist Sea.

northward drift of each block, in agreement with faunal, sedimentary and palaeoclimatic evidence (Webby 1980, 1984; McKerrow 1988; Torsvik & Trench 1991; Trench, Torsvik & McKerrow 1992b).

Mid-Silurian palaeopoles from Baltica and Eastern Avalonia differ, however, (Trench & Torsvik 1991a, b; Torsvik *et al.* 1992), and they imply that the Tornquist Sea had a latitudinal width of 1000–1500 km at that time (Fig. 1). The Silurian palaeomagnetic data therefore contradict biogeographic arguments for Late Ordovician closure of the Tornquist Sea (Cocks & Fortey 1982; 1990).

Taken at face value, the existing southern British palaeomagnetic data also indicate Silurian separation across the Iapetus Ocean (Fig. 1a) unless one invokes large-scale post-Silurian sinistral movement relative to northern Britain (Fig. 1b). This latitudinal separation conflicts with sedimentological evidence indicating proximity of southern Britain to northern Britain by Wenlock time (Murphy & Hutton 1986; Soper & Woodcock 1990). Whereas the position of Baltica now appears to be well constrained for the mid-Silurian (see Douglass 1988; Trench & Torsvik 1991b; Torsvik *et al.* 1992), the position of Eastern Avalonia is controlled by a single palaeomagnetic pole (Piper 1975) from Late Llandovery–Early Wenlock (mid-Silurian) andesites of SW England. Furthermore, this pole is based on only five palaeomagnetic sites with samples subjected to limited demagnetization experiments.

In this contribution, we report on a resampling of Early Wenlock volcanics (11 sites) and Upper Old Red Sandstone (four sites) from the Eastern Mendips, SW England (Fig. 2). In the light of these new data, we demonstrate that the previous palaeomagnetic result from the Silurian volcanics was significantly in error.

The new data also resolve both of the tectonic problems recounted above. First, the discordance between palaeomagnetic and biogeographic data bearing on the closure of the Tornquist Sea is eliminated. Secondly, the new data imply that latitudinal separation across the British sector of the Iapetus ocean was insignificant by Early Wenlock times. By combining palaeomagnetic data from Baltica and southern Britain, we also present a new apparent polar wander (APW) path for Eastern Avalonia which differs significantly from earlier paths.

BACKGROUND GEOLOGY AND PALAEOMAGNETIC SAMPLING

The Silurian rocks of the East Mendips (Fig. 2a) occupy the axial part of an east–west trending anticline in the surrounding Upper Palaeozoic beds (Hancock 1982) locally termed the Beacon Hill Pericline (Green & Welch 1977). The geology of the area has been described by Green (1962, 1970), Van de Kamp (1969), Green & Welch (1977) and Hancock (1982). The lithostratigraphic nomenclature of Hancock (1982) is adopted in the present study (see Fig. 2c). As a consequence of Hancock's work, the whole of the Silurian volcano-sedimentary sequence is now ascribed to the Early Wenlock (*M. riccatonensis* zone) and is regarded as younging entirely to the north (Fig. 2b). Previous studies had suggested an upper Llandovery–early Wenlock age for the volcanic sequence and had placed the axial trace of the Beacon Hill Pericline *within* the Silurian inlier. The Silurian rocks are overlain by the Portishead Beds of Upper Old Red Sandstone (ORS) age. The ORS overlies the Silurian with unconformity to the north of the inlier and by thrust contact south of the inlier (Hancock 1982, Fig. 2b).
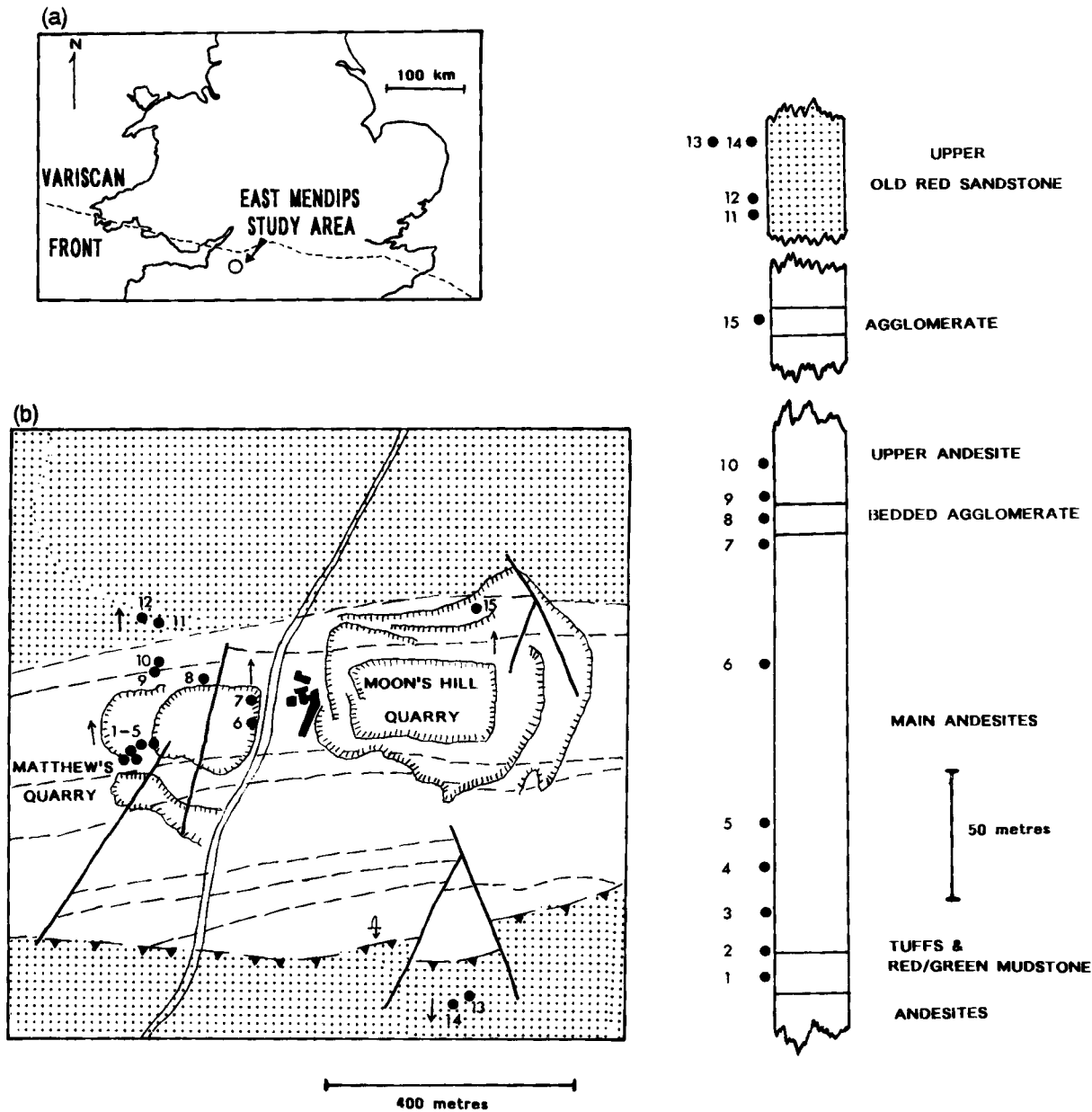
Figure 2. (a) Location of the Eastern Mendips within southern Britain. Note that the survey area lies within the Hercynian (Variscan) fold and thrust belt, i.e. to the south of the Variscan Front. (b) Geological sketch map of the Eastern Mendips Silurian Inlier in the vicinity of Matthew's and Moon's Hill Quarries (adapted from Hancock 1982). Numbered solid circles refer to palaeomagnetic sampling sites. Stippled ornament = Upper Old Red Sandstone; no shading = Silurian volcanics. Arrows indicate dip directions. Dashed lines are geological contacts and marker horizons in the Silurian sequence. Solid lines are faults. Inverted triangles indicate the inferred position of a thrust fault (after Hancock 1982). (c) Measured geological section (true thickness) through part of the Silurian volcanic sequence. Stratigraphic units are named according to Hancock (1992) although calculated thicknesses differ. Sampling levels with respect to the stratigraphic units (Hancock 1982) are as follows: Site 1 = Unit 6; Sites 2–7 = Unit 7; Site 8 = Unit 8; Sites 9 & 10 = Unit 9; Site 15 = Unit 10.

The predominant deformation of the Silurian inlier and Upper Old Red Sandstone is related to the Hercynian orogeny which has produced a number of east–west trending, asymmetric fold structures in the Mendips area. Some pre-Hercynian deformation is evidenced by the angular unconformity between the Silurian and Upper ORS.

Fifteen palaeomagnetic sites were collected from the Matthew's and Moon's Hill Quarries of the Silurian inlier (Fig. 2b). Of these, 11 sites span an approximately 250 m

