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RESEARCH NOTE

A revised Palaeozoic apparent polar wander path for Southern Britain (Eastern Avalonia)

Allan Trench and Trond H. Torsvik
Department of Earth Sciences, University of Oxford, Parks Road, Oxford OX1 3PR, *UK*

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SUMMARY

A revised apparent polar wander path (APWP) is presented for Palaeozoic Southern Britain. The new path, based on a structural reinterpretation of existing data combined with new data from Wales, differs significantly from previous estimates in the following ways:

(1) the locus of the Ordovician path segment is extended by approximately 25 degrees of arc;
(2) revised time-calibration of the APWP suggests more Ordovician APW than previously calculated; and
(3) the new path implies Middle Ordovician separation across the British sector of Iapetus to be greater than previous palaeomagnetic estimates based on APWP analyses (*c.* 3300 km; Northern Britain *c.* 15S, Southern Britain *c.* 45S).

Key words: apparent polar wander path, Eastern Avalonia, Iapetus Ocean, Palaeozoic palaeomagnetism, Southern Britain.

1 INTRODUCTION

Previous Palaeozoic palaeomagnetic data compilations for Britain have been made by Briden *et al.* (Briden, Morris & Piper 1973; Briden, Turnell & Watts 1984; Briden *et al.* 1988), Piper (1987) and Torsvik *et al.* (1990a). Of the major tectonic elements in Britain, i.e. (i) North of the Great Glen Fault, (ii) South of the Great Glen Fault and North of the Iapetus suture, and (iii) South of the Iapetus suture (Southern Britain), the APWP for the latter block has been the least well defined. The present synthesis seeks to remedy this point, and in this account we present a revised APWP for Southern Britain. In Palaeozoic times, Southern Britain formed a constituent of the Avalonian terrane, which also comprised the Ardennes of Belgium and northern France, the Avalon peninsula of Newfoundland, much of Nova Scotia, southern New Brunswick and coastal New England (McKerrow 1988).

In this paper we use the compilation by Torsvik *et al.* (1990a) as a starting point for discussion (Fig. 1a). Indeed, Fig. 1(a) differs little from the assessments of Briden *et al.* (1984, 1988) due to a lack of new studies during the intervening period. For clarity, identical pole abbreviations to these earlier studies have been adopted in this study (Table 1, Fig. 1).

Figure 1(a) comprises three groups of poles which relate to the Ordovician, Silurian–Devonian and Carboniferous–Permian periods. The Ordovician poles plot close to 2S, 10E but we draw attention to three outlying poles from the Shelve Inlier intrusions (SH), Carrock Fell Gabbro (CA) and Tramore Volcanics (TV).

The palaeomagnetic pole subsequently shifted westwards by Silurian–Devonian times to a 'corner' position as indicated by determinations from the Old Red Sandstone of Wales (ORS) and Silurian Somerset/Gloucester lavas (SG). Finally, the south pole 'backtracked' into southerly latitudes by Carboniferous–Permian times. The 'corner' and 'back-track' poles are also identified in Northern British APWPs (Torsvik *et al.* 1989, 1990a; Trench *et al.* 1989) relating to the coherent drift of the British Isles following closure of the Iapetus Ocean. We therefore confine our discussion primarily to the Ordovician period where the Southern British APWP is less clearly defined, notably due to the outlying poles.

2 PALAEOMAGNETIC DATA COMPILATION

In our analysis, we re-examined the original publications to cross-check all pole calculations and to assign a quality factor (QF) to each pole (Van der Voo 1988). QF depends on whether an individual study satisfies certain reliability

