

Implications of palaeomagnetic data from the Tortworth Silurian inlier (southern Britain) to palaeogeography and Variscan tectonism

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SUMMARY

Palaeomagnetic data are presented from early Silurian (Upper Llandovery) lavas from the Tortworth Silurian inlier of south-west England. Two magnetization components are recognized on the basis of contrasting demagnetization characteristics. A lower unblocking-temperature component (<350 °C) is oriented parallel to the Earth's present magnetic field at the sampling site ($N = 46$, declination = 352°, inclination = 69°, $k = 52.1$, $\alpha_{95} = 2.9^\circ$). A higher unblocking-temperature component (350–600 °C) is inferred to be primary on the basis of a stratigraphy-parallel reversal pattern (combined tilt-corrected mean: $N = 42$, declination = 056°, inclination = -30°, $k = 22.6$, $\alpha_{95} = 4.7^\circ$). Geological implications of these new data are as follows.

(1) The calculated Upper Llandovery (c. 430 Ma) palaeolatitude for the site (16°S) is consistent with tectonic models invoking pre-Wenlock closure of the Iapetus Ocean across Britain.

(2) The declination of the primary magnetization indicates substantial clockwise rotation within this sector of the Variscan thrust belt. Rotation is most likely to be linked to early Variscan northward thrust transport with components of dextral transpression. The amount of clockwise rotation is approximately 85° in the south (Mendips) and decreases to 33–63° in the north (Tortworth).

(3) The polarity of the primary magnetization (Lower Trap lava: reversely polarized; Upper Trap lava: normally polarized) is consistent with that expected from a preliminary analysis of the Silurian magnetic-field reversal pattern.

Key words: palaeogeography, palaeomagnetism, UK.

INTRODUCTION

Studies of palaeomagnetism, biogeography, structural geology and sedimentary provenance are beginning to yield a coherent picture of Silurian palaeogeography and tectonics across palaeo-Europe. Present consensus favours Mid-Silurian closure of the British sector of the Iapetus Ocean with the European palaeocontinents resembling their present relative geography at near equatorial latitudes (Scotese & McKerrow 1990; Trench & Torsvik 1992; Soper *et al.* 1992; Torsvik *et al.* 1993). Additional Silurian palaeomagnetic data are required, however, as existing palaeopole determinations, although increasing in reliability, remain few in number. For example, the Mid-Silurian position of southern Britain relies solely upon the recent revision of palaeomagnetic data from early

Wenlock (c. 425–430 Ma) lavas of the East Mendips inlier (Torsvik *et al.* 1993).

Likewise, suggestions that Variscan tectonism (late Carboniferous) was accompanied by rotational deformation in south-west Britain (McClelland 1983; Trench & Torsvik 1992; Torsvik *et al.* 1993) require additional palaeomagnetic data sets for corroboration. The present study therefore aimed to address these outstanding problems by examining the palaeomagnetic signature of Upper Llandovery lavas of the Tortworth inlier, south-west England (Fig. 1).

BACKGROUND GEOLOGY AND PALAEOMAGNETIC SAMPLING

The Tortworth inlier (Figs 1a–c) contains a sequence of early Ordovician to Carboniferous sediments, overlain

