

# A new Silurian palaeolatitude for eastern Avalonia and evidence for crustal rotations in the Avalonian margin of southwestern Ireland

Conall Mac Niocaill

Department of Earth Sciences, University of Oxford, Parks Road, OX1 3PR, UK. E-mail: conallm@earth.ox.ac.uk

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## SUMMARY

Palaeomagnetic data are presented from Mid-Silurian (Homerian, Upper Wenlock, ~425 Ma) sediments from the Dingle Peninsula, SW Ireland, which forms part of the northern margin of the Palaeozoic microcontinent of Avalonia. Three remanence components were recognized. After removal of a low-temperature component ('L'), oriented parallel to the present Earth field at the sampling area, two higher-stability components were isolated: an intermediate-unblocking-temperature component ('I') with mean *in situ*  $D = 196.9^\circ$ ,  $I = 11.0^\circ$ ,  $\alpha_{95} = 10.8$ , with a corresponding palaeopole at  $330.0^\circ\text{E}$ ,  $30.6^\circ\text{S}$  ( $dp = 5.6$ ,  $dm = 11.0$ ), and a high-unblocking-temperature component ('H') with mean tilt-corrected  $D = 218.6^\circ$ ,  $I = 22.1^\circ$ ,  $\alpha_{95} = 7.9$ , with a corresponding palaeopole at  $309.5^\circ\text{E}$ ,  $18.3^\circ\text{S}$  ( $dp = 4.4$ ,  $dm = 8.4$ ). A primary (Wenlock) age is indicated for the 'H'-component by a positive intraformational conglomerate test, whereas the 'I'-component is thought to be a secondary mid-Carboniferous partial remagnetization.

These data confirm that the sector of the Iapetus Ocean between Avalonia and Laurentia was essentially closed, within the limits of palaeomagnetic resolution, by the Wenlock. There is still, however, a discrepancy between the declinations recorded by similar-aged sequences to the north and south of the Iapetus Suture. These point to either an approximately  $30^\circ$  clockwise rotation of the entire Avalonian microcontinent relative to Laurentia during closure, or local vertical axis rotations of the sampling sites in southern Britain.