section of Early Wenlock andesite lavas, agglomerates and tuffs (Fig. 2c, Table 1) embracing volcanic units 6 to 10 described by Hancock (1982). Individual lavas cannot be identified with any reliability although Van de Kamp (1969) suggests the presence of at least four flow units within the Main Andesites (see Fig. 2c). Within the Silurian section, sample sites were chosen at locations which displayed well developed bedding. The remaining four sites are within the Upper ORS.
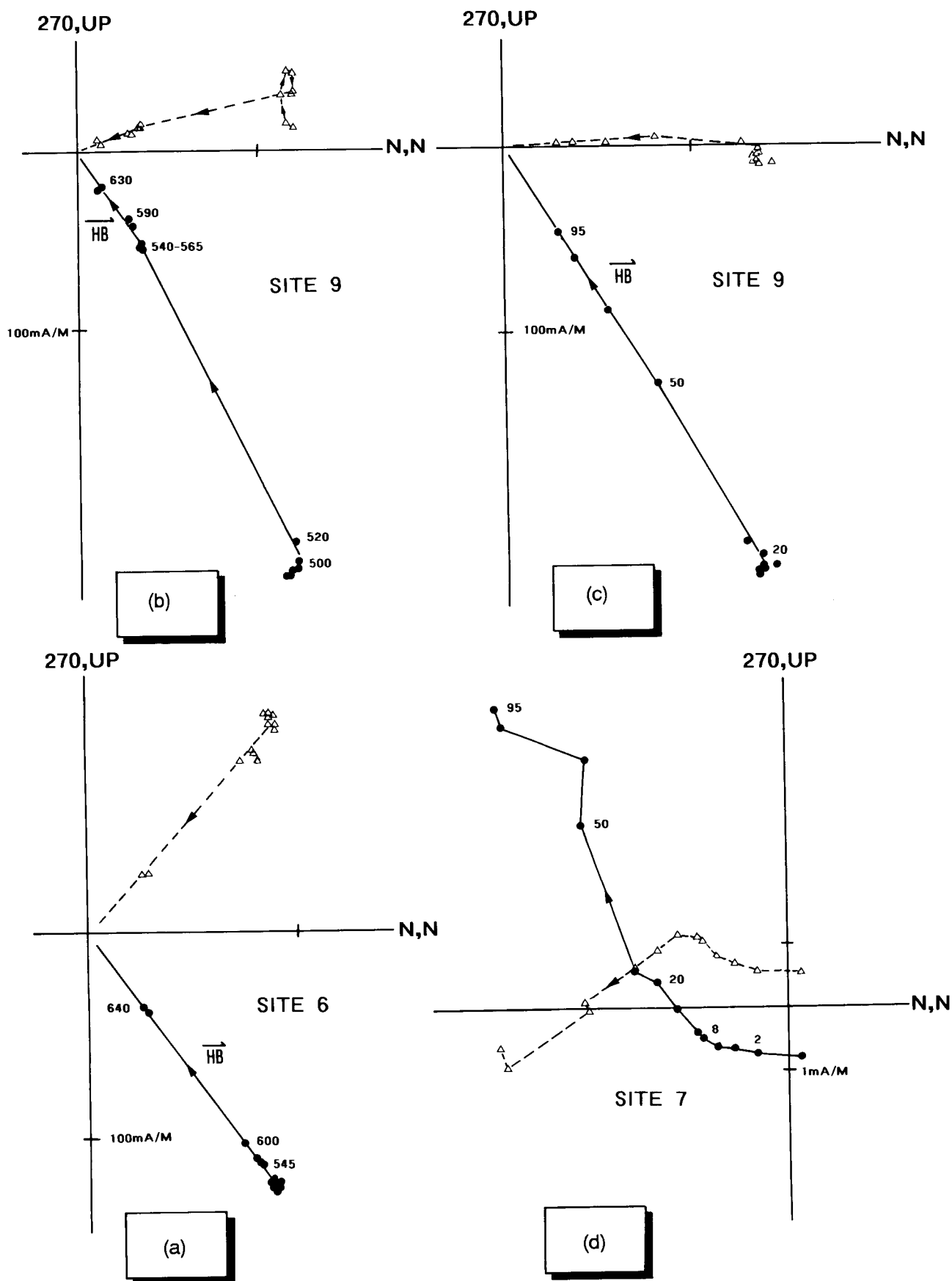
Figure 3. Representative orthogonal projections of stepwise demagnetization data from the mid-Silurian volcanics. In all projections, solid (open) symbols refer to projections on the horizontal (vertical) plane. *In situ* coordinates. Intensities of magnetization are illustrated on the axes of the diagrams. (a) High-temperature (HB) unblocking temperature component at Site 6. Type 1 demagnetization. (b) High-temperature (HB) component at Site 9. Note the angular discordance between the magnetite (<580°) and haematite (>580°) unblocking temperature ranges. (c) Type 1 HB component revealed by stepwise AF demagnetization. (d) AF 'demagnetization' fails to resolve the magnetization structure of a sample from Site 7.

PALAEOMAGNETIC EXPERIMENTS

The natural remanent magetization (NRM) of samples was measured with a JR-5 spinner magnetometer. The stability of NRM was principally tested by means of stepwise thermal demagnetization experiments. Two samples from each site were also subjected to stepwise alternating field (AF) demagnetization utilizing a two-axis tumbler system. Characteristic remanence components were calculated using least-square analysis (Torsvik 1986).

Silurian andesites and tuffs

The magnetization structure of the Silurian volcanics can be divided into two categories, termed Type 1 (single-component) and Type 2 (multi-component) behaviour.

Type 1

Samples from the upper part of the Main Andesites and the Upper Andesite (Fig. 2c, sites 6–7, 9 and 10) are characterized by almost single component and very stable magnetizations (Fig. 3a). The temperature unblocking spectra indicate magnetite (or low-titanium titanomagnetite, 500–580 °C) and haematite (>580 °C) as the chief remanence carriers. Directional stability is sometimes observed to 670 °C, but more commonly samples display viscous behaviour above 640 °C. All high-blocking temperature magnetization components (hereafter denoted HB), are of normal palaeomagnetic polarity assuming a southerly palaeolatitude for southern Britain during the Lower Palaeozoic (Briden, Turnell & Watts 1984; Torsvik *et al.* 1990; Trench & Torsvik 1991a). They display *in situ* negative inclinations and north–easterly declinations (Fig. 3a–c). In some cases, a subordinate lower unblocking-temperature component is present but cannot be uniquely isolated (e.g. Fig. 3b, <500 °C). In Sites 9 and 10, some samples show slightly different magnetization directions corresponding to the magnetite (<580 °C) and haematite (>580 °C) unblocking-temperature ranges (Fig. 3b). As the directions do not diverge by more than a few degrees of arc, we have combined the two temperature ranges to represent the characteristic HB component (Table 1). Slight angular differences between magnetite and haematite magnetizations have been recognized with volcanic successions elsewhere (e.g. Browning & Beske-Diehl 1987; Trench *et al.* 1992a) where they are attributed to slight age differences in remanence acquisition. The minor angular differences between the two unblocking-temperature ranges most likely reflect secular variation during Wenlock times. Thin-section studies (Piper 1975) reveal magnetite–ilmenite exsolution lamellae attributable to high-temperature deuteric oxidation (classes 3–5 of Ade-Hall *et al.* 1968) and abundant haematite which probably has a late magmatic origin.

AF treatments successfully demagnetized Type 1 samples dominated by magnetite (Fig. 3c). Note again a minor angular difference between the component isolated in the 20–50 mT and 50–95 mT range, i.e. probably covering the magnetite and haematite coercivity spectra.

Thermomagnetic analyses (Type 1) indicate Curie temperatures at around 580 °C and 680 °C, i.e. magnetite and haematite. Heating/cooling curves are normally quite

Table 1. Site and overall mean directions from Silurian East Mendips volcanics. Geographic site location: N51.2 and W 2.5. Statistical parameters after Fisher (1953).

High unblocking component (HB) *in situ*

Site	Dec	Inc	N	α95	k	So	Corrected Dec	Corrected Inc
1	072	-18	12	3.1	191.1	260/45	087	-18
2	085	-31	5	7.7	98.9	260/45	106	-18
3	070	-28	6	12.6	29.1	261/56	099	-24
4	079	-30	3	30.5	17.4	247/65	099	- 3
5	061	-35	6	16.4	17.7	259/60	104	-30
6	046	-23	6	6.0	100.1	257/70	092	-35
7	057	-18	5	11.1	48.4	271/70	099	-37
9	057	- 6	10	3.0	155.2	255/75	076	-19
10	052	-19	10	11.2	17.3	255/75	089	-26
Mean	064	-24	9	9.5	30.4		095	-24

$(\alpha_{95}=8.8, k=35.2)$

VGP $12.9°N$ & $271°E$ dp/dm = 5/9 (Corrected for bedding)

Intermediate unblocking component (IB) *in situ*

Site	Dec	Inc	N	a_{95}	k	So	Corrected Dec	Corrected Inc
1	194	+15	13	5.1	66.2	260/45	212	+54
2	211	+21	5	15.6	24.9	260/45	238	+49
4	198	+20	4	17.0	30.1	247/65	248	+52
8Cg1	181	+36	4	25.8	13.6	268/93	354	+51
Mean	197	+23	4	16.4	32.3		253	+63

$(\alpha_{95}=41.2, k=5.95)$

VGP $25°S$ & $339°E$ dp/dm=9/17 (in situ)

Low unblocking component (LB) *in situ*

Site	Dec	Inc	N	a95	k	So	Corrected Dec	Corrected Inc
1	014	+77	10	2.6	339.1	260/45	356	+33
2	039	+62	6	7.7	75.9	260/45	013	+24
3	022	+71	6	12.6	29.1	247/65	351	+11
Mean	028	+70	3	13.3	86.4		000	+23

$(\alpha_{95}=23.8, k=27.87)$

VGP $72°N$ & $067°E$ dp/dm=19/23 (In situ)

similar (Fig. 4a), indicating only minor magneto-mineralogical alteration. In a few instances, however, secondary magnetite is observed during cooling (Fig. 4b).

Type 2

Sites from the lower part of the Main Andesite section (sites 1–5 and 7) display multi-component magnetizations. Three components are observed at sample level (e.g. site 1; Fig. 5) which are characterized as follows:
(1) a low unblocking-temperature component, LB, (Tb < 200 °C) has an *in situ* northerly declination and steeply downward inclination (Fig. 5c);
(2) an intermediate unblocking-temperature component, IB, (Tb 200°–500 °C) has *in situ* SSW declinations with shallow positive inclinations (Fig. 5c);
(3) a high unblocking-temperature component, HB, (Tb > 550 °C) has *in situ* NE declinations and negative inclinations (Fig. 5c). This HB component is comparable to that described for Type 1 samples.

AF demagnetization proved unsuccessful for Type 2 samples due to the presence of high-coercivity haematite/maghemite (see below). Indeed, many samples show a steady increase in the intensity of magnetization (Fig. 3d) up to the maximum available AF field of 95 mT.