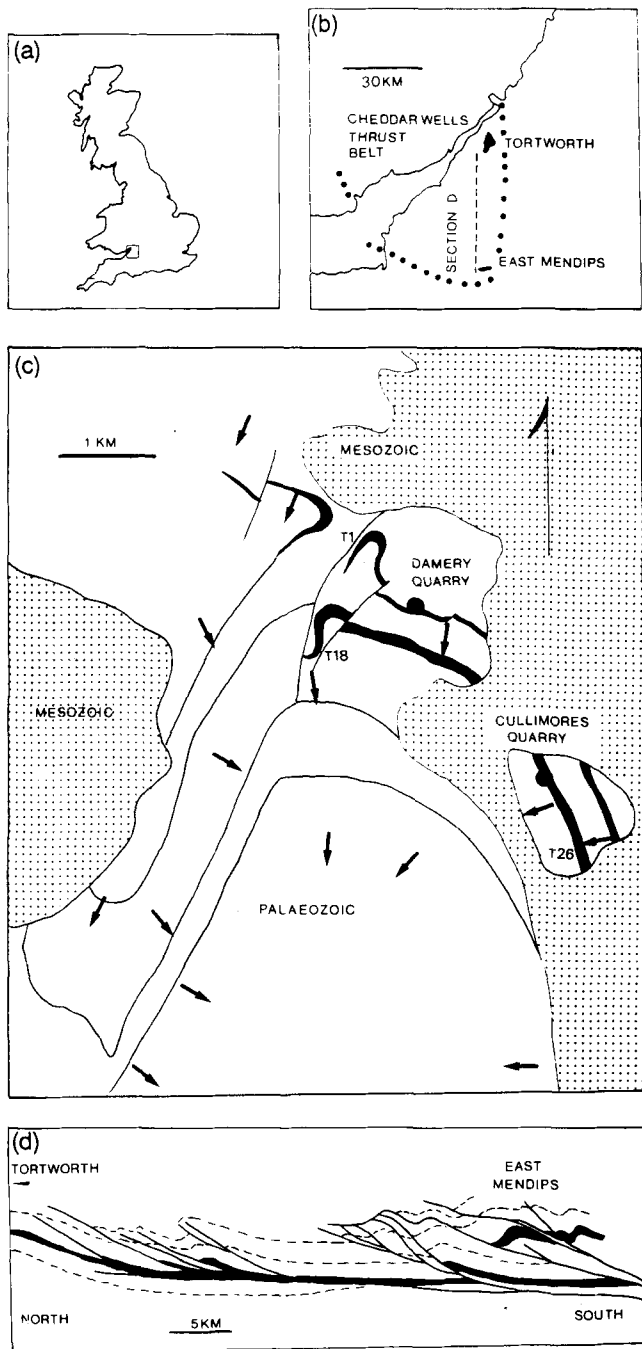


Figure 1. (a) Location of the study area within Britain. (b) The location of the Tortworth (51.7°N, 2.5°W) and East Mendips (51.2°N, 2.5°W) Silurian inliers in relation to the Cheddar Wells Thrust Belt (Green 1992) otherwise termed the Bristol–Mendips foreland thrust belt (Williams & Chapman 1986). (c) Geological sketch map of the Tortworth Silurian inlier (after Curtis 1972) depicting main lithological units. The Upper and Lower Traps are shown in black ornament. Palaeomagnetic sampling localities of this study (Damery & Cullimore's Quarries) and those of Morris *et al.* (1973) are depicted (T1, T18 and T26). Selected dip arrows after Curtis (1972) and this study are indicated. (d) Simplified cross-section between the Tortworth and East Mendips Silurian inliers after Williams & Chapman (1986). The approximate location of the section is shown in (b) Black ornament used to highlight the structure is not the same as the black in (c).

unconformably by flat-lying Mesozoic deposits. Although there are many sedimentary breaks within the Palaeozoic sequence, angular discordances are minor (Curtis 1972); the main structures are related to Variscan tectonism. Variscan deformation of the area occurred at intervals throughout much of the late Palaeozoic (Shackleton, Ries & Coward 1982) with maxima in the Westphalian. The major movements in Somerset are thought to have been produced by a northward-propagating, southward-dipping thrust-stack comprising six major thrust slices and it is possible that the Tortworth inlier is underlain by the basal thrust (Fig. 1d; Williams & Chapman 1986). Metamorphism of the area does not exceed zeolite facies (Oliver 1988) with conodont alteration indices not exceeding 2 (i.e. palaeotemperatures <140 °C; Aldridge 1986). Very low-grade metamorphism in the Palaeozoic of south-west Britain is interpreted to result from the combined effects of stratigraphic and tectonic burial (Warr, Primmer & Robinson 1991).

Palaeomagnetic experiments are reported here from the two Upper Llandovery volcanic horizons, termed the Lower Trap (Locality 1 at Damery Quarry) and the Upper Trap (Locality 2 at Cullimore's Quarry) of the Tortworth inlier (Fig. 1c). Unfortunately, *extremely poor exposure* in the study area prevented additional sampling of these lavas at sites for which a reliable structural control could be established. The lavas were extruded in latest Llandovery (late Telychian) times (Ziegler, Cocks & McKerrow 1968) which corresponds to an age of 425 Ma using the time-scale of McKerrow, Lambert & Cocks (1985) or 432 Ma using the time-scale of Harland *et al.* (1989). The Lower Trap is a fine-grained grey-black olivine basalt, locally displaying amygdaloidal texture with a maximum thickness of ~30 m; while the Upper Trap, with a maximum thickness of ~45 m, is a blue-grey pyroxene andesite with quartz xenocrysts and local amygdaloidal texture (Curtis 1972).

PREVIOUS PALAEOMAGNETIC WORK— TORTWORTH AND EAST MENDIP SILURIAN INLIERS

Tortworth

Morris *et al.* (1973) briefly describe palaeomagnetic results from two of five attempted localities within the Lower (site T1) and Upper (site T18) Trap lavas (Fig. 1C). Samples from their remaining three sites, including both localities reported in the present study (Damery Quarry, their site T19; Cullimore's Quarry, their site T20) failed to yield systematic directional data. A mean direction of declination 261°, inclination +34°, $k = 12.0$, based upon 11 samples, is quoted following alternating-field (AF) demagnetization and tilt correction. Significantly, Morris *et al.* (1973) noted that the lavas displayed opposite polarity but omitted to note their stratigraphic order.

Piper (1975) resampled the Lower Trap lava at Damery Quarry (his site 5) as part of a wider study of Silurian lavas of the Tortworth and East Mendips inliers. He reports a site mean direction of declination 239°, inclination 62°, $k = 37$, based upon nine samples, following AF demagnetization and tilt correction. Based on petroscopic examination and Curie-temperature measurements, Piper (1975) concluded

that deuterically oxidized titanomagnetite (oxidation class 3–5) was the principal remanence carrier.

East Mendips

Palaeomagnetic work in the East Mendips Silurian inlier has recently been summarized by Torsvik *et al.* (1993). These authors present new data, supported by agglomerate tests, which indicate a primary origin for the predominant magnetization component (declination 095° , inclination -24° , $k = 35.2$, $\alpha_{95} = 8.8^\circ$ based upon nine sites).

PALAEOMAGNETIC EXPERIMENTS

The natural remanent magnetization (NRM) of samples was measured with a JR-5 spinner magnetometer. The stability of NRM was tested using stepwise thermal demagnetization experiments given that AF demagnetization had earlier failed to identify systematic demagnetization characteristics at these sites (Morris *et al.* 1973). Characteristic remanence components were calculated using least-squares analysis.