**Key words:** apparent polar wander, Avalonia, continental deformation, palaeogeography, palaeomagnetism, Silurian.

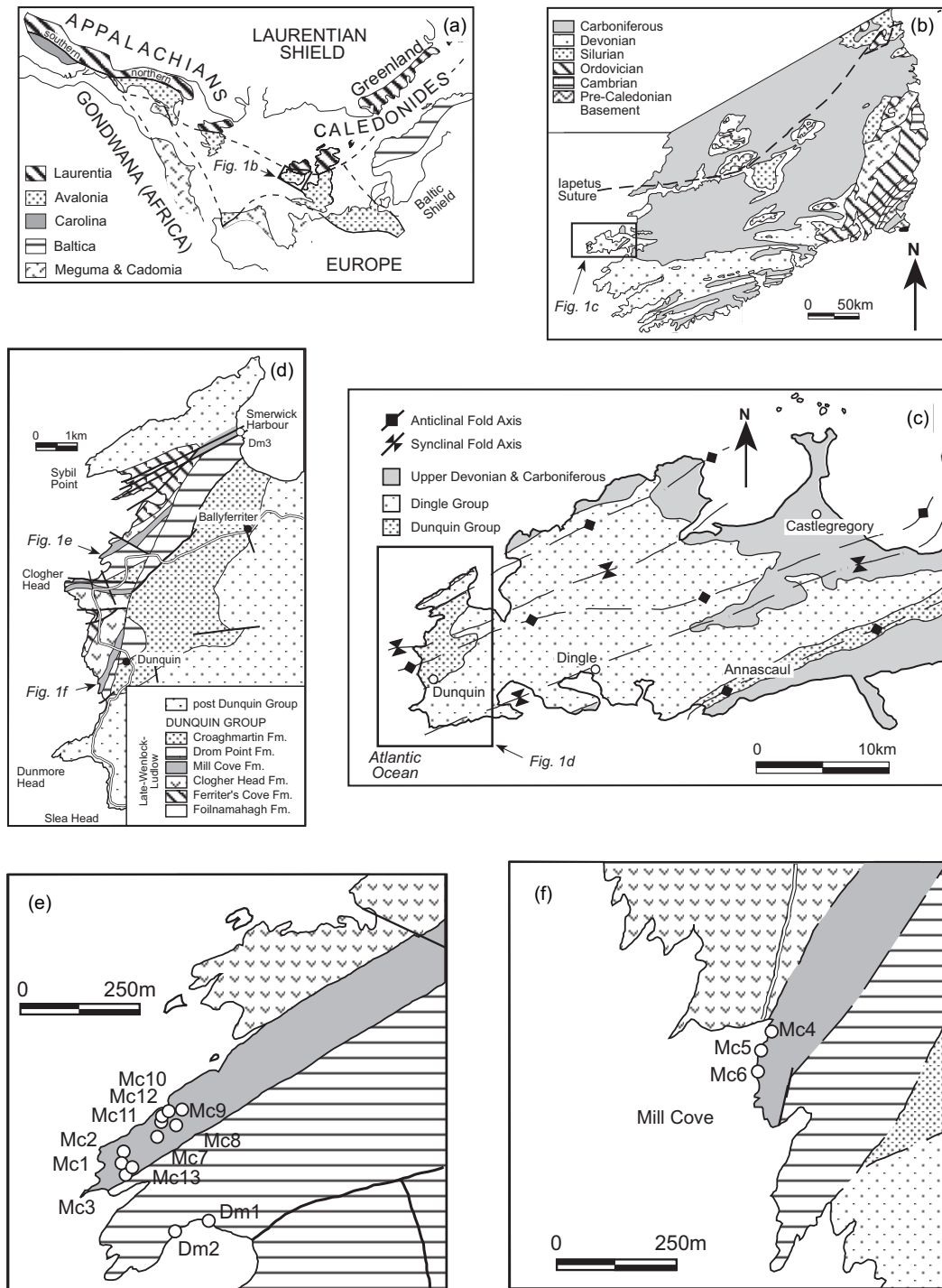
## INTRODUCTION

The history of the Iapetus Ocean marks a complete 'Wilson cycle' (Wilson 1966) of continental rifting, ocean floor spreading, convergence and final closure, which lasted from Late Precambrian to mid-Palaeozoic times. This cycle was accompanied by a protracted history of deformation, terrane migration and accretion associated with the convergence of the palaeocontinents of Laurentia and Baltica, and the Avalonian microcontinent (e.g. Mac Niocaill *et al.* 1997). Palaeontological and sedimentological data and palaeomagnetically determined palaeolatitudes indicate that closure of the sector of the Iapetus ocean between Laurentia and Avalonia was essentially complete by the Late Silurian (Torsvik *et al.* 1993; Mac Niocaill & Smethurst 1994; van der Pluijm *et al.* 1995). Notwithstanding the broad agreement between these disparate lines of evidence, there is a paucity of reliable palaeomagnetic data for eastern Avalonia to constrain the precise timing and geometry of final closure (e.g. Pickering 1989; Soper & Woodcock 1990; Channell *et al.* 1993; Torsvik *et al.* 1994). Notably, there are only three

reliable determinations of palaeolatitude for eastern Avalonia for the whole of the Silurian. These can be used for palaeolatitude positioning of Avalonia in plate reconstructions; however, they cannot be used as palaeomagnetic poles to orient Avalonia due to the effects of tectonic rotations of the sampling areas. Additional Silurian palaeomagnetic data are needed to chart more accurately the final convergence and accretion of Avalonia to Laurentia and to assess the geographical extent of the observed tectonic rotations. This study presents the first Silurian palaeomagnetic data from the Irish sector of Avalonia, and offers further constraints on the Silurian palaeogeography of the Avalonian margin.

## GEOLOGICAL SETTING AND SAMPLING

The Silurian lithologies of the Dingle peninsula, southwest Ireland (Fig. 1) provide the westernmost exposures of Silurian outcrops in Europe (Holland 1987) and are divided into two main groups: the Dunquin Group, Wenlock to Ludlow in age,



**Figure 1.** (a) Schematic cartoon illustrating the position of the study area within the Caledonian–Appalachian orogen, in a pre-Atlantic configuration. (b) Simplified map of the geology of SE Ireland illustrating the location of the Dingle peninsula within the Avalonian margin of Ireland and the Iapetus Suture. (c) Geological map of the Dingle peninsula illustrating the location of the Silurian–Devonian inliers of the Dunquin and Dingle Groups. (d) Detailed geology of the Dunquin inlier (after Sloan & Williams 1991). One site (DM3) was sampled from the Drom Point Formation at Smerwick Harbour, whereas all other sites were located in the sections to the north of Clogher Head (e) and at Mill Cove (f).

and the overlying Dingle Group, which ranges from Ludlow to Devonian (Downtonian) in age (Holland 1969). The Dunquin Group, which occurs in two inliers in the Dingle peninsula, the Dunquin and Annascaul inliers, consists of mudstones, siltstones and sandstones, which contain a variety of fossils including trilobites, corals and brachiopods, with intermittent

tuffs and ignimbrites within the sequence. Sloan & Williams (1991) subdivided the group into six formations, namely the Foilnamahagh Formation, the Ferriters Cove Formation, the Clogher Head Formation, the Mill Cove Formation, the Drom Point Formation and the Croaghmartin Formation, in ascending chronological order. Sampling was carried out in

the Mill Cove and Drom Point Formations in the Dunquin inlier, which occurs in the western part of the peninsula.

The Mill Cove Formation consists of a 105-m-thick sequence of red/purple siltstones and sandstones with interbedded tuffs and agglomerates (Sloan & Williams 1991). Although the formation is not conspicuously fossiliferous, recovered fauna indicate a late Wenlock age (Homerian, Benton & Underwood 1994). The overlying Drom Point Formation consists of some 300 m of yellow/brown siltstones containing characteristic Homerian brachiopods (Holland 1988; Sloan & Williams 1991).

These lithologies have undergone a polyphasal deformation history corresponding to various phases of the Caledonian and Hercynian orogenies, but the timing of these various events has proved controversial. Horne (1974, 1976) has proposed a phase of localized uplift (Caledonian) in Ludlow time, with a related unconformity between the Dunquin Group and the overlying Dingle Group, but Holland (1987) has disputed this and provided evidence that, in some parts of the peninsula at least, the contact between the two groups is conformable. There followed a phase of folding (Acadian) in the late Devonian that produced a series of NE–SW folds in the peninsula and these were then further compressed, overturned and faulted by Hercynian folding during the Carboniferous (Namurian) (Phillips & Holland 1981; Todd 1989).

Samples for palaeomagnetic analysis were collected, using a portable field drill, from 16 sites in the Dunquin Group. Of these, 13 sites (94 samples) were located in the red/purple mudstones and siltstones of the Mill Cove Formation. 10 of these sites (MC1–3, 7–13) were located in the section to the north of Clogher Head (Figs 1d and e), and a further three sites (MC4–6) were located at Mill Cove, between Clogher Head and Dunmore Head (Figs 1d and f). At one site 14 samples were collected from six red mudstone clasts in an intraformational conglomerate (site MC12, Fig. 1e) in the section to the north of Clogher Head.

Three further sites (20 samples) were sampled in the grey siltstones of the overlying Drom Point Formation, with two sites (DM1–2) being located towards the base of the Formation north of Clogher Head (Fig. 1e) and the third (DM3) located at Smerwick Harbour to the northeast (Fig. 1d). For this study a site consisted of 5–10 individually oriented cores collected over 2–3 m (stratigraphically) of outcrop. Individual cores were oriented using a magnetic compass.