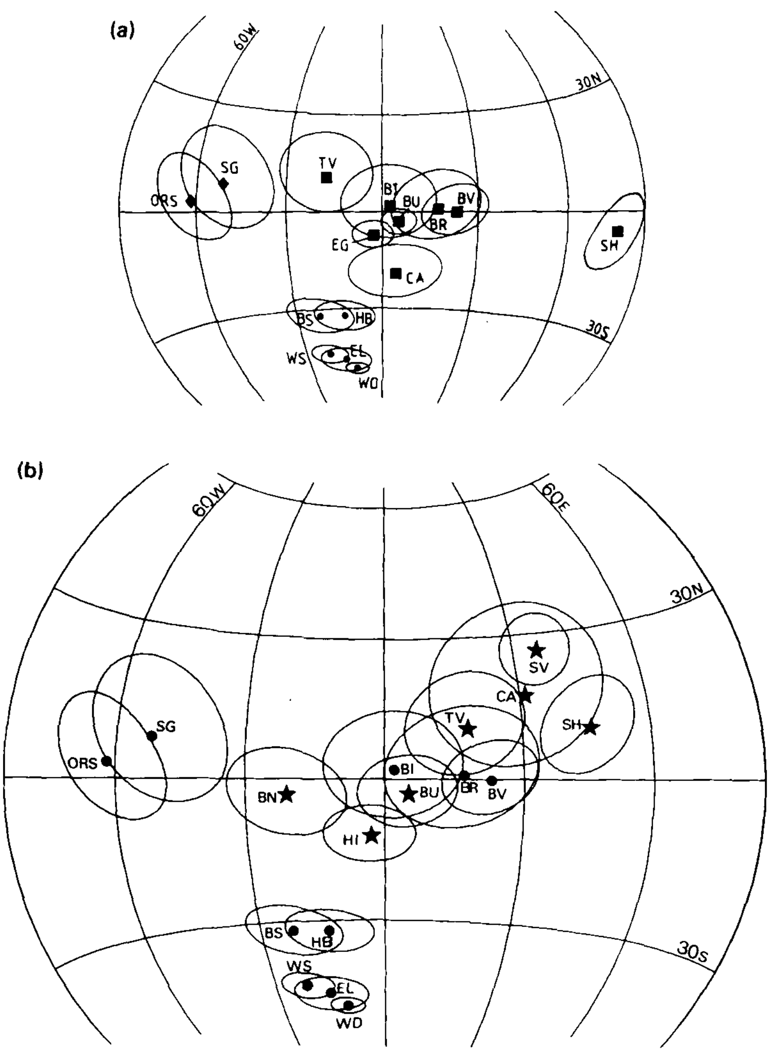

Figure 1. (a) Ordovician to Permian poles from Southern Britain south of the Iapetus suture (After Torsvik *et al.* 1990a). All poles are depicted with the oval of 95 per cent confidence about the mean pole. Squares: Ordovician, diamonds: Silurian–Devonian, circles: Carboniferous–Permian. Poles are listed in Table 1. (b) Revised poles from Southern Britain used in the computation of the new APWP. Amended Ordovician poles are indicated with stars. Equal-area projections.

criteria (Table 1), and can vary between 1 (poor reliability) and 7 (key pole). Our assessment of the poles formed the basis for the subsequent APWP analysis. Our minimum requirements for pole consideration were (i) that poles were based on >25 samples, and (ii) that some demagnetization experiments had been performed.

2.1 Revision and assessment of Ordovician poles

During the compilation of results, we found that the positions of the three outlying Ordovician poles (SH, CA and TV) all required substantial revision.

The pole obtained from dolerite/andesite intrusions of the Shelve Ordovician inlier, mid-Wales (SH), was originally reported in *in situ* coordinates i.e. uncorrected for regional Ashgill (late Ordovician) deformation of the inlier. In fact, many of the intrusions pre-date this folding (Lynas, Rundle & Sanderson 1985) and should be structurally corrected. Reanalysis of the original palaeomagnetic data (Piper 1978) for both andesites and dolerites, yields a positive fold test at the 95 per cent confidence level (Trench & Torsvik 1990) producing an amended pole at 10N 46E (Fig. 1b).

The Carrock Fell Gabbro pole (CA) was originally reported assuming (i) near-vertical intrusion of the gabbro, and, (ii) a lack of major subsequent structural rotation (Briden & Morris 1973). As radiometric studies indicate a Llanvirn age for the gabbro (Rundle 1981; Thirlwall & Fitton 1983), post-Llanvirn folding must be considered if the gabbro has retained an original remanence. A revised structural interpretation for the area (Harris & Dagger 1987) places the Carrock Fell gabbro on the northern limb of a major antiform correlated with Silurian (F2) structures of Roberts (1971). Correction for this antiform produces an amended pole at 17N 31E (Table 1, Fig. 1b). This rotation also restores igneous layering within the gabbro to a near-horizontal attitude (Harris & Dagger 1987). The F2 structure also affects the Binsey Formation (BN) and High Ireby Formation (HI) lavas (originally combined in the

Table 1. Palaeomagnetic poles for Palaeozoic Southern Britain used in the APWP analysis. Explanation of table columns is as follows: 'Codes' denote those used in Fig. 1. Age: rock or magnetic age assigned in APWP analysis. Latitude and longitude of palaeopole. Implied palaeolatitude indicated at sampling site. k and $a95$ are statistical parameters given by Fisher (1953). Reliability criteria 1–7 are from Van der Voo (1988) as below: 1, well-determined age for the rocks and magnetization age is not demonstrably different from the rock age; 2, sufficient number of samples (>25) and high enough precision ($k > 10$ and $a95 < 16$ degrees); 3, demagnetization achieved and published in sufficient detail; 4, positive field tests; 5, sufficient structural control, i.e. no suspicion exists about possible local rotations; 6, presence of reversals; 7, lack of similarity with younger palaeopoles.