Lower Trap (Damery Quarry, Locality 1)

NRM directions from the Lower Trap lie close to the Earth's present magnetic field direction at the site (Fig. 2a,

'nrm₁'). NRM intensity and susceptibility average to 570 ± 262 mA/m and 20.4 ± 5.6 SI $\times 10^{-3}$ units respectively. Upon detailed thermal demagnetization, two components of magnetization are recognized (Figs 2b, 3c and 3d). The lower unblocking-temperature component, termed LB, demagnetizes at temperatures below 350°C , and displays a northerly declination and steep positive inclination when viewed in *in situ* coordinates (Fig. 2b, 'lb'). The higher unblocking-temperature component, termed HB, demagnetizes between 350 and 550°C (Figs 3c and d), and displays SW declination and steep positive inclination in *in situ* coordinates (Fig. 2b, group hb₁). Some magnetic viscosity is observed at higher temperatures where demagnetization trajectories become 'noisy' (Fig. 3d, temperatures $>425^\circ\text{C}$). Following tectonic correction (see below), the HB component maintains a SW declination but shallows in inclination (Table 1). Curie temperatures between 550 and 580°C (Fig. 4), the thermal unblocking spectra and petroscopic studies (Piper 1975) suggest that deuterically oxidized titanomagnetite is the foremost remanence carrier.

Upper Trap (Cullimore's Quarry, Locality 2)

NRM directions from the Upper Trap form a non-Fisherian distribution with NE declination and negative inclination

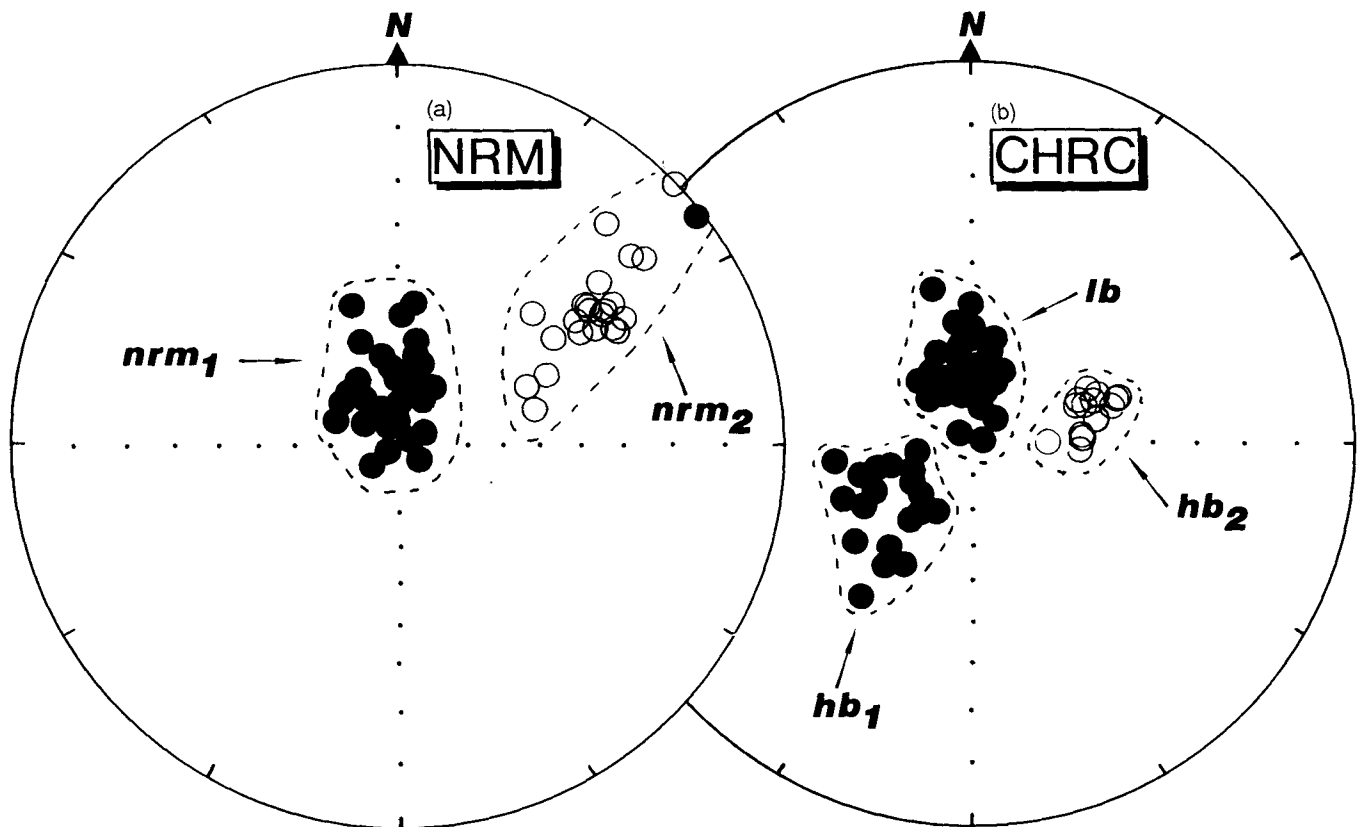


Figure 2. (a) NRM directions from the Lower Trap (nrm₁) and Upper Trap (nrm₂) Llandovery lavas. Equal-angle projection. Throughout this paper, solid (open) symbols refer to directions projected on the lower (upper) hemisphere of the stereonet. (b) Characteristic remanence directions obtained from the Lower and Upper Traps. All directions are shown in the *in situ* reference frame: lb, lower unblocking-temperature magnetization component from both localities; hb₁, higher unblocking-temperature magnetization component from the Lower Trap (locality 1); hb₂, higher unblocking-temperature magnetization component from the Upper Trap (locality 2).