### PALAEOMAGNETIC ANALYSIS

Measurements of natural remanent magnetism (NRM) were carried out using CCL cryogenic and JR5a spinner magnetometers (reliably measuring down to approximately 0.05 and 0.1 mA m<sup>-1</sup>, respectively). Standard progressive thermal demagnetization was carried out on a total of 114 individual samples. The demagnetization behaviour of the samples from the Drom Point Formation proved to be very erratic and no coherent components of NRM were retrieved from these sites. Accordingly, only the data forthcoming from the 13 sites of the Mill Cove Formation are described. Components of NRM were identified from least-squares analysis on linear segments of the orthogonal vector trajectories. Some problems were encountered with mineralogical alteration of the samples at

high temperatures, notably above 550–600 °C, with a pronounced rise in the bulk susceptibility. In these cases repeat measurements of the NRM, at that particular demagnetization step, were carried out in order to detect possible spurious or viscous magnetization components. Systematic reorientation of the samples in the furnace during the series of treatments was also used to detect laboratory-induced magnetizations.

To aid in the identification of the magnetic mineral carriers, Curie temperature and high-temperature susceptibility measurements were also carried out at the Institute of Solid Earth Physics, Bergen (Norway) and the Department of Earth Sciences, University of Oxford, respectively.

### REMANENCE COMPONENTS

NRM directions from the Mill Cove Formation were generally directed downwards, with variable inclinations, in the south-west quadrant (Fig. 2). NRM intensities range between 0.006 and 0.06 A m<sup>-1</sup>.

Progressive thermal demagnetization revealed the presence of three components of NRM, which are referred to throughout the text in terms of their relative unblocking temperatures ( $T_{ub}$ ): L (low:  $T_{ub} < 200$  °C), I (intermediate:  $T_{ub} > 200$  °C and  $< 630$  °C) and H (high:  $T_{ub} > 630$  °C). The low-temperature component 'L' was encountered in about half the samples analysed, but it was rarely completely resolved from the higher-stability components. Component L is stable between room temperature and 200 °C and usually constitutes only a minor proportion of the total NRM. 'L'-component directions are somewhat scattered, but, where best defined, point down in a northerly direction (e.g. Fig. 3c). The 'L'-component is therefore regarded as a viscous remanent magnetization (VRM) of probable recent origin.

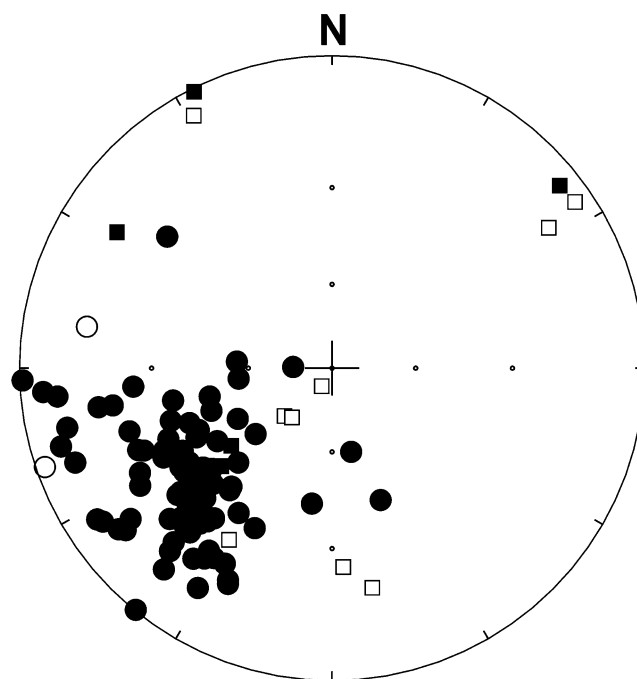
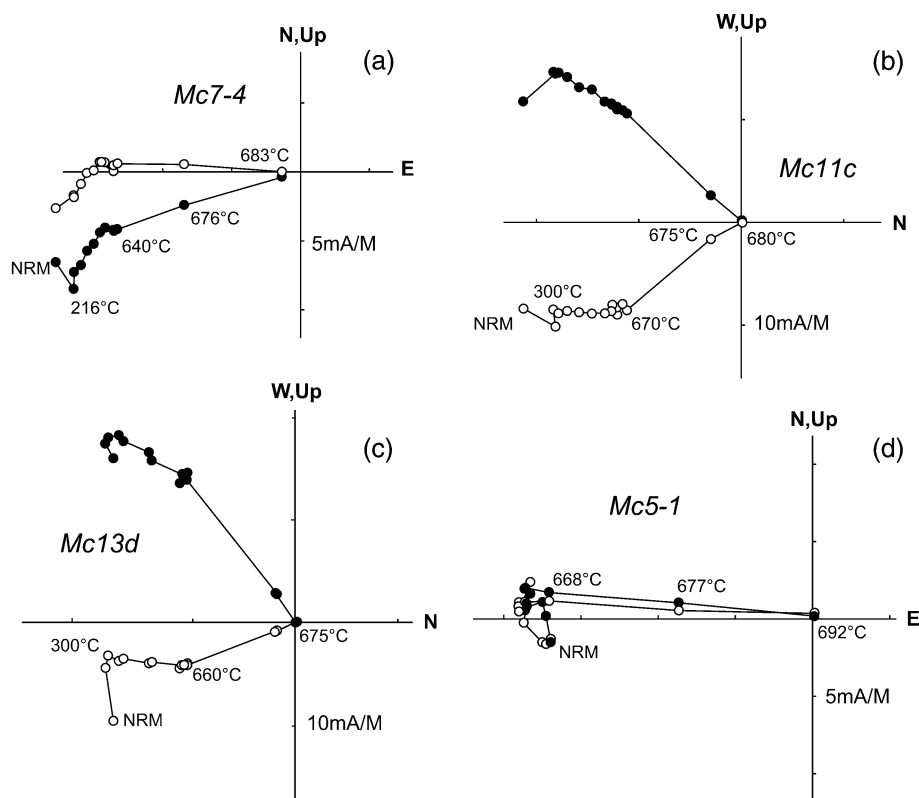


Figure 2. Sample NRM directions of the samples from the Mill Cove Formation. Open (closed) symbols represent projections on the upper (lower) hemisphere. Samples marked with squares are from the clasts in the conglomerate at site MC12. Equal-area projection.