Thermomagnetic analyses on Type 2 samples show Curie temperatures of approximately 580 °C and 650 °C attributable to magnetite and haematite respectively (Fig. 4c).
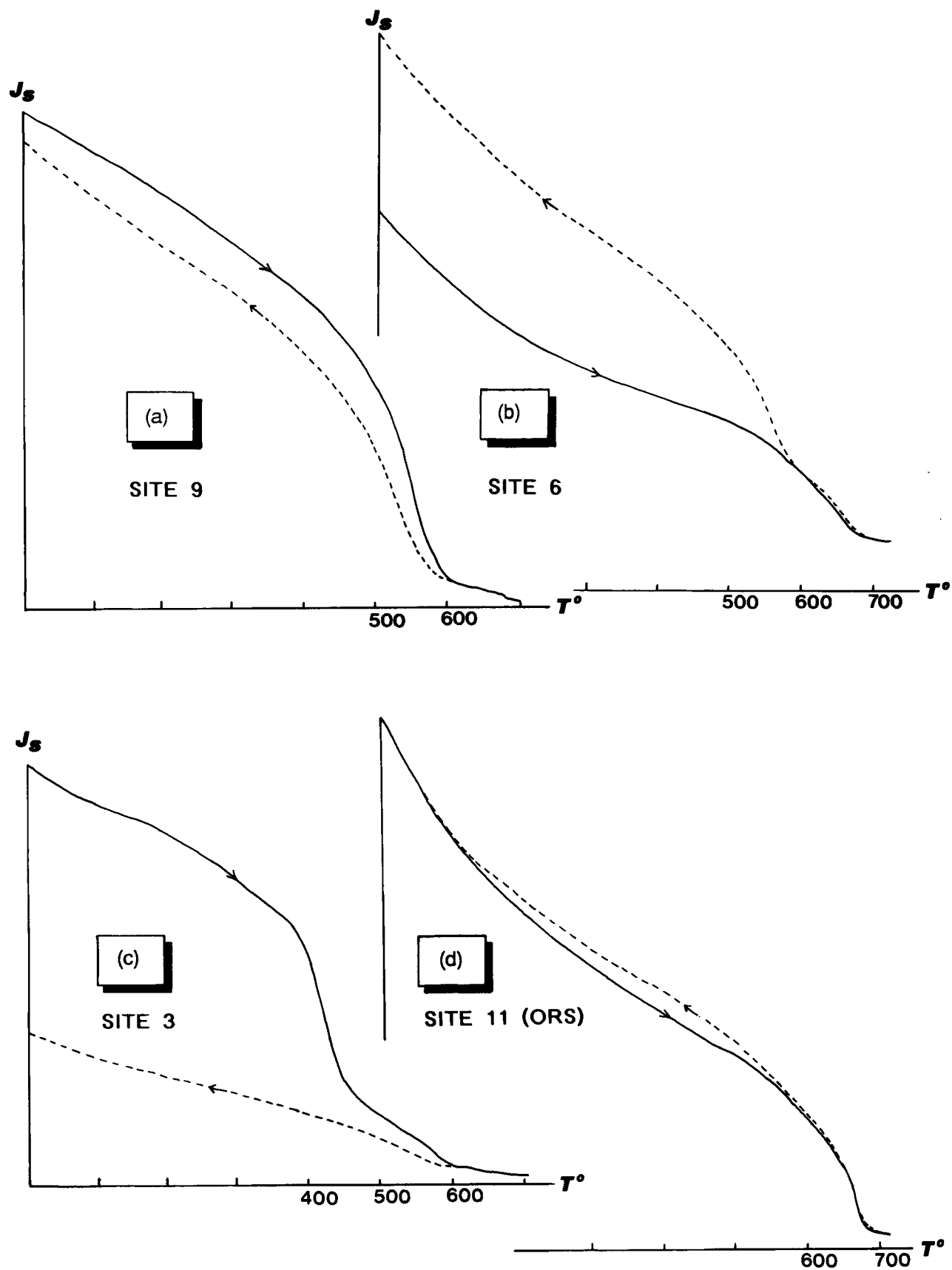
Figure 4. Thermomagnetic analyses from representative samples of the Silurian volcanics (A, B, C) and Upper ORS (D). Samples were heate in air. The heating curve is shown as a solid line: the cooling curve is shown as a dashed line.
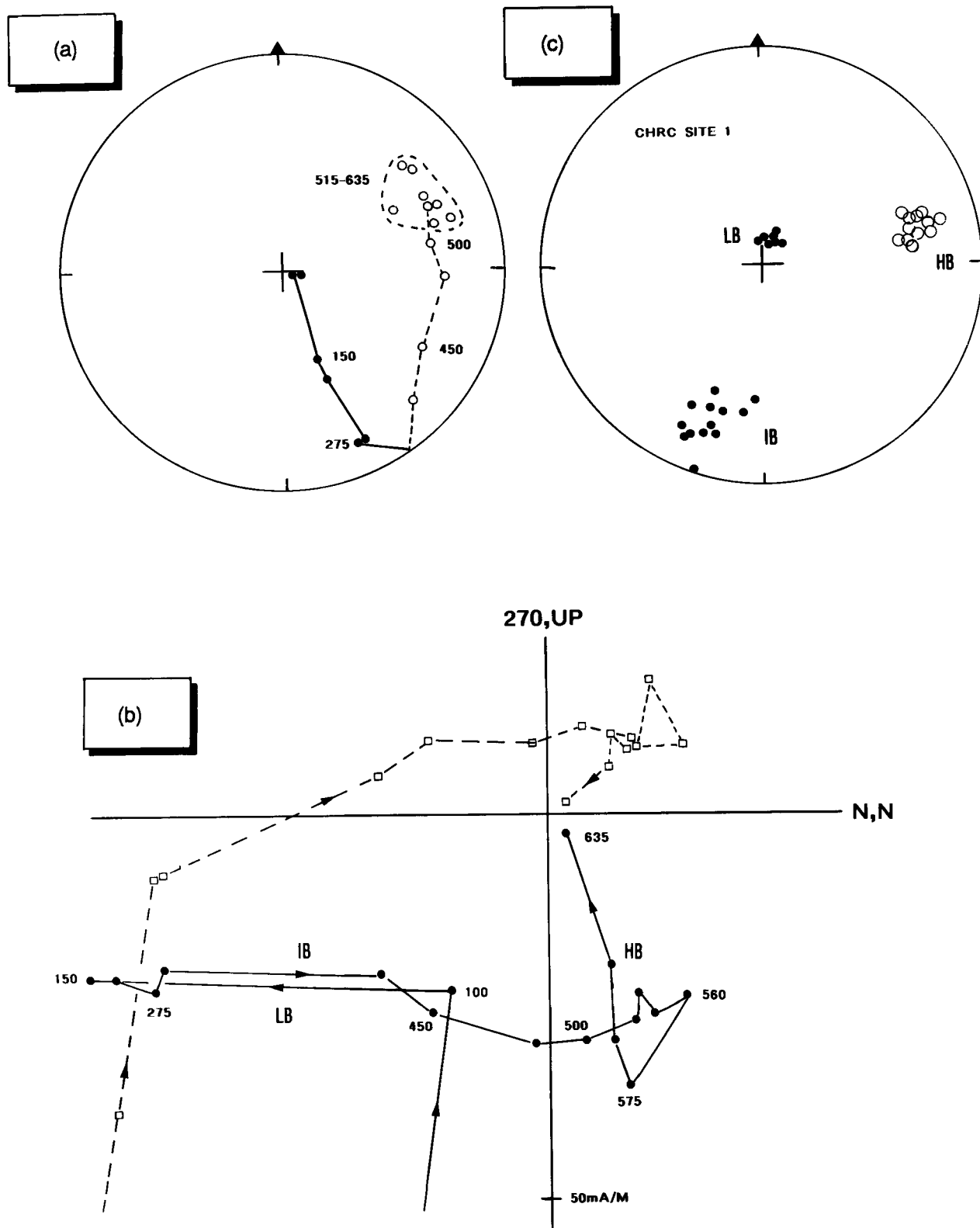
Figure 5. Representative demagnetization data for Type 2 behaviour of Silurian volcanics. (a) Equal angle projection of progressive thermal demagnetization of a single sample (*in situ* coordinates). (b) Orthogonal projection showing Type 2 demagnetization behaviour. Solid (open) symbols refer to the horizontal (vertical) projection. *In situ* coordinates. Low (LB), intermediate (IB) and high (HB) unblocking-temperature components are labelled on the diagram. Numbers next to data points refer to maximum demagnetization temperatures (degrees Celsius). The intensity of magnetization (milliAmps per metre) is indicated on the axis of the diagram. (c) Direction of characteristic unblocking-temperature components (CHRC), LB, IB and HB determined for site 1. Equal angle projection. *In situ* coordinates.

The heating/cooling curves are irreversible indicating mineralogical changes during treatment. A large decrease in saturation magnetization on cooling probably reflects inversion of maghemite below 500 °C to form haematite (Fig. 4c).

Upper Old Red Sandstone (ORS)

The Upper ORS is characterized by multi-component magnetizations. A low unblocking-temperature component, LB, (Tb < 200 °C) is present in most samples, but is difficult to estimate due to blocking-temperature overlap with a SSW-directed IB component with shallow positive inclinations *in situ* (Fig. 6a). This intermediate blocking-temperature component, IB, is comparable to those recorded in the Silurian volcanics (Type 2) and demagnetizes at similar unblocking temperatures (Tb = 200 °–500 °C). A higher unblocking-temperature component (HB), is observed at temperatures in excess of 560 °C (e.g. Fig. 6a and 6c) and is sometimes offset from the origin (Fig. 6b) suggesting the presence of a further, unresolved magnetization at high temperatures. Viscous behaviour precludes identification of the latter component, however. The thermal unblocking spectra and thermomagnetic analysis (Fig. 4d) suggest haematite as the chief remanence carrier.

While the *in situ* IB direction is similar at all four ORS sites (compare Fig. 6a, b and c), the HB components from the NW (Sites 11 and 12) and SE fold limbs (Sites 13 and 14) differ in direction. From the NW limb, the HB component has SW declinations and negative inclinations (Fig. 6a) whilst samples from the SE limb display SW/SE declinations and positive inclinations (Fig. 6b and c).

PALAEOMAGNETIC STABILITY TESTS

Agglomerate tests—Silurian volcanics

All agglomerate samples from Site 15 (Upper agglomerate; Fig. 2c) are characterized by Type 1 single-component magnetization behaviour (e.g. Fig. 7a). Agglomerate HB components from Site 15 are randomly dispersed between clasts but show consistent intra-clast magnetization directions (Fig. 7b). The agglomerate test from Site 15 therefore indicates that component HB is a primary magnetization.