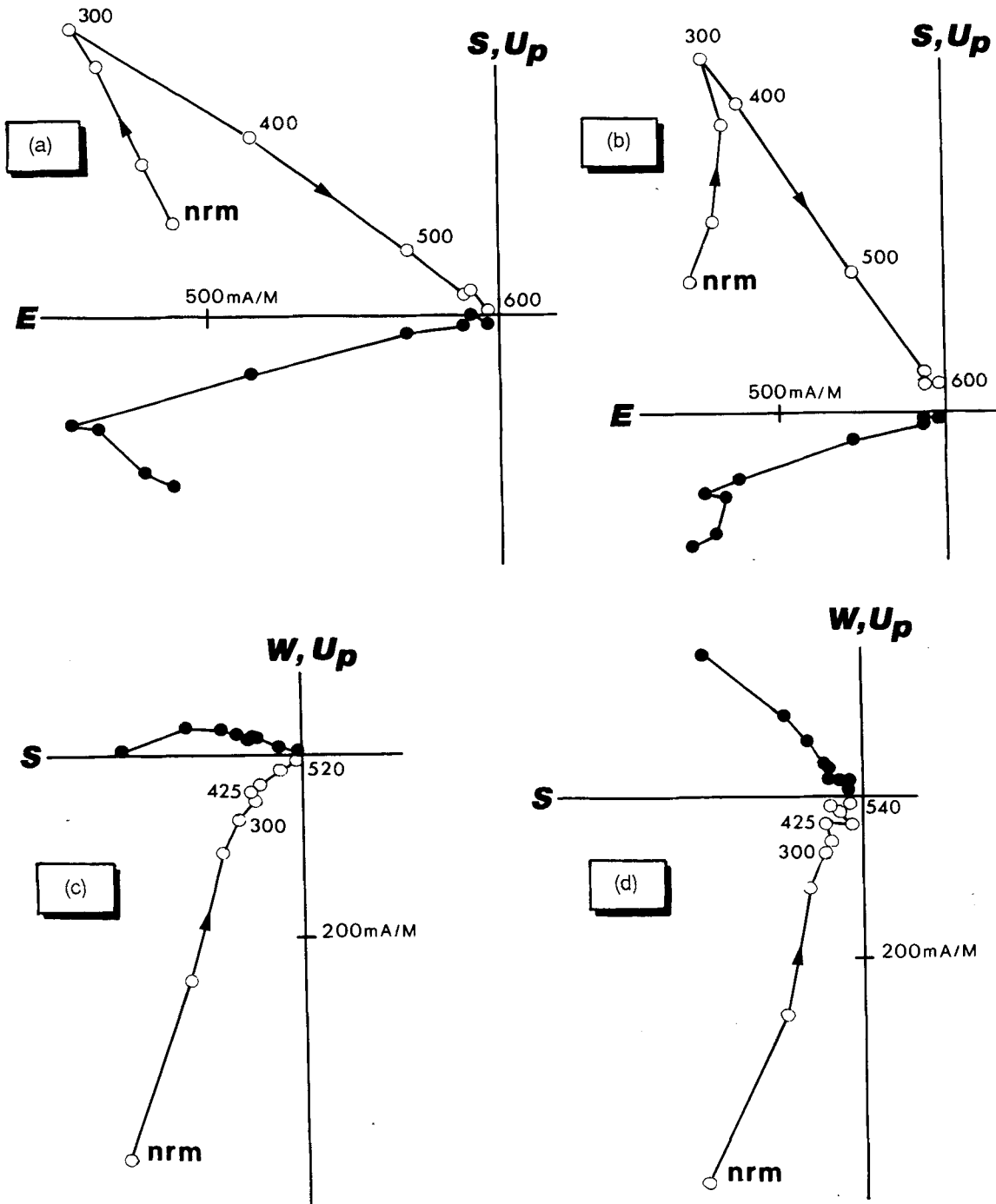


Figure 3. Orthogonal projections showing characteristic demagnetization characteristics of the Upper (a and b) and Lower (c and d) Traps. In all examples, solid (open) symbols refer to projection on the horizontal (vertical) plane. Plots are shown in coordinates corrected for tectonic dip (MODEL0, Classic fold-test along bedding strike; Table 1). Intensities of remanence are indicated on the axes of each diagram.

(Fig. 2a, 'nrm₂'). NRM intensity and susceptibilities average to 836 ± 113 mA/m and 18.1 ± 3.5 SI units $\times 10^{-3}$ respectively. Two magnetization components are recognized (Figs 3a and b) which are termed LB and HB (comparable to the Lower Trap). Component LB demagnetizes at temperatures below 350 °C and has an *in situ* direction close to Earth's present magnetic field (Fig. 2B, 'lb'). Component HB demagnetizes at temperatures between 350 and 600 °C,

decays towards the origin of the orthogonal projection (Figs 3a and b), and displays an *in situ* NE declination and moderate negative inclination (Table 1). Upon tectonic correction (see below), component HB displays moderate-shallow negative inclinations and ENE declination (Table 1). Curie temperatures close to 580 °C are observed, but there is a noticeable decrease in saturation magnetization (oxidation) after heating and cooling (Fig. 4).

Table 1. Palaeomagnetic data from Upper Llandovery lavas of the Tortworth Silurian Inlier (51.7°N–2.5°W).