**Figure 3.** Example orthogonal plots of progressive demagnetization data from the red mudstones of the Mill Cove Formation. The plots illustrate the change in magnetic remanence vector during stepwise demagnetization. Solid (open) symbols represent projections into the horizontal (vertical) planes. All plots are in *in situ* coordinates.

The intermediate-temperature component 'I' was recovered from samples at eight sites. Component 'I' is removed by thermal demagnetization treatments between 200 and 500–600 °C (Figs 3a–c). Before bedding correction the 'I'-component is usually directed with shallow inclinations to the south-southwest. Where present it contributes to some 30–40 per cent of the total NRM. Site mean component 'I' directions are tabulated in Table 1 and its age and mode of origin are discussed in a later section.

The high-temperature component 'H' was recovered from over 90 per cent of the non-conglomeratic samples (75 out of 80) from the Mill Cove Formation and constitutes the dominant proportion of the total NRM. Component 'H' directions are tabulated in Table 1 and are illustrated in Fig. 3. The 'H'-component unblocked at thermal treatments between 630 and 690 °C, with in most cases 80–90 per cent of the total 'H'-component unblocking between 660 and 690 °C (Fig. 3), indicating that haematite is the major magnetic mineral phase carrying this component. This agrees with the results from Curie temperature determinations, which reveal haematite as the predominant magnetic mineral phase present in these rocks (Fig. 4). The 'H'-component is directed shallowly down to the west-southwest or southwest (Table 1) before bedding correction.

#### 'FIELD TESTS' ON THE AGE OF MAGNETIZATION

##### Tectonic correction

Mean directions for both the 'I'- and 'H'-components are tabulated in Table 1 and illustrated in Fig. 5 before and

after bedding correction. Given the lack of variation in the attitude of the beds, tilt correction does not yield a significant change in the clustering of either the 'I' or the 'H'-component directions. In the case of the 'H'-component the fact that the directions are almost parallel to the bedding strikes also contributes to the non-significance of the fold test. Correction for bedding does not therefore provide any constraints on the age of either component.

##### Conglomerate test

14 samples were collected from six mudstone clasts in the intraformational conglomerate at site Mc12. Thermal demagnetization again revealed a multicomponent remanence structure with similar unblocking temperature characteristics to those observed in the bedded mudstones. The intermediate-unblocking-temperature component (e.g. Fig. 6b) was comparable with *in situ* 'I'-component directions from the sedimentary sequence. This indicates a secondary origin for the 'I'-component. Within-clast high-temperature components are consistent, whereas interclast magnetizations are dispersed (Fig. 6c). This observation indicates a primary origin for the 'H'-component.

#### INTERPRETATION AND DISCUSSION

Despite the inconclusive fold test, the correspondence of the 'I'-component directions from the clasts in the intraformational conglomerate and the sedimentary sequence indicates a secondary origin for the 'I'-component. One possible method of dating the 'I'-component therefore is to compare it with the APW path for Avalonia (e.g. Fig. 7). The pole from the *in situ*

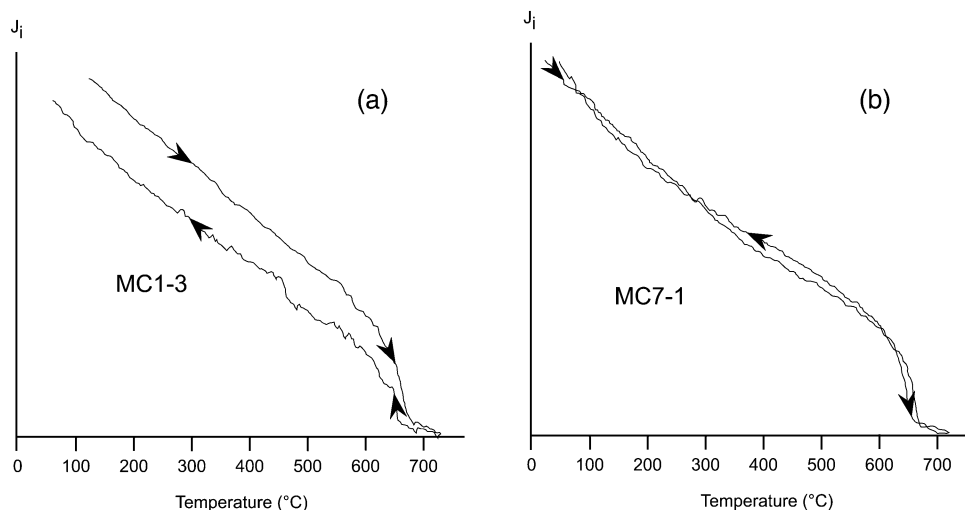
**Table 1.** Site mean directions from the Mill Cove Formation, Dingle. Lith. = lithology with Silt. = siltstone and Mud. = mudstone; Strike and Dip = strike and dip of the strata with the dip being 90° clockwise of the strike;  $N/N_0$  = number of samples used in the analysis/number of samples analysed; Dec/Inc = mean declination and inclination *in situ*;  $k$  = Fisher's (1953) precision parameter;  $\alpha_{95}$  = half-angle of the cone of 95 per cent confidence about the mean; Dec\*/Inc\* = mean declination and inclination after tectonic correction is applied. For the group statistics, abbreviations are as for site statistics except  $D/I$  = mean declination/inclination;  $N$  = number of sites; Long/Lat = latitude/longitude of the corresponding palaeopole;  $dp/dm$  = semi-axes of 95 per cent confidence about the pole.