The lower agglomerate (Bedded agglomerate of Fig. 2c) from Site 8 is also dominated by a Type 1 magnetization structure, but Type 2 demagnetization was observed in two clasts. The latter clasts revealed IB components (four samples) comparable with *in situ* IB directions observed from the andesites (Type 2 samples) and from the Upper ORS. These considerations imply a secondary origin for the IB component.

Within-clast HB magnetizations from Site 8 are consistent whereas inter-clast magnetizations are dispersed. This observation further implies a primary origin for the HB component. We note the presence of a subordinate cluster of HB component directions from clasts 8–3 to 8–6 (mean DEC = 0.13°, INC = −2°, *in situ* coordinates and DEC = 106°, INC = −74° when corrected for bedding). However, as these directions are discordant to magnetizations in the surrounding andesites, an origin due to either thermal-overprinting or high-temperature agglomerate deposition is discounted.
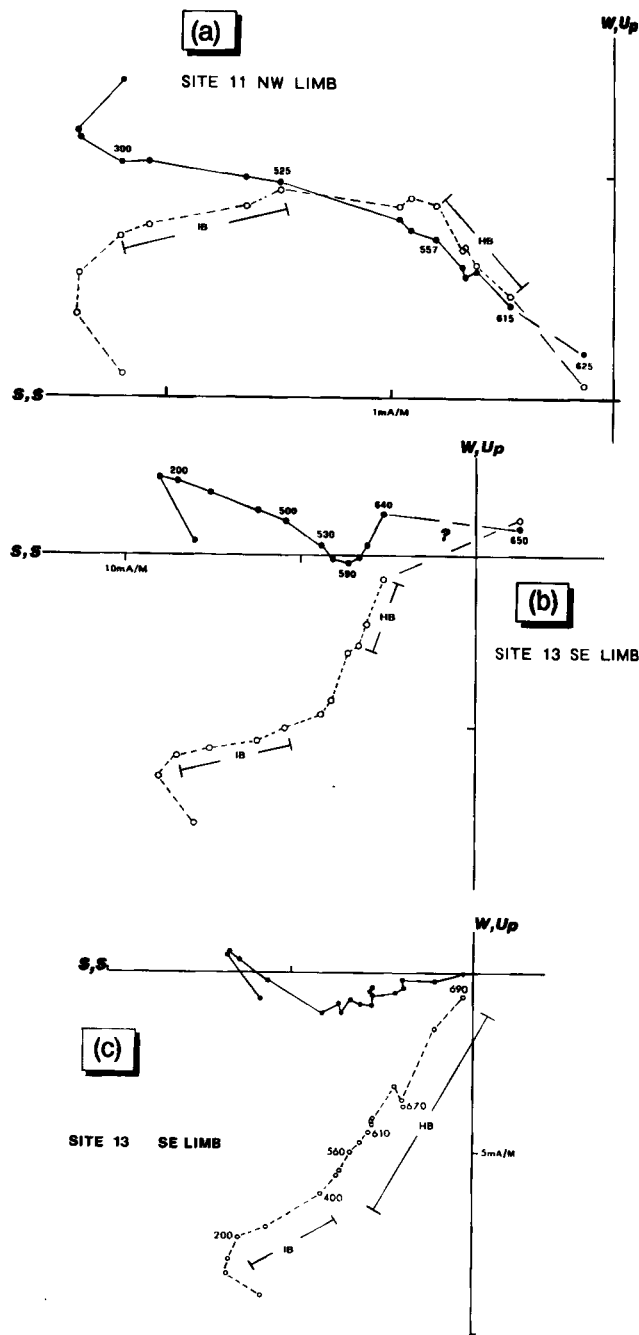

Figure 6. Representative demagnetization data from the Upper Old Red Sandstone (ORS). Solid (open) symbols in the orthogonal projections refer to horizontal (vertical) projections respectively. Unblocking-temperature components and intensity of magnetization are indicated on the diagrams. In (a & c) note that the HB component converges to the origin whilst in (b) it is clearly offset from the origin.

Fold test—Silurian volcanics

The site mean directions of components LB, IB and HB are shown in Fig. 8(a) (*in situ*) and (b) (tilt-corrected). Tilt corrections were performed about the observed strike and dip at each site. As the strike of the volcanics is almost parallel to the HB component, however, a fold test on this component proves statistically inconclusive (Table 1). A marginal improvement in remanence dispersion is, however, noticed after bedding correction (Fig. 8b; Table 1).
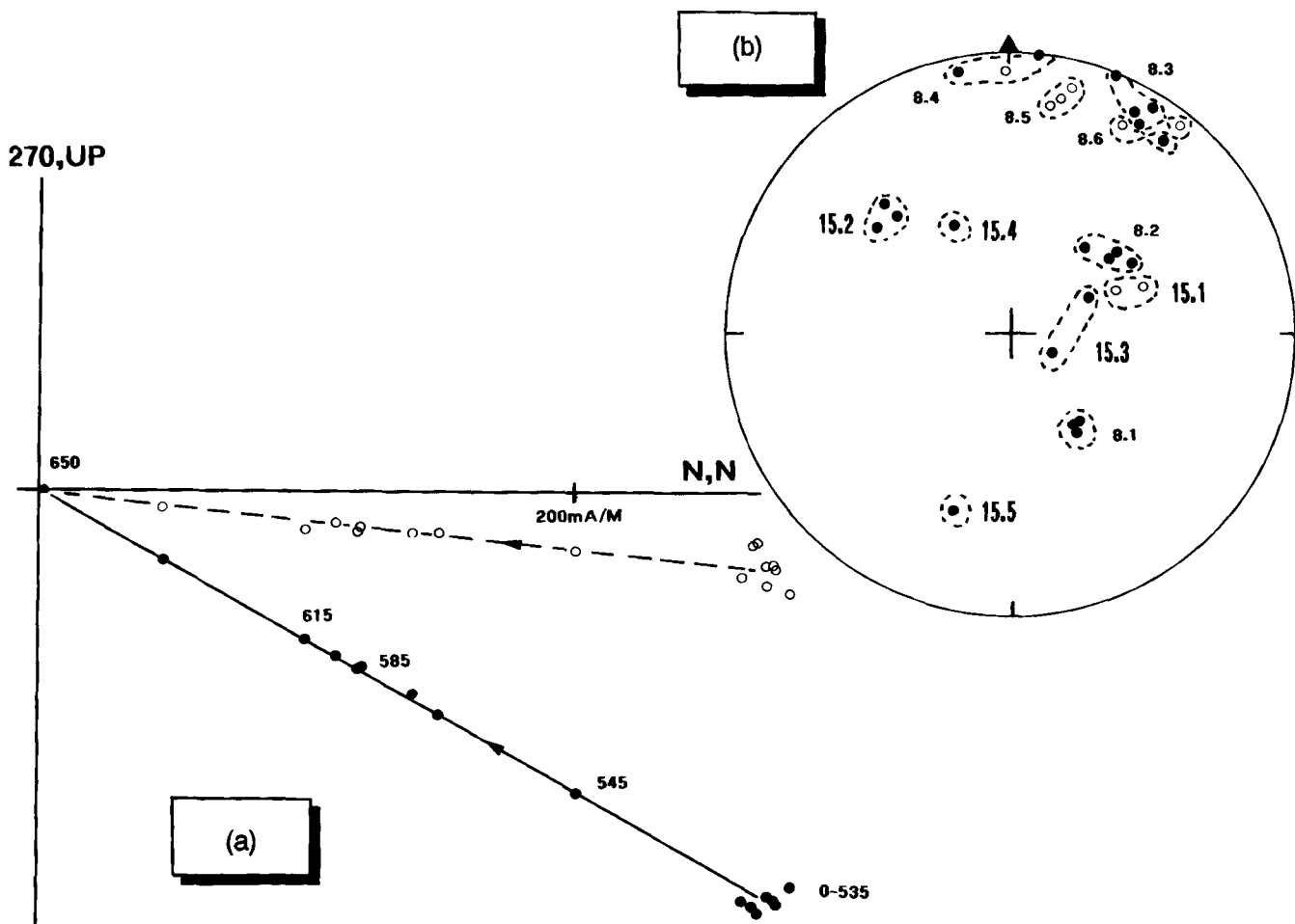
Figure 7. (a) An example of Type 1 (single component) demagnetization observed in an agglomerate clast from Site 8. Solid (open) symbols refer to the horizontal (vertical) projection. *In situ* coordinates. (b) Equal-angle projection of all high unblocking-temperature magnetization components from volcanic agglomerates at Sites 8 and 15. Solid (open) symbols refer to the lower (upper) hemisphere. Individual clasts are labelled 8.1, 15.1, 15.2, etc. Directions obtained from the same clast are encircled.

Conversely, IB components from agglomerate Site 8 (two boulders) and three andesite lava sites (1, 2 and 4) are comparable, and this, combined with a statistically significant negative fold-test (95 per cent confidence) establishes a secondary and post-fold origin for the IB component. The *in situ* LB component resembles a present-day field direction at the site and is therefore interpreted as a recent viscous magnetization.

Fold test—Upper Old Red Sandstone

In situ IB components from the Upper ORS are significantly better grouped at the 95 per cent confidence level before bedding correction using the McElhinny (1964) fold test (Figs 9 and 10). The IB component is therefore either of (1) post-fold origin or (2) late syn-fold origin due to the pronounced peak in the precision parameter (k) at 10 per cent unfolding (Fig. 10). We also note that IB components in the mid-Silurian volcanics and the sediments are comparable (see Tables 1 and 2).

In situ HB components are dispersed and display optimum grouping at 70 per cent unfolding (Fig. 10). The grouping at 70 per cent unfolding is significantly better than

the *in situ* distribution, but is not statistically different from 100 per cent unfolding, i.e. a prefold magnetization. The HB component is therefore pre- or early syn-tectonic in origin. Note the directional similarity between the 10 per cent corrected IB and 70 per cent corrected HB component suggesting that both components may be associated with folding.