IN-SITU	MODEL0	MODEL1	MODEL2	N	α_{95}	k	POLARITY
<u>Lower Trap</u>							
LB1	352 +70			26	4.4	42.6	NORMAL
HB1	226 +59	222 +26	220 +26	227 +26	22	5.2	36.3 REVERSE
<u>Upper Trap</u>							
LB2	352 +67			20	3.8	74.4	NORMAL
HB2	069 –55	072 –33	069 –33	072 –33	20	2.6	162.7 NORMAL
<u>Average</u>							
HB1+HB2	056 –30				42	4.7	22.6 MIXED

MODEL0 – Classic fold–test along bedding strike; $S_0=127/33$ (site 1); $S_0=168/22$ (site 2)

MODEL1 – Unplunging (098/17) & unfolding (site 1=149/20; site 2=211/23) based on all available structural data

MODEL2 – Unplunging (179/22) & unfolding (site 1=089/25; site 2=084/4) based on structural data from sites 1 & 2

LB=Low unblocking; HB=High unblocking; N=number of samples; α_{95} =95% confidence circle; k=precision parameter

TECTONIC CORRECTIONS AND AGE OF MAGNETIZATION COMPONENTS

Component LB

The *in situ* distribution of component LB for both lavas is identical (Fig. 2 and Table 1) to that expected of a present-day axial dipole field at the site. This fact, coupled with the low unblocking temperature of the magnetization indicates a recent viscous remanent magnetization (VRM) origin.

Component HB

Poles to bedding from the Silurian–Carboniferous beds of the Tortworth inlier (Fig. 5) reveal a syncline which plunges 17° towards 188° (consistent with the outcrop pattern of Fig. 1). Taking only the bedding at the two sampling localities implies a syncline plunging 20° to 239° (Fig. 5). Tectonic corrections to component HB (Table 1 and Fig. 6) have been performed to accommodate each of these possible structures (unplunging plus unfolding) together with a simple tectonic correction using the observed strike and dip at each locality. Note in all cases that the inclination/bedding angle of a primary magnetization is unaffected by the plunge of a fold structure.

Unfortunately, the existence of only two sampling localities results in an inconclusive fold test (at the 95 per cent confidence level) upon tectonic correction. Given the observation of a magnetic-field reversal between the time of extrusion of the Lower (reverse) and Upper Trap (normal) and the correspondence of ‘unfolded’ inclinations (Fig. 6) with those from the early Wenlock Mendip volcanics (~50 km apart), we interpret component HB to be of

primary origin. The Lower and Upper Trap directions, however, are not antipodal and they differ by some 30°–39° dependent on the selected unfolding and unplunging model. Within the Damery Quarry region (Fig. 1), minor faulting and slickensides have been observed (Curtis, M.L.K., private communication 1993), and it is suggested that the declination differences could be resolved by local block-rotations between the two investigated areas. We note that a partial/complete ‘strike restoration’ (strikes are 127° and 168°; Table 1) will essentially eliminate the declination discrepancy.

TECTONIC AND STRUCTURAL IMPLICATIONS

Identification of a primary remanence direction from the Tortworth Silurian inlier, when combined with palaeomagnetic data from the East Mendips Silurian inlier (Torsvik *et al.* 1993), carries significant structural/tectonic implications for both the Silurian and late Carboniferous development of this region.

Silurian palaeogeography

The calculated Upper Llandovery palaeolatitudes for the Tortworth area (14 and 18°S) are in excellent agreement (Fig. 7) with that predicted by recently proposed tectonic models for the closure of the Iapetus Ocean across Britain in Silurian time (Trench & Torsvik 1992; Soper *et al.* 1992; Torsvik *et al.* 1993). In these scenarios, biogeography (Cocks & Fortey 1982) and palaeomagnetic data (Van de Voo 1988; Torsvik & Trench 1991) indicate that, while Avalonia was widely separated from Laurentia during the Ordovician, both continents were adjacent by the early