Intermediate-temperature remanence components from the Dunquin Group										
Site No.	Lith.	Strike	Dip	$N/N_0$	Dec (°)	Inc (°)	$k$	$\alpha_{95}$	Dec*	Inc*
Mc1	Silt.	057	38	0/10	–	–	–	–	–	–
Mc2	Silt.	044	52	2/5	191.3	1.0	–	–	201.6	–24.5
Mc3	Silt.	049	46	5/9	191.1	29.5	11.9	23.2	182.4	–2.4
Mc4	Silt.	033	30	0/5	–	–	–	–	–	–
Mc5	Silt.	041	30	0/7	–	–	–	–	–	–
Mc6	Silt.	039	30	0/5	–	–	–	–	–	–
Mc7	Silt.	043	43	2/7	195.4	16.6	–	–	191.5	–5.4
Mc8	Silt.	049	45	3/5	194.1	23.9	19.1	29.0	187.8	–4.8
Mc9	Silt.	054	50	2/5	193.0	24.1	–	–	188.6	–11.3
Mc10	Mud.	063	45	6/6	202.9	0.0	28.3	12.8	212.2	–27.1
Mc11	Mud.	060	43	5/9	210.1	0.6	137.7	6.5	216.8	–19.4
Mc13	Mud.	053	52	7/7	196.1	–7.9	34.0	10.5	215.0	–33.6
Group statistics										
	$D$ (°)	$I$ (°)	$N$	$k$	$\alpha_{95}$	Long °E	Lat °N	$dp$	$dm$	
<i>In situ</i>	196.9	11.0	8	27.4	10.8	330.0	–30.6	5.6	11.0	
Tilt-corrected	198.8	–16.4	8	21.5	12.2	323.5	–43.6	6.5	12.6	
High-temperature remanence components from the Dunquin Group										
Site No.	Lith.	Strike	Dip	$N/N_0$	Dec (°)	Inc (°)	$k$	$\alpha_{95}$	Dec	Inc*
Mc1	Silt.	057	38	9/10	233.5	27.9	19.4	12.0	216.5	19.6
Mc2	Silt.	044	52	4/5	227.3	6.7	46.5	13.6	220.7	6.7
Mc3	Silt.	049	46	8/9	243.9	24.6	29.1	10.4	220.1	27.2
Mc4	Silt.	033	30	5/5	219.7	17.2	80.6	8.6	209.9	18.2
Mc5	Silt.	041	30	6/7	262.9	18.1	34.3	11.6	250.1	35.9
Mc6	Silt.	039	30	5/5	235.8	17.7	22.9	16.3	224.4	23.6
Mc7	Silt.	043	43	7/7	245.7	23.1	15.8	15.7	222.5	31.9
Mc8	Silt.	049	45	4/5	239.6	32.9	30.3	16.9	210.6	29.6
Mc9	Silt.	054	50	5/5	248.0	43.1	14.3	21.0	203.9	35.1
Mc10	Mud.	063	45	6/6	229.3	23.8	157.4	5.4	216.7	7.6
Mc11	Mud.	060	43	9/9	228.5	32.0	144.0	4.3	209.7	15.8
Mc13	Mud.	053	52	7/7	234.3	15.2	143.6	5.1	221.7	10.3
Group statistics										
	$D$ (°)	$I$ (°)	$N$	$k$	$\alpha_{95}$	Long °E	Lat °N	$dp$	$dm$	
<i>In situ</i>	237.1	23.9	12	32.2	7.8	293.5	–08.5	4.4	8.3	
Tilt-corrected	218.6	22.1	12	31.1	7.9	309.5	–18.3	4.4	8.4	

'T'-component mean direction (330.0°E, 30.6°S) plots near the mid-Carboniferous segment of the APW path of Trench & Torsvik (1991) for Avalonia, whereas the pole from the tilt-corrected 'T'-component mean direction (323.5°E, 43.6°S) plots some 20° clockwise from the late Carboniferous segment of the APW path. Thus, on the basis of comparison with the APW path for Avalonia, it would appear that the 'T'-component is of mid-Carboniferous age, consistent with its post-dating Namurian deformation in the region. It should also be noted that this component is very similar to the 'B'-component direction obtained by Storetvedt *et al.* (1993) in the overlying Dingle Group. The 'B'-component obtained by those authors failed a fold test, indicating a secondary origin of the magnetization,

which they claimed to be 'middle-Devonian or younger'. In view of the similarity between the 'T'-component in this study, the 'B'-component in the study of Storetvedt *et al.* (1993) and mid-Carboniferous reference poles from southern Britain, and the timing of deformation in the region, it is quite likely that these directions represent a mid-Carboniferous overprint acquired during Namurian (Variscan) deformation.