ROCK UNIT	CODE	AGE	POLE POSITION LAT	POLE POSITION LONG(E)	PALAEOLATITUDE OF SITE	k	a95	1	2	3	4	5	6	7	Q	REFERENCE	COMMENTS
POLES USED IN APWP CONSTRUCTION.																	
Stapely Volcanics	SV	473	27	36	-51	90	5	x	x	x	x			x	5	McCabe & Channell (1990a)	
Shelve Intrusions	SH	470	10	46	-32	15	9	x	x	x	x		x	x	6	Trench & Torsvik (1990);	tectonically corrected data of Piper(1978)
Binsey Formation	BN	468	-3	345	-30	17	10	x	x	x	x			x	5	Briden & Morris(1973)	now tectonically corrected for F2 structure.
Builth Volcs/Intrus	BU	468	-3	5	-35	23	8	x	x	x	x			x	5	Trench et al. (1990a)	
Carrock Fell Gabbro	CG	465	17	31	-44	14	13	x	x	x				x	4	Briden & Morris (1973);	tectonic correction modified as above.
High Ireby Fm.	HI	462	-12	357	-23	30	8	x	x	x	x			x	5	Briden & Morris (1973);	tectonic correction modifed as above.
Tramore Volcanics	TV	460	11	18	-44	20	9	x	x	x	x		x	x	6	Deutsch (1980);	amended from incorrect original pole listing.
Borrowdale Volcs	BV	460	0	23	-30	14	7	x	x	x	x			x	5	Faller et al. (1977)	
Builth Upper Intrus	BI	458	2	2	-36	37	11	x	x	x			x	x	5	Piper & Briden (1973)	
Breidden Hills	BR	453	0	17	-35	16	12	x	x				x	x	4	Piper & Stearn (1975);	recalculated mean of 13 sites excluding two sites with alpha 95 > 50 degrees.
Somerset\Glouc lavas	SG	430	8	309	-29	29	14	x	x	x	x		x	x	6	Piper (1975)	
ORS Wales	ORS	398	3	298	-21	4	13	x		x	x			x	4	Chamalaun & Creer (1964)	
Bristol Upper ORS	BS	320	-32	338	-5	23	9	x	x			x		x	4	Morris et al. (1973)	
Hendre\Blodwell Intr.	HB	320	-32	347	-4	9	12			x		x			2	Piper (1978);	k and a95 are identical for both intrusions.
Wackerfield Dyke	WD	303	-49	349	+14	174	3	x		x		x		x	4	Tarling et al. (1973);	error amended in original pole calculation.
Whin Sill	WS	281	-44	339	+11	259	5	x		x		x		x	4	Storetvedt & Gidskehaug (1969).	
Exeter Lavas	EL	280	-46	345	+7	7	19	x	x	x		x		x	5	Cornwell (1967)	

Eycott Group pole; EG) and tectonic correction produces revised poles at 3S 345E and 12S 357E respectively (Table 1). Incidentally, recalculation of the CA pole removes the last conflicting data set to the palaeomagnetic recognition of the Iapetus Ocean in Britain (see Briden & Mullen 1984).

A pole quoted by Deutsch (1980) from the Ordovician Tramore Volcanics of SE Ireland proves incorrect when recalculated [the originally published pole was plotted by Torsvik *et al.* (1990a) (Fig. 1a)]. The discrepancy is most likely a typographic error as the published declination/inclination is the correct mean of the listed site mean data. The amended pole (11N, 18E) is therefore plotted in Fig. 1(b).

We rejected the results of only two palaeomagnetic studies after compiling all the available data. We contend the results of Thomas & Briden (1976) from the North Wales intrusions to either record an anomalous field (as suggested by the original authors) or unresolved multicomponents. Notably, data from the Cader Idris Basalts (Thomas & Briden 1976) plot close to a Permo-Carboniferous direction (*in situ*) and may therefore represent an overprint magnetization. We consider the high inclination results reported by Piper *et al.* (1978) from Ordovician minor intrusions in NW England to be based on inadequate demagnetization studies (as approximately 90 and 40 per cent of remanence remains following 'demagnetization' in the published examples).