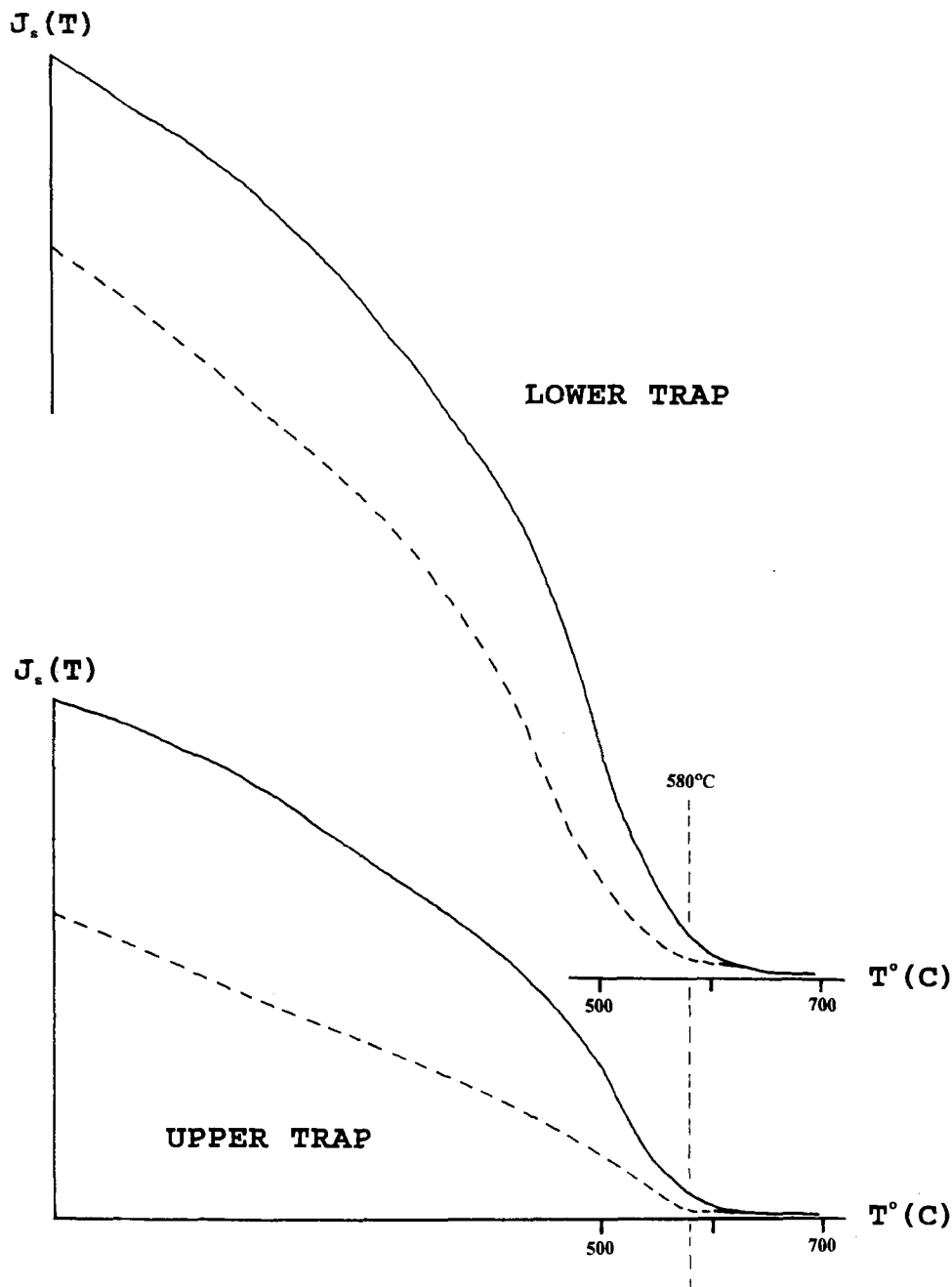


Figure 4. Thermomagnetic analysis for samples from the Lower and Upper Traps.

Wenlock (Fig. 8). Thus, although subduction continued below the eastern margin of Laurentia until the early Devonian (Thirlwall 1988), only continental crust appears to have been subducted in the British area after the Wenlock (McKerrow, Dewey & Scotese 1991).

We note that possible counterclockwise rotation associated with sinistral Silurian closure of Avalonia with Laurentia (Soper *et al.* 1992) is likely to have been removed by subsequent clockwise rotation in the early stages of the Variscan tectonism.

Variscan tectonism

A variety of tectonic interpretations exist for the Variscan orogeny in Europe. Of these, Rast (1988) identifies three

end-member scenarios as follows:

- (1) an intracontinental fold belt (Weber & Behr 1983);
- (2) a dextral strike-slip orogeny (Arthaud & Matte 1977; Badham 1982);
- (3) a continent–continent collisional orogeny (Dewey & Burke 1973; Lorenz & Nicholls 1984).

Present consensus favours oblique late Palaeozoic collision between Gondwana, peri-Gondwanan microplates, and Laurussia (Ziegler 1989) inducing predominantly dextral-slip (i.e. a combination of 2 and 3 above). Given this tectonic scenario, we interpret the clockwise rotation of both the Tortworth (Upper Llandovery ~33–63° rotation) and East Mendips Silurian inliers (early Wenlock ~85° rotation) in terms of the northward emplacement of a thrust-stack

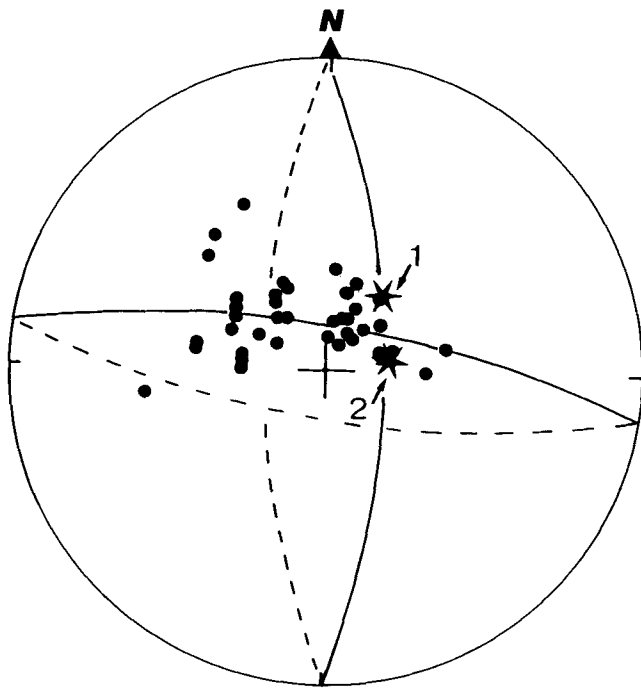


Figure 5. Best-fitted great-circles to poles to bedding from (i) only sampling locations 1 and 2 (stars) and (ii) all available poles to bedding from Silurian–Carboniferous beds of the Tortworth inlier (see text).

(Williams & Chapman 1986) within a dextral strike-slip regime. Thin-skinned rotations, accommodated along thrusts or low-angle decollement planes, precede the latest phases of folding (late Carboniferous–early Permian), since syn- to post-fold Variscan remagnetizations in the Mendips area (Torsvik *et al.* 1993) are non-rotated. Variscan remagnetization features are widespread in the Mendips