The positive intraformational conglomerate test indicates that the 'H'-component records a primary, upper Wenlock magnetization. No significant difference was noted in the remanence inclinations recorded by the mudstones and siltstones (Table 1), indicating that inclination shallowing, due to differential compaction of the two lithologies, does not appear



**Figure 4.** Thermomagnetic curves for two samples from the mudstones of the Mill Cove Formation. Samples were heated in air. These illustrate essentially reversible heating and cooling curves and yield a single Curie temperature for haematite, confirming this to be the main magnetic carrier in the sampled units.

to have affected the remanence direction. The resulting palaeopole, based on the tilt-corrected site means, is located at  $309.5^{\circ}\text{E}$ ,  $18.3^{\circ}\text{S}$ . This agrees well with the palaeomagnetic poles obtained by Torsvik *et al.* (1994) from the Tortworth lavas and Channell *et al.* (1992a) from the lower Old Red Sandstone of Wales (Fig. 7). A comparison is made in Fig. 8 between the palaeolatitude derived from the 'H'-component in Dingle with those obtained elsewhere in Avalonia. The southern British results for the Silurian also have positive field tests but there is some doubt as to their declination, notably in the case of the Browgill redbeds (Channell *et al.* 1993), where the normal polarity directions are smeared. The palaeolatitude derived from the tilt-corrected 'H'-component direction is in good agreement with the palaeolatitudes derived from these other studies. These indicate that the Avalonian margin lay at similar latitudes to the Laurentian margin by Wenlock time, confirming models for Wenlock closure of the Iapetus Ocean across this sector of the Caledonian orogeny.

Given Wenlock closure and suturing between Avalonia and Laurentia, the primary magnetizations recorded in both continents for Wenlock and younger times should be in directional agreement, on both sides of the suture, if no further differential motion took place between them. However, the declination of the 'H'-component recovered from the Mill Cove Formation in Dingle, and the other reference data from southern Britain, is significantly different from that observed in Silurian units north of the Iapetus suture. Fig. 9 presents a comparison of the pole positions for the Avalonian microcontinent in southern Britain with an APW path for Laurentia (Mac Niocaill & Smethurst 1994). It can be readily seen that the southern British pole positions are located clockwise, by varying amounts, of the expected directions (filled black dots in Fig. 9) if Avalonia and Laurentia were completely 'welded' to each other. Two possibilities suggest themselves for this observation: (1) closure of the Iapetus was synchronous with a  $30^{\circ}$ – $40^{\circ}$  clockwise rotation of the entire Avalonian microcontinent; or (2) the sampling sites in southern Britain have undergone varying degrees of local vertical-axis rotations. In the former case there would be a significant diachroneity in the timing of closure of the Iapetus Ocean between the British

Caledonides and the North American Appalachians, with a later closure in the Northern Appalachians. Such a diachroneity is not seen in the geological record, with geochronological (e.g. Doig *et al.* 1990), palaeomagnetic (e.g. van der Pluijm *et al.* 1995) and geological evidence (e.g. van Staal *et al.* 1998) all indicating a similar timing in both the British and North American sectors of the orogen. It is suggested, therefore, that the offsets in the measured declinations across the Iapetus Suture are the result of local tectonic rotations, about vertical axes, as a result of Caledonian and/or Variscan deformation in southern Britain. Such local-scale rotations have previously been documented, as a result of post-Silurian deformation, on the Laurentian margin of the Iapetus (Mac Niocaill *et al.* 1998).

In either case, the timing of such rotations, whether local-scale vertical-axis rotations or rotation of the entire Avalonian microcontinent, can be constrained by the overprints present in these rocks. As previously noted, the 'I'-component in this study represents a mid-Carboniferous overprint and therefore any tectonic rotation of the 'H'-component must pre-date this. Similarly, rotation of the Mendips Silurian inlier (Torsvik *et al.* 1993) pre-dates the acquisition of an approximately 350 Ma magnetic overprint. Obviously, more regional studies are required to provide substantive constraints on the regional extent and timing of these rotations.

## CONCLUSIONS

The Mid-Silurian (Homerian, Upper Wenlock,  $\sim 425$  Ma) Mill Cove Formation preserves a multicomponent remanence structure. An intermediate-unblocking-temperature component 'I', with mean *in situ*  $D = 196.9^{\circ}$ ,  $I = 11.0^{\circ}$ ,  $\alpha_{95} = 10.8$ , marks a mid-Carboniferous remagnetization event. A high-unblocking-temperature component 'H', with mean tilt-corrected  $D = 218.6^{\circ}$ ,  $I = 22.1^{\circ}$ ,  $\alpha_{95} = 7.9$  and a corresponding palaeopole at  $309.5^{\circ}\text{E}$ ,  $18.3^{\circ}\text{S}$  ( $dp = 4.4$ ,  $dm = 8.4$ ), is constrained by a positive intraformational conglomerate test to be primary in origin.

The palaeolatitude derived from the 'H'-component ( $11^{\circ} \pm 5^{\circ}$ ) is in good agreement with other recent palaeolatitude determinations for the Avalonian margin, and confirms that the sector of the Iapetus Ocean between Avalonia