INTERPRETATION

Secondary components

Given the negative stability tests, the IB component recorded in the East Mendips Silurian volcanics (Table 1; Sites 1–2 and 4) and the Upper ORS (Table 2; Sites 11–14) is interpreted as a magnetic overprint. When compared with recently published APW paths for Southern Britain (Torsvik *et al.* 1990; Trench & Torsvik 1991a), a Carboniferous (Hercynian) age is indicated (Fig. 11). Similar Hercynian remagnetization features were identified in the Lower ORS by Channell *et al.* (1992), and tentatively ascribed to fluids during Hercynian thrusting. Carboniferous remagnetization components which predate (Stearns & Van der Voo 1987)
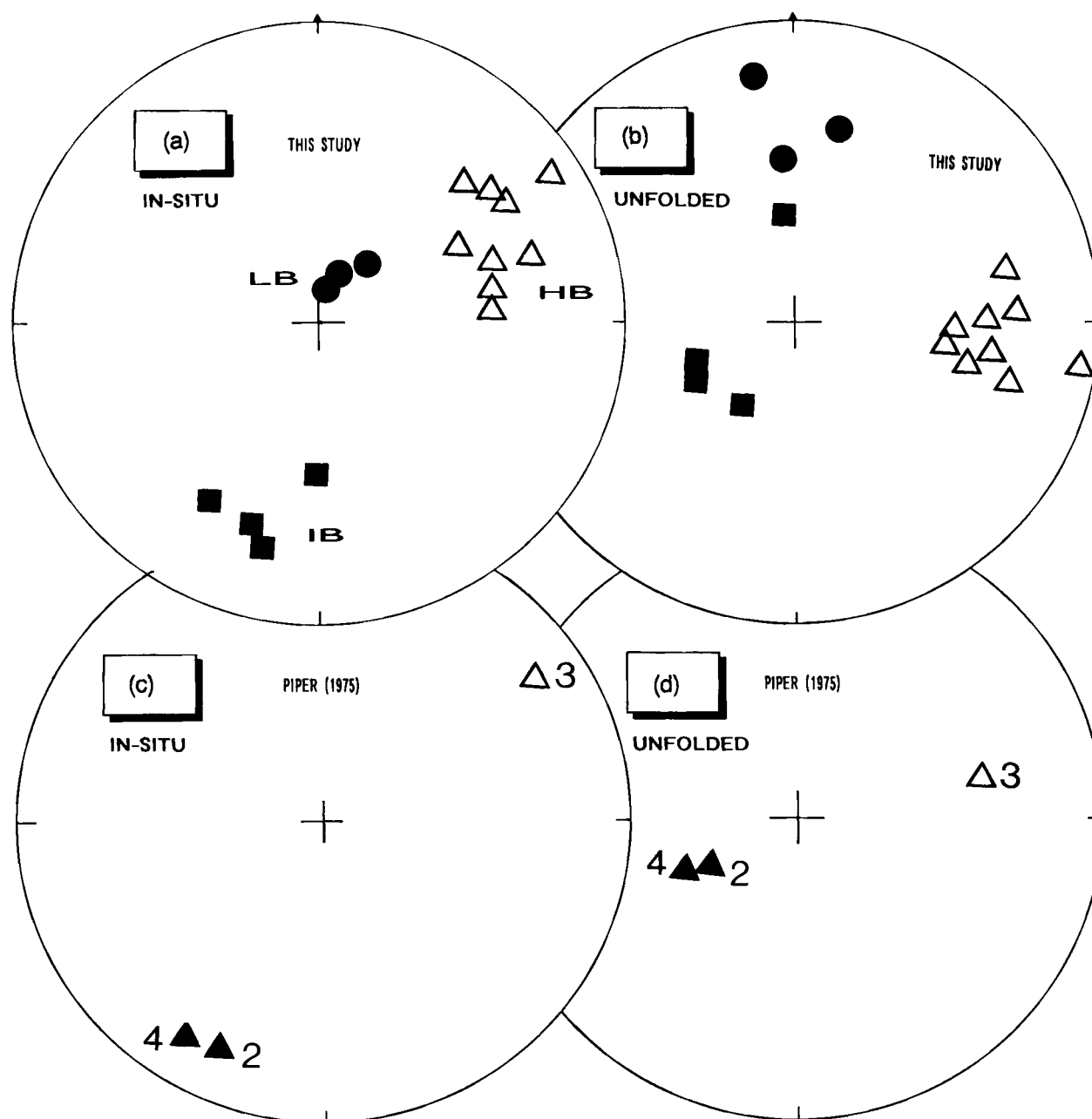
Figure 8. Site-mean directions of characteristic remanence components from (a, b) this study, and (c, d) Piper (1975), viewed in equal-angle projection. In all diagrams, solid (open) symbols refer to the lower (upper) hemisphere. (a) Low (LB), intermediate (IB) and high-temperature (HB) components from this study. *In situ* coordinates. (b) Characteristic components from this study in tilt-corrected coordinates. (c) *In situ* site-mean data presented by Piper (1975) from Moon's Hill Quarry. (d) Tilt-corrected site-mean data of Piper (1975).

and post date (McClelland-Brown 1983) Hercynian structures are also recognized within the Old Red Sandstone of the Welsh Basin. These studies serve to demonstrate the close temporal association between Hercynian deformation and remagnetization. A previous palaeomagnetic study of the Portishead Beds near Bristol (Morris *et al.* 1973) yielded an inconclusive fold test (Hercynian deformation) but identified magnetizations of probable Hercynian age (*in situ* mean Dec. 203° Inc. 15°; Corrected mean Dec. 198° Inc. 10°).

The upper ORS HB component is early syn- or alternatively pre-fold in origin. In either case, we advocate a

Hercynian secondary origin given the observations that (1) an underlying, but as yet unidentified magnetization, probably represents the primary component, and (2) palaeomagnetic pole position (both in a 70 or 100 per cent unfolding stage) overlaps with the post-fold IB directions found in both the Silurian and the upper ORS sequences.

Primary components

The HB component of normal polarity from the mid-Silurian volcanics is interpreted as primary in origin
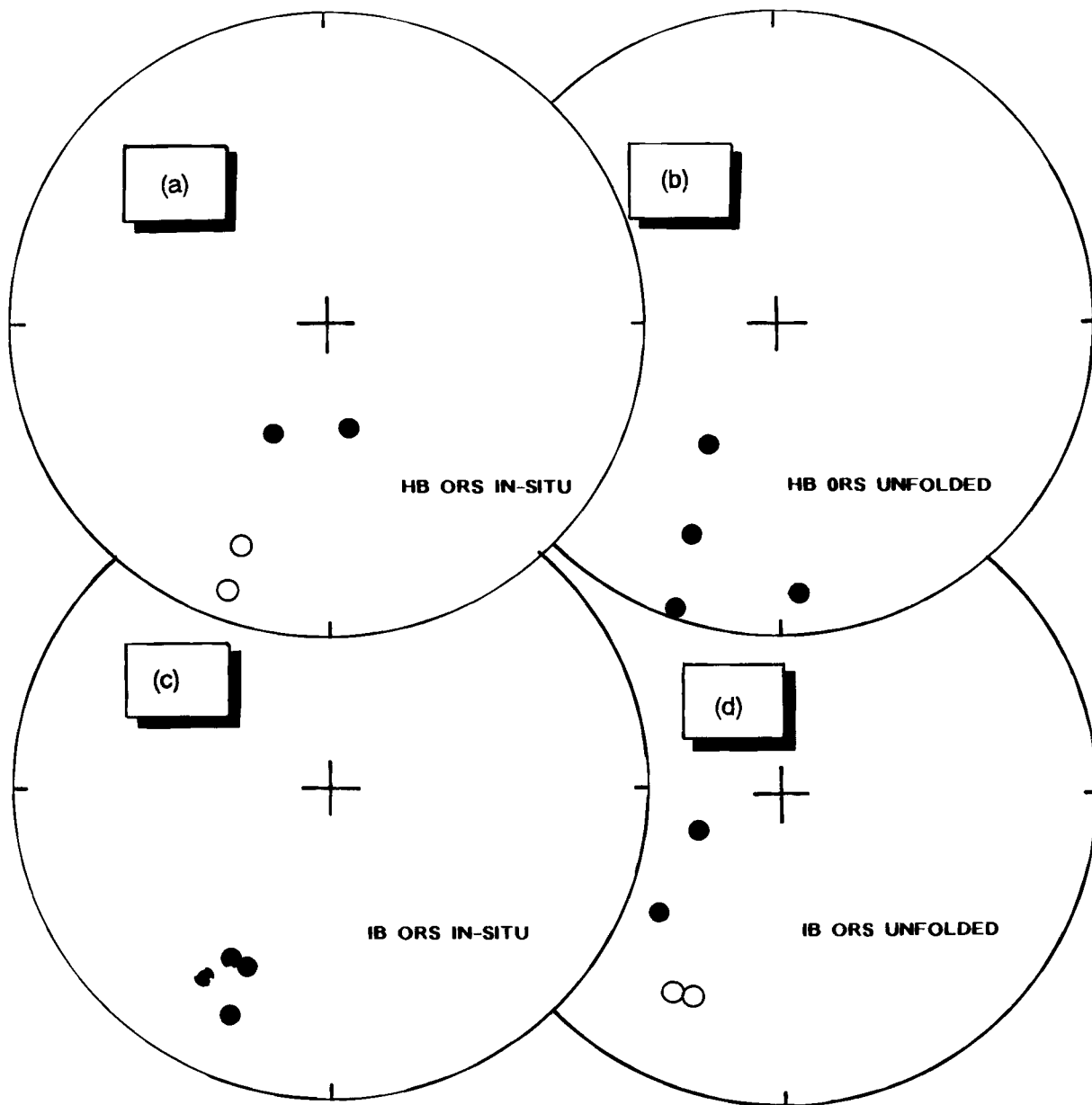
Figure 9. Characteristic remanence components (site means) identified in the Upper ORS. Equal-angle projections. Solid (open) symbols lie on the lower (upper) hemisphere. (a) High unblocking-temperature (HB) component, *in situ* coordinates. (b) HB component in tilt-corrected coordinates. (c) Intermediate unblocking-temperature (IB) component, *in situ* coordinates. (d) IB component in tilt-corrected coordinates.

given the positive agglomerate tests and the marginal improvement in grouping following tectonic correction.