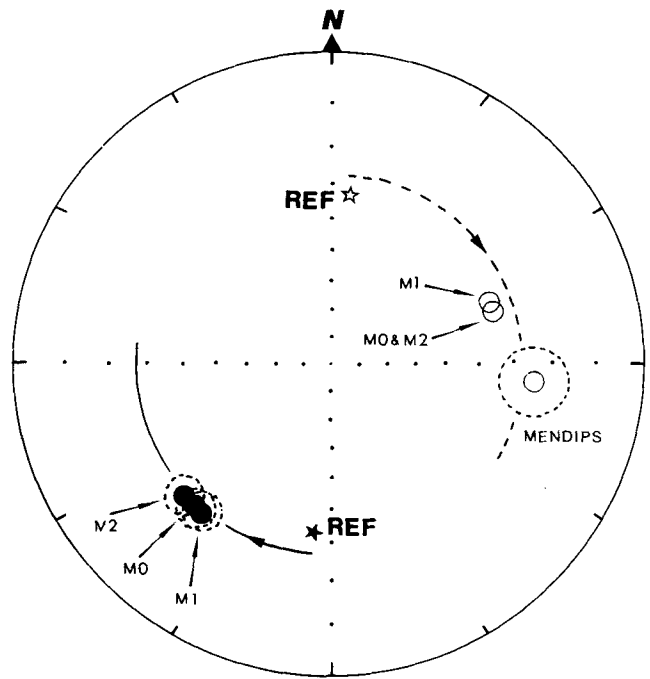


Figure 6. Tectonic correction of the mean declination and inclination from the Lower (reverse) and Upper (normal) Traps. M0 = simple tectonic correction using strike and dip at each locality; M1 and M2 = unplinging plus unfolding (*cf.* Table 1). The mean direction (tectonically corrected) from the early Wenlock Mendips lavas is also shown. The reference palaeofield direction (REF) at the site (51.5°N, 2.5°W; mean of Mendips–Tortworth region) is declination = 189.4°, inclination = 32.7°. This is based on a reference pole of 20.2°S–348°E– A_{05} = 3.8 (mean of five Baltica Mid-Silurian poles listed in Torsvik *et al.* 1993). Average of Mid-Silurian poles from Laurentia (North American data in a Bullard, Everett & Smith (1965) fit or Scottish data) yields almost identical poles (*cf.* Torsvik *et al.* 1993).

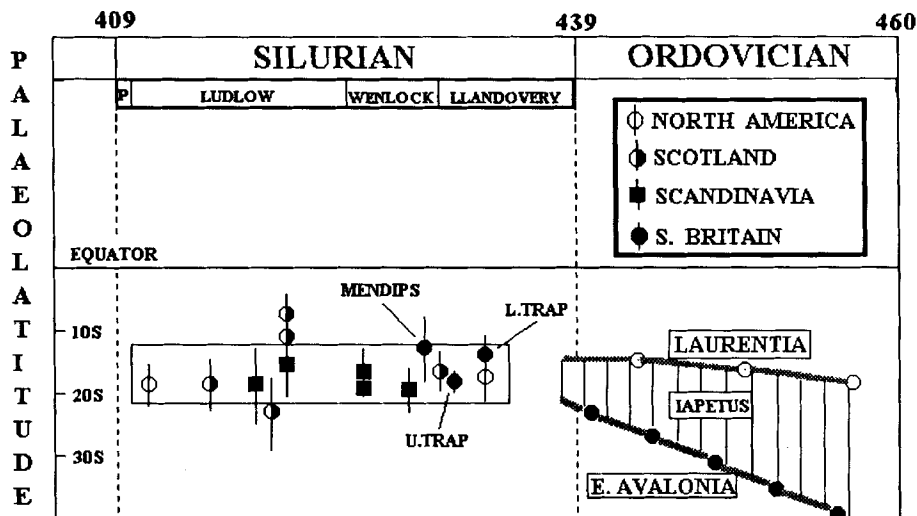


Figure 7. Comparison of Silurian palaeolatitudes (and error bars) obtained from North America and Scotland (Laurentia), Scandinavia (Baltica) and southern Britain (eastern Avalonia). Note that the broad agreement; mostly within 10° of latitude, from Upper Llandovery times. The largest latitude scatter is observed with the Scottish, i.e. Mid-Silurian granites, and probably least reliable data set. All poles are listed in Torsvik *et al.* 1993. Pre-Silurian palaeolatitudes estimates for Laurentia and eastern Avalonia are taken from Mac Niocaill & Smethurst (1994) and Torsvik *et al.* (1993) respectively. Note that all palaeolatitudes estimates are according to a reference location of 51.5°N and 2.5°W. The Laurentian palaeolatitudes pathway compares with that of Van der Voo (1988) and Van der Pluim, Johnson & Van der Voo (1993), but differs somewhat from their plot due to our use of a European reference locality.