2.2 New Middle-Ordovician poles

Recent palaeomagnetic studies from Southern Britain by McCabe & Channell (1990a) and Trench *et al.* (1991) further contribute to the available palaeomagnetic data set. McCabe & Channell (1990a) report a pole from Llanvirn (Mid-Ordovician) Stapely volcanics of the Shelve inlier at 27N, 36E (Fig. 1b). The Stapely volcanics are intruded by the Shelve dolerites (pole SH above). Although these authors initially favoured a late Ordovician magnetization age, further deliberation suggests a primary Llanvirn origin (Trench & Torsvik 1990; McCabe & Channell 1990b).

A reinvestigation of Llanvirn volcanics from the Builth inlier, mid-Wales, (Trench *et al.* 1990, 1991) confirms a previously reported pole (Briden & Mullen 1984; BU, originally 3S 355E). The reliability of the pole, however, is increased as the data set and sampling area are substantially enlarged. Furthermore, additional field tests now unambiguously establish the magnetization age as pre-Llandeilo (Mid-Ordovician) (Trench *et al.* 1991; McCabe & Channell 1990b).

The poles from the Builth (BU, BI) and Shelve inliers (SV, SH) do not overlap at the 95 per cent confidence level (Fig. 1b) which indicates either substantial APW or structural rotation to have occurred. Trench *et al.* (1991) favour a predominantly structural origin for the difference in poles noting their similar magnetization ages. As neither pole can be unambiguously established as 'unrotated' however, no rotation correction about a local vertical axis has been applied prior to APWP calculation. Accordingly, neither study meets the criterion for 'sufficient structural control' in the assessment of a quality factor (criteria 5; Table 1). This criterion is generally not met for poles of pre-Carboniferous age.

3 APWP ANALYSIS

To produce a time-calibrated APWP, we used the method outlined by Jupp & Kent (1987) which aims to fit a spherical smoothed spline to a given data set on a sphere. In order to achieve this, a working age was assigned to each pole (Table 1). This was generally based upon geological information pertaining to the rock age for each respective study. Stratigraphic ages were converted to approximate absolute ages using the time-scale of Harland *et al.* (1982). In cases where no independent magnetic age constraint was available, and the palaeomagnetic pole falls on a demonstrably younger part of the APWP between well-dated poles, a secondary 'magnetic age' was assigned. Pole positions were 'weighted' in the spline analysis using their individual error parameters (a95 per cent, Table 1). No key poles were assigned (*cf.* Torsvik *et al.* 1990a) as no poles achieved a quality factor of 7 (Table 1). A moderate smoothing parameter (200) was assigned in our analysis (see program description detailed in Torsvik *et al.* 1990b).

4 THE REVISED SOUTHERN BRITISH APWP AND ITS TECTONIC IMPLICATIONS

The revised APWP for Southern Britain is compared with its predecessor and with paths for Palaeozoic Northern Britain in Fig. 2(a and b). The revision of poles CA, SH, TV, and BU together with the addition of pole SV yields a significantly extended Ordovician spline which can be traced back into the northern hemisphere. The time-calibration of the path is also affected, notably indicating more substantial Ordovician APW. We note however that unaccounted block rotations within the data set (e.g. poles SV and SH versus BU and BI) may produce an exaggerated APW along a small circle centred on Southern Britain and also distort the absolute timing of the path. Indeed, the raw pole data do not display a smooth east–west migration with decreasing magnetic age indicating some influence of local structural effects (Table 1). We do consider remagnetization of the westerly Ordovician poles as a possibility however as these data are substantiated by positive field tests (criterion 4, Table 1).

The Devonian–Permian segments of the old and new paths differ slightly due to minor revisions of magnetic age and smoothing parameter (*cf.* tables 2 and 3 of Torsvik *et al.* 1990a). Siluro-Devonian time calibration should be treated cautiously given that the APW segment is presently constrained by only two poles (ORS, SG).