PREVIOUS PALAEOMAGNETIC DATA FROM THE SILURIAN VOLCANICS

The data reported herein conflict with results obtained by Piper (1975) from three palaeomagnetic sites within Moon's Hill Quarry. Piper obtained one site of normal magnetization (Site 3) and two sites of apparent reverse magnetization following tectonic correction (Sites 2 and 4). These data are reproduced in Figs 8(c) (*in situ*) and (d) (tilt corrected). We draw attention to the similarity between sites 2 and 4 of

Piper (1975) (*in situ* coordinates) and the *in situ* overprint direction identified in this study (Fig. 8a). When combined with two additional sites at Tortworth (40 km North of Moon's Hill) and Downhead (8 km East of Moon's Hill), Piper's combined data passed a fold test. In the light of the new data reported here, we present a revised interpretation of these data.

First, we note that the AF demagnetization used by Piper (1975) is unlikely to have adequately demagnetized the volcanics at all sites (*cf.* Fig. 3d). In this study, AF demagnetization has been shown to be adequate *only* for Type 1 demagnetization. In fact, the unsuitability of AF treatment is clear from Fig. 1 of Piper (1975) where a number of samples exhibit a higher NRM intensity after AF
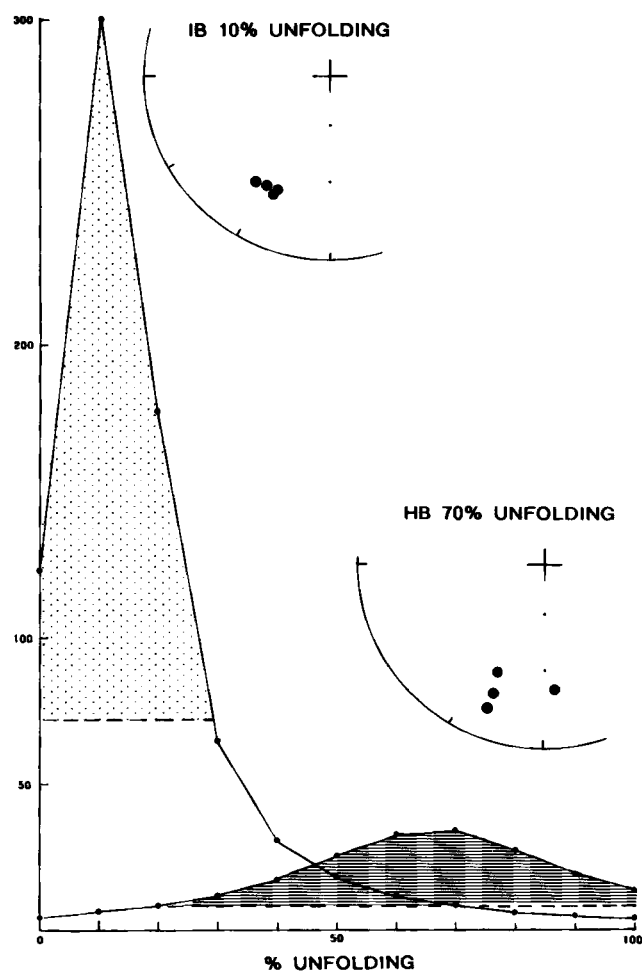
Figure 10. Fisher precision parameter (*k*) during progressive unfolding of the IB and HB components from the Upper ORS. Areas below the shaded region on each curve are significantly poorer group at 95 per cent confidence relative to optimum grouping (peak in *k* value). Site mean distributions at optimum unfolding (10 per cent for IB, 70 for HB) are also shown in equal-angle projection (lower hemisphere).

'demagnetization' than prior to cleaning. We reinterpret the previous data as follows:

(1) the NE-directed magnetization identified by Piper (Site 3 and Site 1 from the Downhead area) is directly comparable with our normal polarity HB components (compare Figs 7a and c). These data probably represent Type 1 demagnetizations.

(2) The 'reversely magnetized' SW group reported by Piper (1975) represents a composite and uncleaned magnetization direction dominated by the (Hercynian) IB component (Sites 2 and 4) and the recent LB component (Site 5). Previous tectonic correction of these data was therefore inappropriate.

In the light of the new data and our revised interpretation of existing data, we therefore argue that the previously reported reversal stratigraphy, palaeolatitude (29 °S), palaeomagnetic pole position and positive fold test from the

Table 2. Site mean directions from the Upper Old Red Sandstone, East Mendips

High unblocking component (HB)

	In situ						Corrected 70%	Corrected 100%
Site	Dec	Inc	N	a95	k	So	Dec/Inc	Dec/Inc
11	201	-15	6	14.5	27.2	263/65	203/25	210/42
12	200	- 5	2	106.2	7.9	252/28	201/10	202/17
13	168	+52	10	16.1	9.9	099/46	175/21	176/8
14	206	+47	7	10.4	34.5	099/46	201/16	201/2
Mean	196	+20	4	46.7	4.9		195/18	196/17
							(k=33.9)	(k=13.4)
							(a95=16)	

VGP   28°S & 341°E   dp/dm =9/17   (70% Correction)

Intermediate unblocking component (IB)

	In situ						Corrected 10%	Corrected 100%
Site	Dec	Inc	N	a95	k	So	Dec/Inc	Dec/Inc
11	204	+13	7	14.6	18.0	263/65	205/19	246/58
12	214	+18	6	13.0	27.5	252/28	215/20	226/33
13	205	+25	10	13.8	13.2	099/46	204/21	204/-19
14	210	+25	7	7.0	74.9	099/46	209/21	209/-18
Mean	208	+20	4	8.3	122.9		208/20	218/+13
							(k=310)	(k=3.9)
							(a95=5.2)	

VGP   24°S & 327°E   dp/dm =3/5   (10% correction)

Silurian volcanics were artefacts of inadequate demagnetization and inappropriate tectonic correction.

TOWARD A NEW APW PATH FOR EASTERN AVALONIA

The inclination of the primary HB component in the Silurian volcanics implies a palaeolatitude of 13 ± 5 °S for
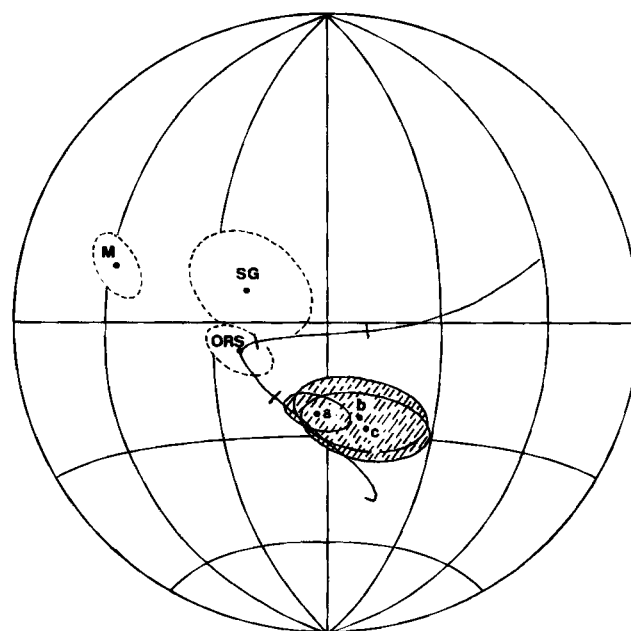
Figure 11. Revised pole (*M*, this study) and previous pole position (SG, Piper 1975) from the East Mendips Silurian Inlier. Poles determined from the overprint magnetizations are also shown. ORS refers to a pole from the Lower Old Red Sandstone (Channell *et al.* 1992). The solid line refers to the Southern British APW path of Trench & Torsvik (1991). Equal-area projection.
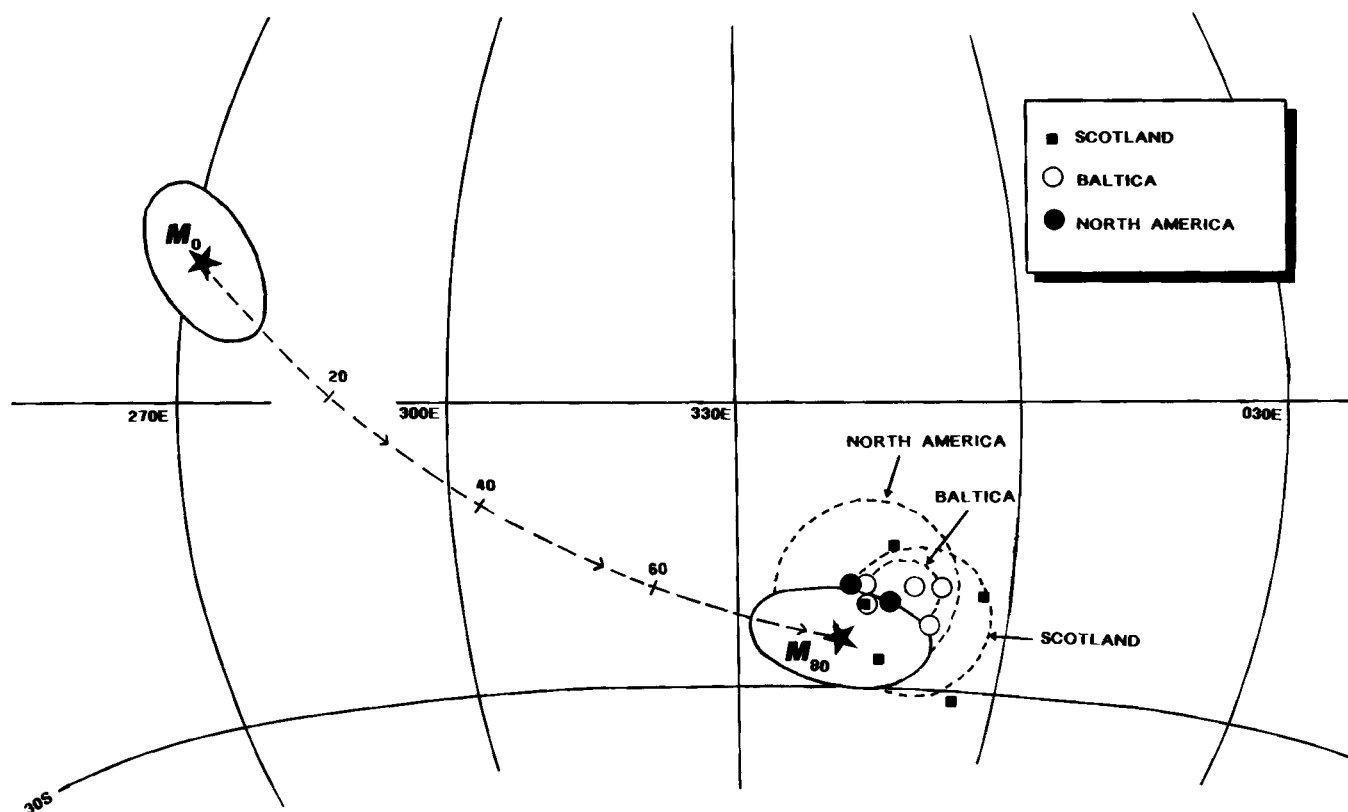
Figure 12. The new palaeomagnetic pole from the East Mendips inlier (*M*) compared to coeval results from North America (solid circles; European coordinates using a Bullard *et al.* 1965 fit), Scotland (solid squares) and Baltica (open circles). An 80° clockwise restoration is shown, about a local vertical axis, which brings the *M* pole into agreement with the remaining poles. Equal-area projection. 95 per cent confidence ellipses are shown.