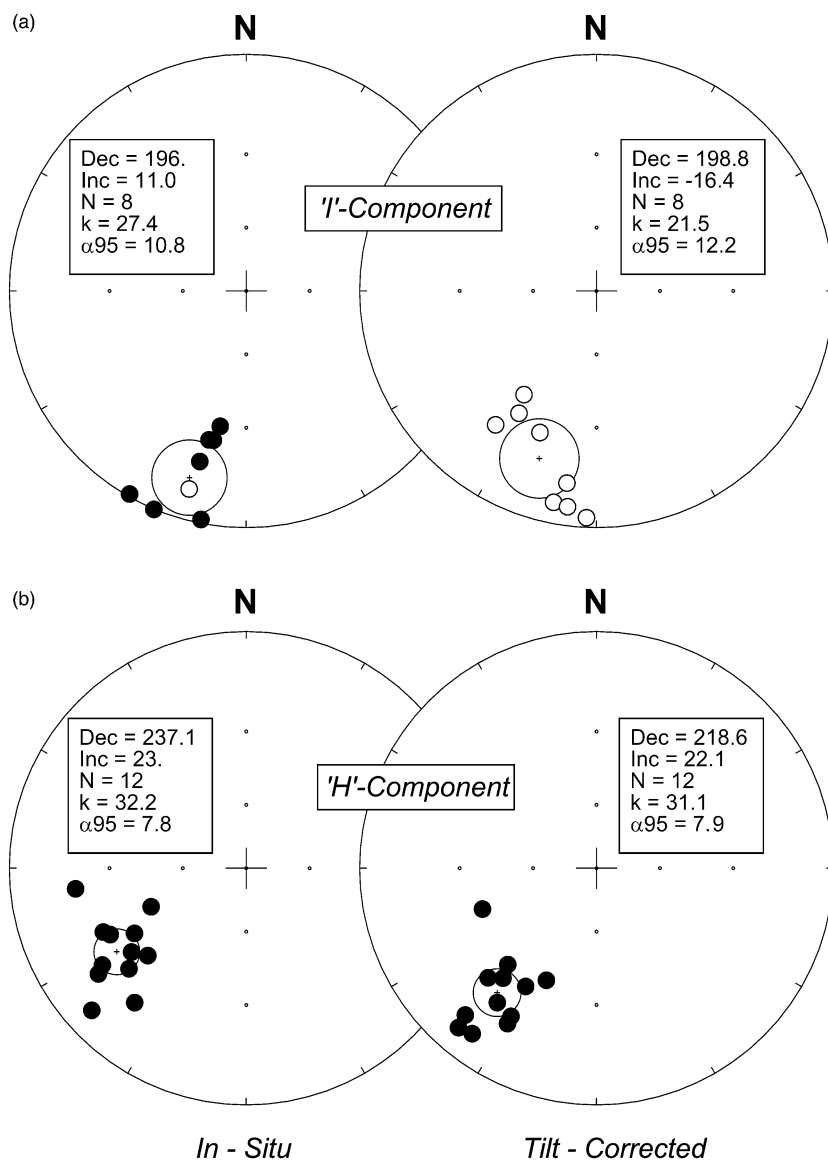


Figure 5. Stereographic projection of site-level 'I'- (a) and 'H'-component (b) remanence directions *in situ* and in tilt-corrected coordinates. The fold tests are inconclusive in both cases.

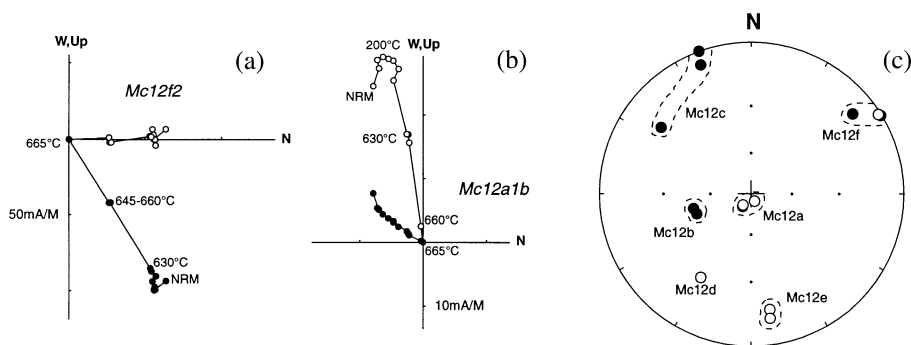
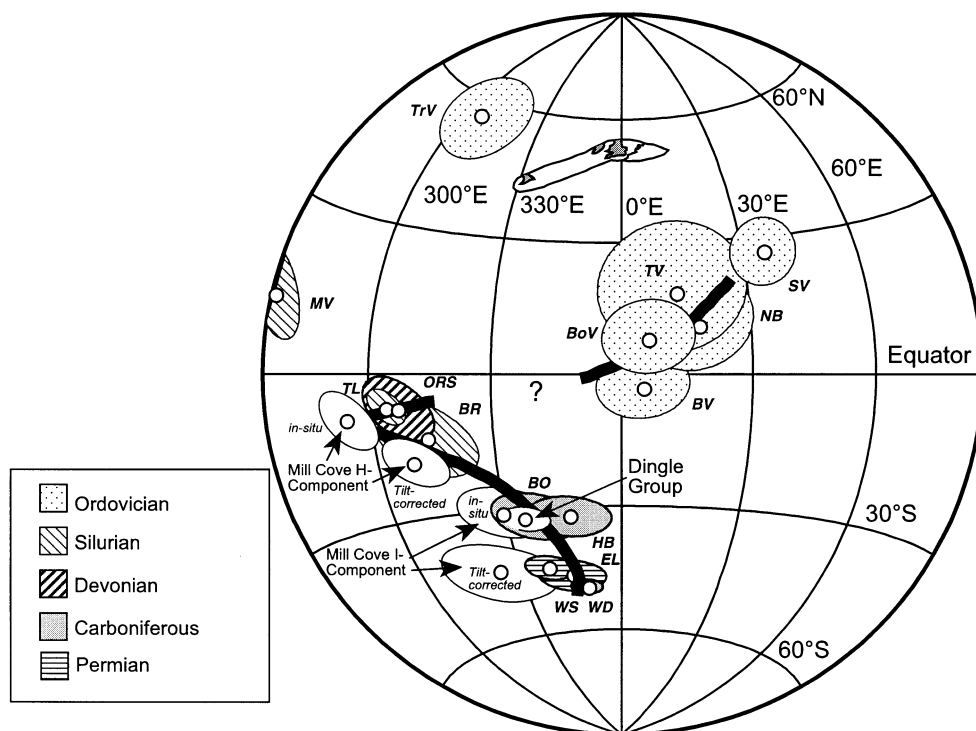


Figure 6. (a), (b) Example orthogonal diagrams of progressive demagnetization of samples from the clasts in the conglomerate at site MC12. Conventions and symbols as for Fig. 3. (c) Stereographic projection illustrating the high-unblocking-temperature (H-component) magnetization components from the clasts in the conglomerate. Directions from the same clast are circled and yield a positive intraformational conglomerate test, indicating that the H-component is primary in origin.