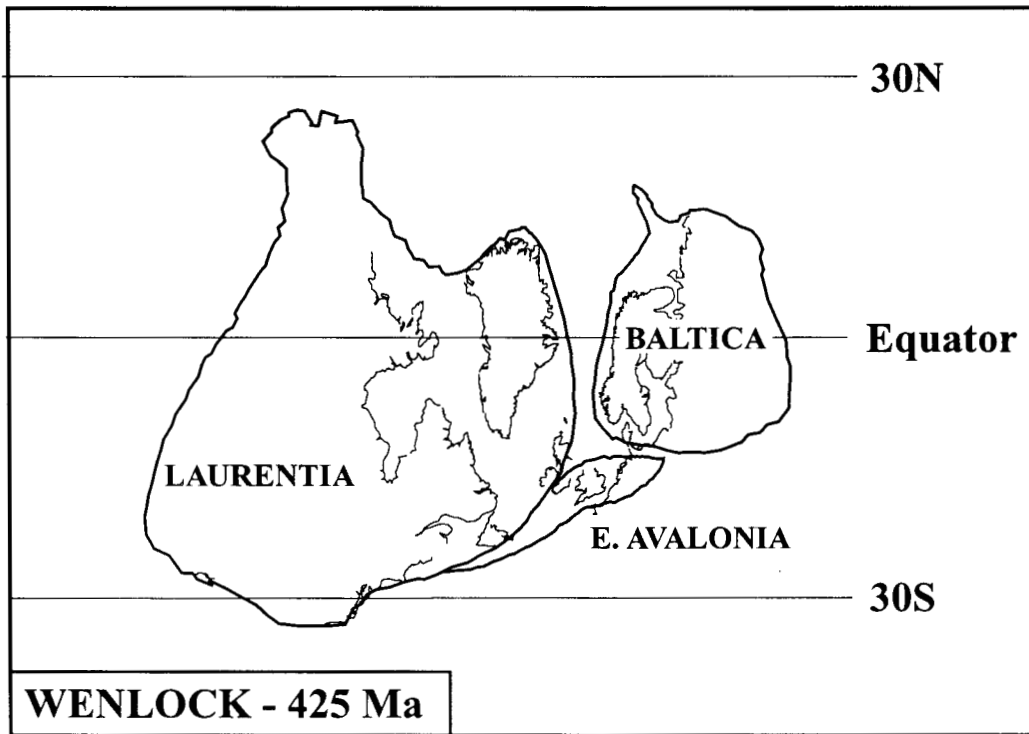


Figure 8. A palaeogeographic reconstruction for Laurentia, eastern Avalonia and Baltica in Mid-Silurian times (c. 425 Ma). Reconstruction poles are listed in Trench & Torsvik (1992) and Torsvik *et al.* (1993).

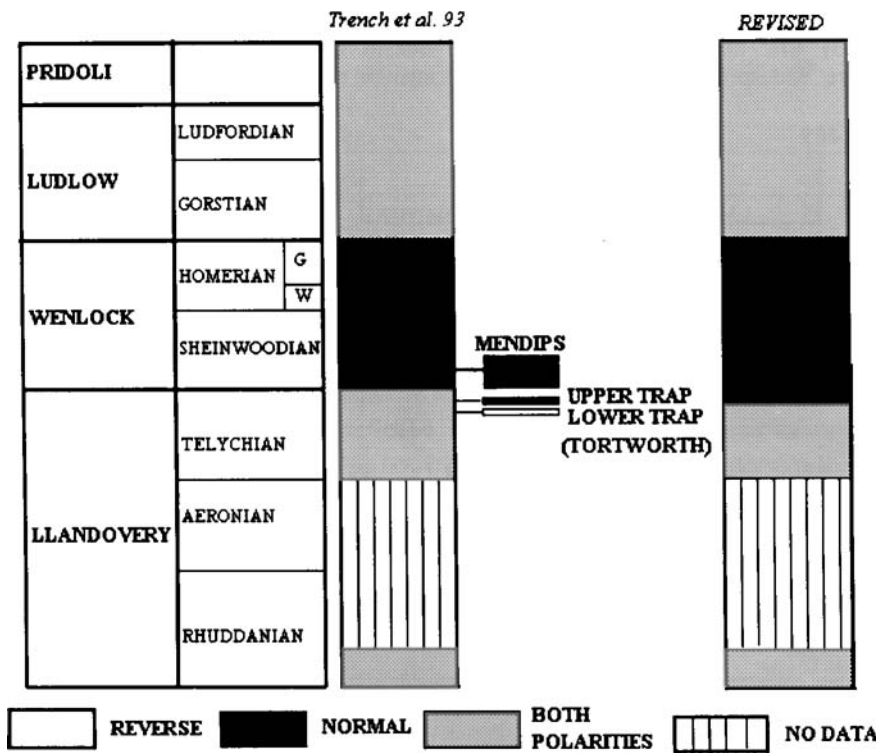


Figure 9. Revised magneto-polarity chart for the Silurian period (revised from Trench *et al.* 1993). The normal polarity data from the Upper Trap (Upper Llandovery) suggest that the Wenlock normal interval starts in the Upper Llandovery.

area, but apparently absent in the Tortworth area. This may reflect less tectonic cover to the north of the fold belt. However, it is quite rational to assume that the LB component (<300 °C) from Tortworth has replaced the Variscan overprint component.

THE POLARITY OF THE SILURIAN MAGNETIC FIELD

The polarity data from the present study can be compared to existing Silurian data from palaeomagnetic studies conducted elsewhere in the world (Fig. 9). When formulated into a preliminary polarity time-scale (Trench *et al.* 1993), these studies indicate that Llandovery times were characterized by rapid reversals whereas Wenlock times experienced a predominantly normal polarity magnetic field. The present data concur with this pattern (Fig. 9) and may constrain the onset of the Wenlock normal interval to uppermost Llandovery times.

CONCLUSIONS

(1) The upper Llandovery lavas of the Tortworth Silurian inlier carry two magnetization components revealed upon thermal demagnetization: LB, a viscous magnetization of recent origin and HB, a dual-polarity magnetization of primary Silurian origin.

(2) The inclination of component HB implies an average palaeolatitude of 16°S for Tortworth during late Llandovery times. This latitude is consistent with closure of the Iapetus Ocean across Britain by Mid-Silurian times.

(3) The declination of component HB requires that the Tortworth inlier has experienced a clockwise rotation in the order of 33–63°. This result compares favourably with a similar, but larger (85°), clockwise rotation determined for the East Mendips Silurian inlier. Both rotations are interpreted to have occurred during late Carboniferous Variscan thrusting within a dextral transpressional environment.

(4) The respective polarity of component HB in the Lower (reverse) and Upper (normal) Trap lavas is consistent with a Silurian palaeofield which displayed mixed polarity during Llandovery times and predominantly normal polarity during Wenlock times.

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