Southern Britain in Early Wenlock times at comparable latitudes to Baltica and the southern margin of Laurentia. However, the resulting HB palaeopole (13N, 271E) falls away from any of the respective APW paths for southern Britain, Baltica and Laurentia suggesting considerable local structural rotation of the East Mendips inlier. Note that the previous apparent agreement of a pole from the Silurian volcanics (Piper 1975) with the APW path for southern Britain is now discredited (see above). In order to constrain the magnitude of the postulated structural rotation, we consider the locus of Silurian and Devonian APW relative to Baltica and Laurentia.

APW paths for southern Britain (Eastern Avalonia; Fig. 11), Baltica and Laurentia (Briden *et al.* 1984; Van der Voo 1990; Torsvik *et al.* 1990, 1992; Trench & Torsvik 1991a) are characterized by a Siluro–Devonian (S–D 'corner' (approximately 5S, 310E, European coordinates; Bullard, Everett & Smith 1965 fit). The overwhelming majority of S–D 'corner' poles are of *Late Silurian to Early Devonian* age and *Mid-Silurian* poles from Baltica and Laurentia (Scotland and North America; Table 3) plot some 30° of arc away from the S–D 'corner' at approximately 20S, 345E (European coordinates).

The new *Mid-Silurian* pole from the East Mendips Inlier can be reconciled with *Mid-Silurian* data from Baltica and Laurentia after restoring approximtely 80° of clockwise rotation about a local vertical axis (Fig. 12). Local rotations aside therefore, the new palaeomagnetic data are consistent with the hypothesis that:

SOUTHERN BRITAIN (EASTERN AVALONIA) FORMED AN INTERGRAL PART OF BALTICA BY MID-SILURIAN TIMES

Using this hypothesis (Fig. 13), we have constructed an updated Palaeozoic APW for Eastern Avalonia which is based on four of the most reliable Ordovician poles from Southern Britain (Table 3) supplemented with mid-Silurian and younger poles from Baltica (Torsvik *et al.* 1992; *cf.* their Table 1) in order to produce a common Baltica–Avalonia (BALONIA) path from mid-Silurian times. A smooth path (Jupp & Kent 1987) was constructed in such a way that individual poles were graded according to their quality factor *Q* (Van der Voo 1988; see also Torsvik *et al.* 1992), and using a low degree of smoothing (smoothing parameter = 200; see GMAP9 software description in Torsvik & Smethurst 1992). The updated APW path for Southern Britain (Fig. 14, Table 4) differs from all published paths (Briden *et al.* 1984; Torsvik *et al.* 1990, Trench & Torsvik 1991a). Whereas earlier APW paths show a rather open S–D 'corner' for southern Britain, the new APW path shows a tight loop from mid-Silurian to Carboniferous times (Fig. 14).

Lower and middle Ordovician poles from southern Britain differ from contemporary poles from Baltica. The convergence of the Baltica and southern Britain paths is presently indicated as of Late Ordovician age (Fig. 14) but this is poorly constrained given the presently available data.
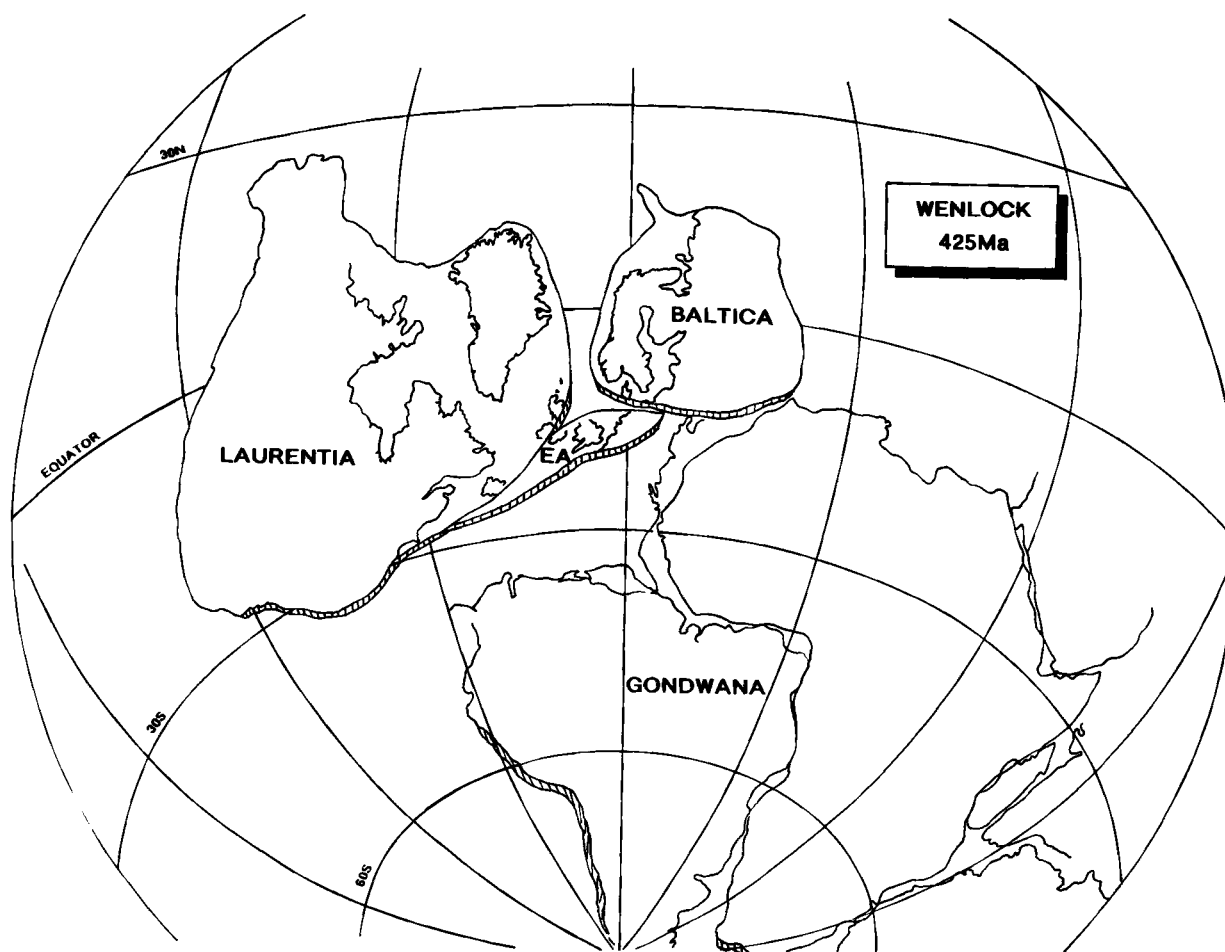
Figure 13. Revised mid-Silurian palaeogeographic reconstruction accounting the new palaeomagnetic data from the East Mendips inlier. Note that the previous requirement for an 'open' Tornquist Sea at this time is removed. Local clockwise rotation of the East Mendips inlier has *not* been applied to the whole of Avalonia. To overcome this, Avalonia is positioned using the mid-Silurian data from Baltica. The Baltica pole yields a palaeolatitude within the 95 per cent confidence limits of the Mendips data. Laurentia is positioned using a mean mid-Silurian pole from the data listed in Table 3 (corrected for opening of the Atlantic). Gondwana is positioned using a pole from the Air plutons (Hargraves, Dawson & Van Houten 1987).

Further studies of Late Ordovician and Silurian rocks from southern Britain are required to better time constrain this path convergence.

CONCLUSIONS

Mid-Silurian volcanics from the East Mendips Inlier record primary HB components, resident in stable low-titanium titanomagnetite and haematite phases of dueteric origin. In addition, some sites show LB and IB components of recent and Hercynian (mid-Carboniferous) origin respectively. These overprints, notably recorded in the lower part of the volcanic sequence, are attributed to a more unstable magnetomineralogy, including maghemite as a remanence carrier.

An overlying sequence of Upper ORS is dominated by secondary syntectonic magnetizations of Hercynian origin. Within the ORS, an HB component was acquired during early Hercynian folding whereas an IB component was acquired later during deformation, or post folding. Both components, at optimum clustering, are comparable in direction with IB components recorded in the Silurian volcanics.

The following magnetotectonic history is suggested for the investigated area:

(1) emplacement of the Silurian volcanic sequence (c. 430 Ma).
(2) Weak folding/tilting, in order to produce the angular unconformity with the upper ORS, and clockwise rotation, perhaps 80° when compared with mid-Silurian palaeo-poles from Baltica and Laurentia. The exact timing and extent of the postulated clockwise rotation is uncertain, but the rotation must predate the Hercynian overprints (point 4 below) which show no evidence for rotation.
(3) Deposition of Upper ORS and Lower Carboniferous (Tournaisian) limestones and shales.

Table 3. Ordovician–Lower Devonian palaeomagnetic poles discussed in the text.