The new path (Table 2) has significant implications for the closure history of the British sector of the Iapetus Ocean, given that oceanic separation can be directly inferred through comparison of the British paths (Fig. 2b). We now estimate a Middle Ordovician width for the British sector of Iapetus to be in the order of 3300 km [comparing the revised Southern British path with the respective Northern British paths of Torsvik *et al.* (1990a)]. This estimate is significantly greater than previous calculations based upon a comparison of APW paths (*cf.* Briden *et al.* 1984, 1988; Torsvik *et al.* 1990a). In conclusion, the revised path reconciles a number of previously anomalous poles in the Southern British data set. We submit that the trend of this path remains better

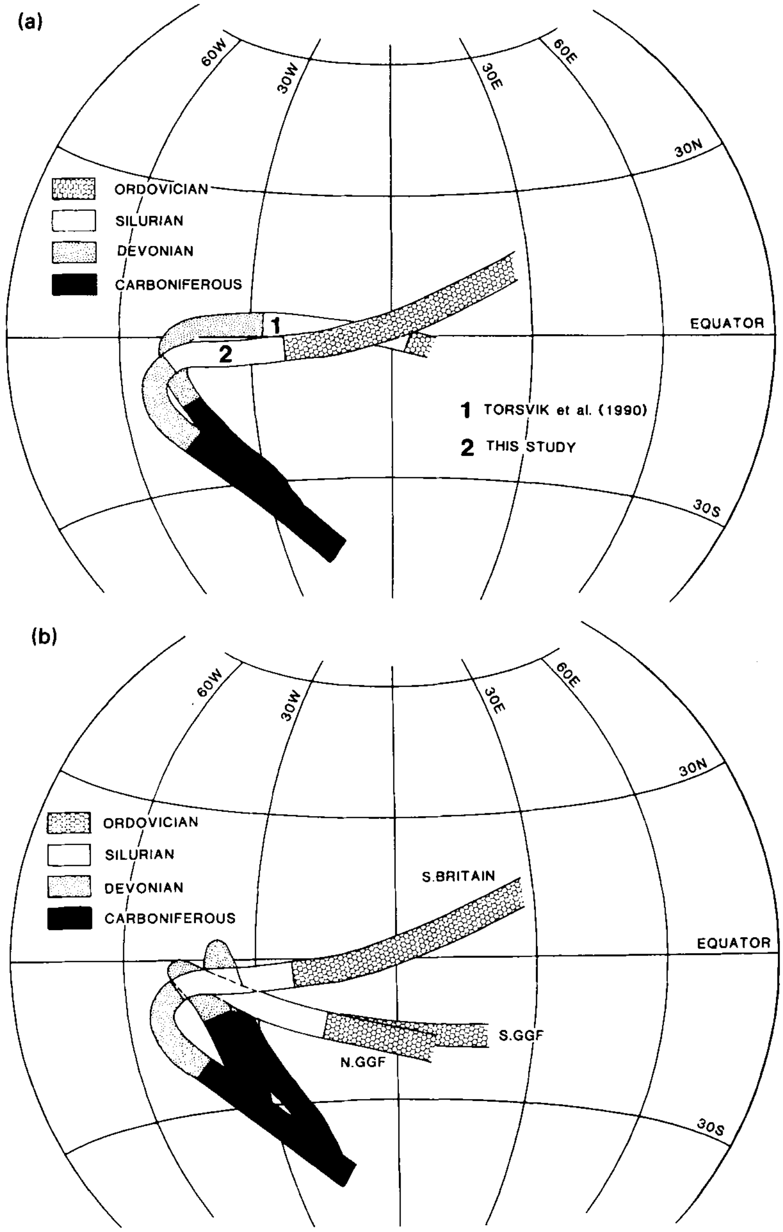

Figure 2. (a) A comparison of the old (1) and revised (2) APWPs for Palaeozoic Southern Britain. Equal-area projection. Geological periods are shaded. Paths 'widths' do not represent formal confidence limits. (b) Comparison of the revised Southern Britain APWP with paths from Northern Britain (Torsvik *et al.* 1990a). N.GGF: North of the Great Glen Fault, S.GGF: South of the Great Glen Fault and North of the Iapetus suture.

Table 2. Listing of revised APWP. Poles are quoted at 10 Myr (470–400 Ma) and 20 Myr intervals (400–280 Ma).

MAGNETIC AGE	LATITUDE	LONGITUDE
280	-47	343
300	-46	347
320	-40	341
340	-30	328
360	-21	317
380	-12	309
400	-6	308
410	-5	311
420	-4	318
430	-3	328
440	-2	340
450	-0.5	354
460	5	008
470	12	023

constrained than its absolute time-calibration for the present, however.

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