Rock Formation	Code	Age	Lat.	Long.	a95	1 2 3 4 5 6 7	Q
(a) SOUTHERN BRITAIN (EASTERN AVALONIA)							
Trefgarne Volcanics	TG	L. Tremadoc/Arenig	493	56N	306E	5.5	1 1 1 1 0 0 1	5
Stapley Volcanics	SV	E. Llanvirn	473	27N	036E	4.9	1 1 1 1 0 0 1	5
N. Builth Sed/Volc/Intr	NB	L. Llanvirn/Llandeilo	468	18N	013E	10.0	1 1 1 1 0 0 1	5
Builth Volc/Intrusive	BV	L. Llanvirn/Llandeilo	468	03S	005E	7.6	1 1 1 1 0 0 1	5
Tramore Volcanics	TV	E. Caradoc	460	11N	018E	8.5	1 1 1 1 0 1 1	6
Mendips Volcanics/Tuffs	MV	E. Wenlock	430	13N	271E	8.8	1 1 1 1 0 0 1	5
Lower Old Red Sandstone	ORS	L. Silurian/Devonian	409	07S	307E	8.5	1 1 1 1 1 1 1	7
(b) MID-SILURIAN, SCANDINAVIA (BALTICA)							
Gotland Visby Limestone		E. Wenlock	428	19S	352E	5.1	1 1 1 0 1 0 1	5
Gotland Dacker limestone		M. Wenlock	425	19S	349E	2.0	1 0 1 0 1 0 1	4
Gotland Follingbo limestone		M. Wenlock	425	21S	344E	6.0	1 0 0 0 1 0 1	3
Gotland Medby Limestone		E. Ludlow	420	23S	351E	8.0	1 0 0 0 1 0 1	3
Ringerike sandstone		Ludlow	418	19S	344E	9.1	1 1 1 1 1 1 1	7
(c) MID-SILURIAN, NORTH AMERICA (LAURENTIA - EUROPEAN CO-ORDINATES)							
Rose Hill Formation		L. Llandovery	433	19S	356E	6.0	1 1 1 1 0 1 1	6
Wabash Reefs Limestone		L. Ludlow-E. Pridoli	411	17S	352E	5.0	1 1 1 1 1 1 1	7
(d) MID-SILURIAN INTRUSIONS, SCOTLAND (LAURENTIA)							
Strontian granite		435+-10 U/Pb	430	21S	344E	5.2	1 1 1 0 0 0 1	4
Foyers granite		415 Rb/Sr, 400 K/Ar	420	27S	346E	5.7	1 1 1 0 0 0 1	4
Ratagen complex		419+-2.9 Rb/Sr	419	15S	347E			
Helmsdale granite		420 U/Pb, 400 K/Ar	420	31S	355E	6.0	1 0 1 0 0 0 1	3
Peterhead granite		415 Rb/Sr	415	20S	357E	5.2	1 1 1 0 0 0 1	4
(e) SILURIAN GONDWANA (AFRICAN CO-ORDINATES)							
Air Intrusives		435 Ar/Ar	435	43S	009E	6	1 1 1 0 1 0 1	5

References as follows:

S.Britain		TG, Trench et al. (1992a)
		SV, McCabe & Channell (1990)
		NB, McCabe et al. (1992)
		BV, Trench et al. (1991)
		TV, Deutsch (1980)
		MV, This study.
		ORS, Channell et al. (1992)
Baltica	Visby Limestone	Trench & Torsvik (1991b)
	Dacker Limestone	Claessen (1979)
	Follingbo Limestone	Claessen (1979)
	Medby Limestone	Claessen (1979)
	Ringerike Sandstone	Douglass (1988)
North America	Rose Hill	French & Van der Voo (1979)
	Wabash Reef	McCabe et al. (1985)
Scotland	Strontian Granite	Torsvik (1984)
	Foyers Granite	Torsvik (1984)
	Ratagan intrusion	Turnell (1985)
	Helmsdale Granite	Torsvik et al. (1983)
	Peterhead Granite	Torsvik (1985)
Gondwana	Air Intrusions	Hargraves et al. (1987)

(4) Hercynian (mid-Carboniferous; post 350 Ma) deformation, syn- to post-tectonic remagnetization of the upper ORS and partial magnetic overprinting of the Silurian volcanics (Type 2).

The new palaeolatitude estimate for Southern Britain for mid-Silurian times (13 ± 5S) is comparable with palaeolatitudes for Baltica. Hence, a wide mid-Silurian Tornquist Sea, as indicated by the previous palaeomagnetic data set (Fig. 1a; see also Trench & Torsvik 1991b), is no longer required. Faunal and palaeomagnetic data both therefore suggest latitudinal closure of the Tornquist Sea prior to Wenlock time. The new palaeomagnetic data also imply latitudinal closure of the British sector of the Iapetus Ocean prior to Wenlock time (compare Figs 1 and 13).
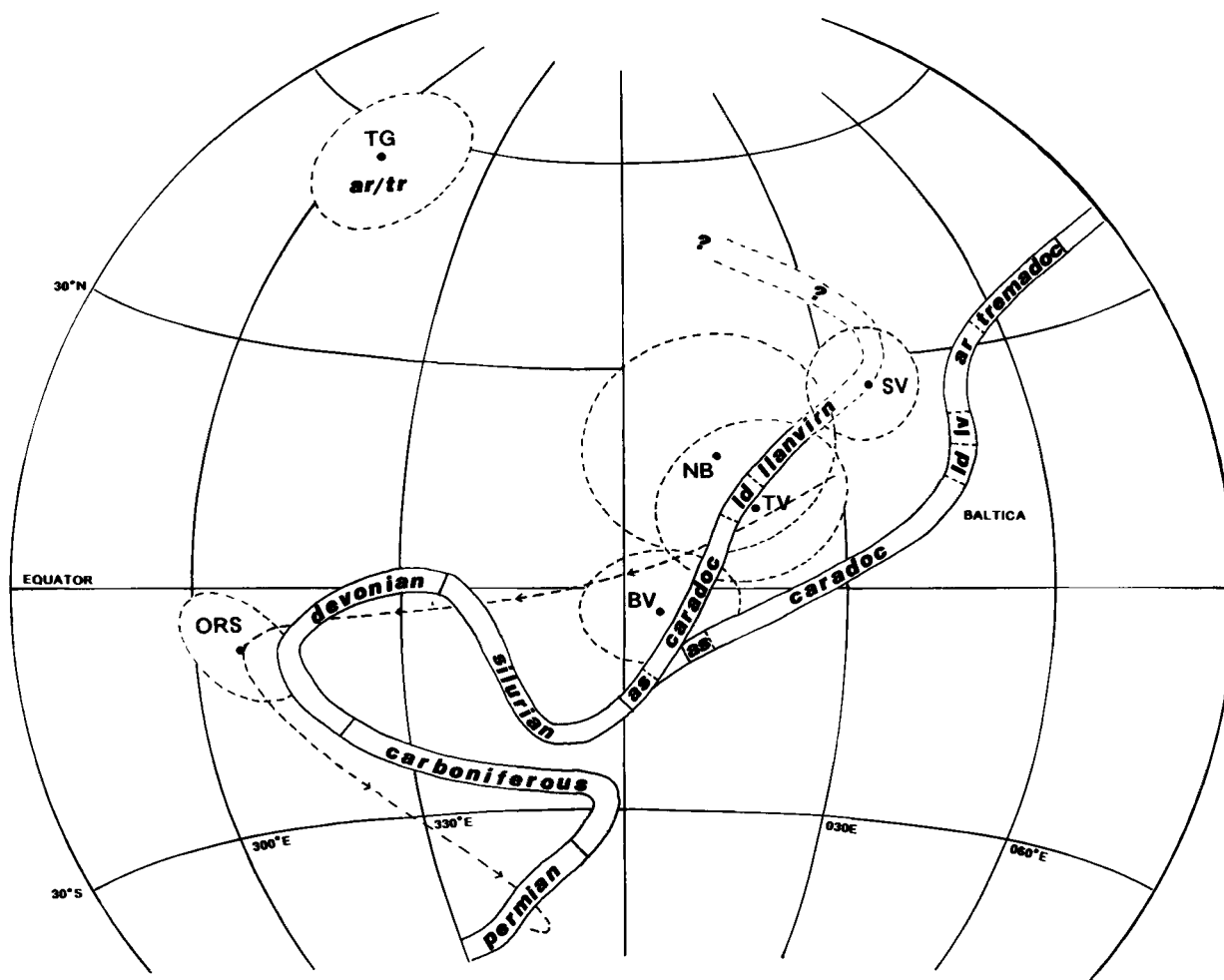
Palaeolatitudes for Baltica and Eastern Avalonia are now comparable from early mid-Ordovician (Llanvirn) times. This implies that separation of Baltica and southern Britain by the Tornquist Sea was in palaeolongitude. As a result, the convergence history between Baltica and Eastern Avalonia cannot be determined from palaeomagnetic data

alone (see Torsvik *et al.* 1992). Nevertheless, the palaeomagnetic data indicate that southern Britain and Baltica experienced comparable northward drifts and counterclockwise rotation from mid-Ordovician times.

The revised mid-Silurian (c. 425–430 Ma) palaeogeography therefore portrays Baltica/Eastern Avalonia (BALONIA) in their present relative position but at near equatorial latitudes (Fig. 13).

ACKNOWLEDGMENTS

Figure 14. Revised APW path for Eastern Avalonia constructed using the hypothesis that Avalonia and Baltica were juxtaposed by Wenlock time (as indicated by the new palaeolatitude estimate from the east Mendips Inlier). Only the most reliable poles from Southern Britain have been included (see Table 3). The Baltica APWP is also shown (after Torsvik *et al.* 1992). The dashed line refers to the old Southern British APW path (see Fig. 11) of Trench & Torsvik (1991). ar = Arenig; tr = Tremadoc; lv = Llanvirn; ld = Llandeilo; as = Ashgil.

Table 4. A revised smooth APW path for Southern Britain (250 to 475 Ma) listed in approximately 10 Ma intervals.

AGE	LATITUDE	LONGITUDE
250	-45.4	336.3
260	-47.5	336.2
270	-44.8	340.4
281	-39.7	346.5
290	-35.5	353.0
299	-30.9	356.9
312	-27.4	357.4
318	-26.6	355.9
331	-26.0	350.0
344	-25.2	340.8
350	-24.2	335.2
362	-20.6	324.6
369	-17.1	318.7
381	-11.1	313.8
389	-6.9	314.3
400	-1.0	322.8
410	0.3	336.5
420	-12.3	344.5
430	-20.0	351.3
441	-15.3	2.6
450	-5.0	10.9
460	5.3	15.6
470	17.2	17.5
475	28.2	16.3

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