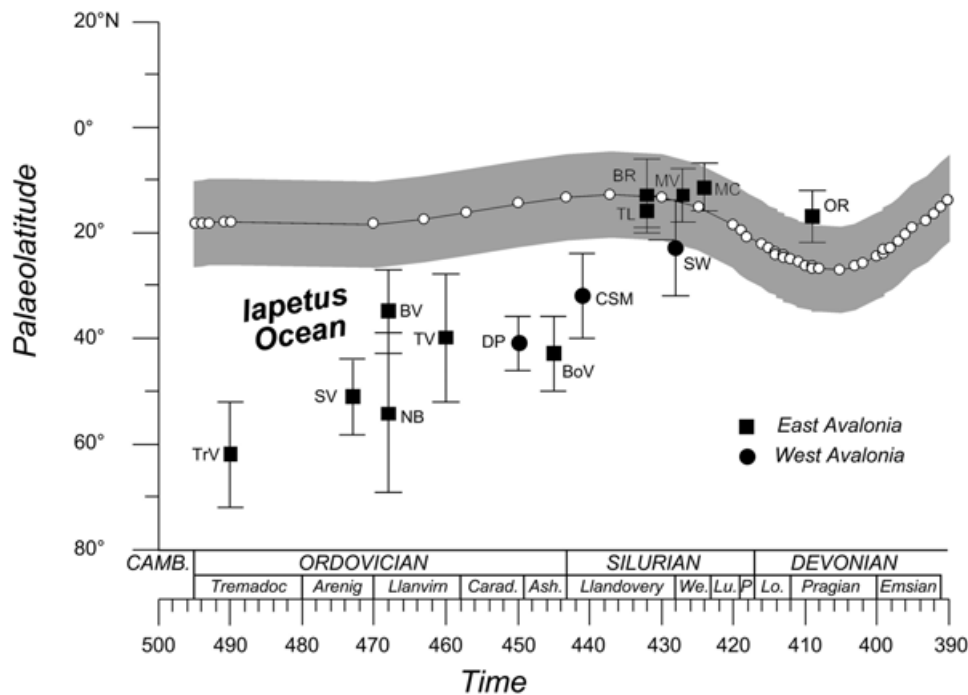
**Figure 7.** Reference palaeopoles from eastern Avalonia with the APW path of Trench & Torsvik (1991). The positions of the *in situ* and tilt-corrected palaeopoles from the 'I'- and 'H'-components in this study are also marked. Codes refer to the entries in Table 2. Equal-area projection.

**Table 2.** Reference Palaeozoic palaeomagnetic data for Avalonia. All poles are listed as south poles, with approximate ages assigned using the timescale of Tucker & McKerrow (1995) for pre-Carboniferous units and Harland *et al.* (1989) for Carboniferous and younger units. Code = labels on poles in the figures.

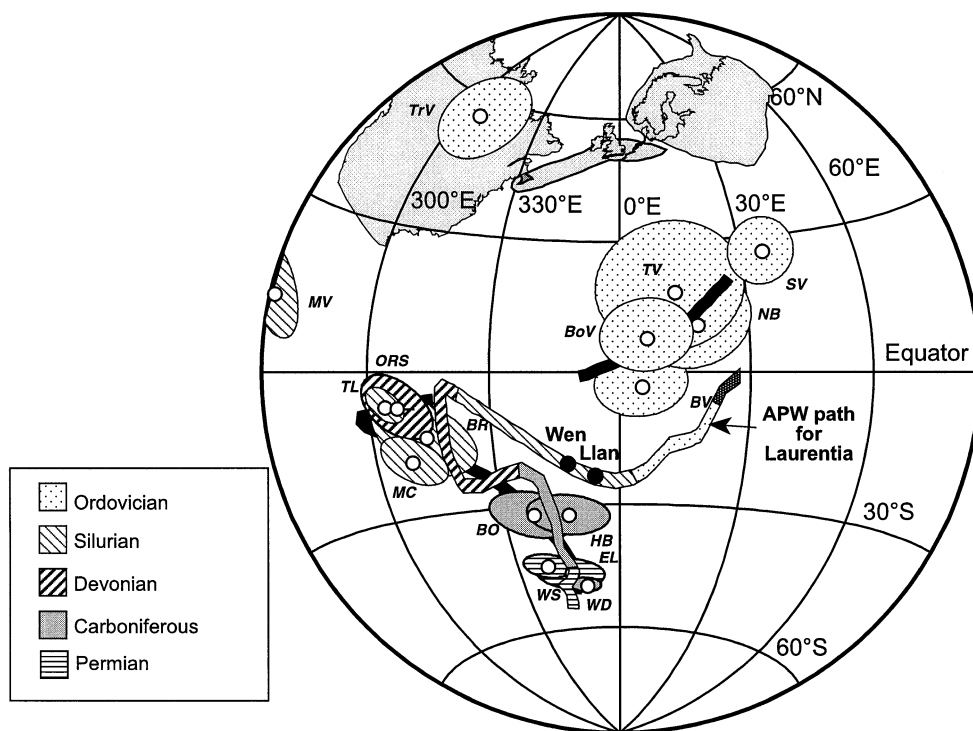
Rock unit	Code	Age	$\alpha_{95}$	Lat	Long	PLat	Reference
<i>East Avalonia</i>							
Exeter Lavas	EL	280	19	-46	345	-	Cornwell (1967)
Whin Sill	WS	281	5	-44	339	-	Storetvedt & Giskehaug (1969)
Wackerfield Dyke*	WD	303	3	-49	349	-	Tarling <i>et al.</i> (1973)
Hendre/Blodwell Intrusives	HB	320	12	-32	347	-	Piper (1978)
Bristol ORS	BO	320	9	-32	338	-	Morris <i>et al.</i> (1973)
Lower ORS, Wales	ORS	409	8.5	-07	307	17 ± 5	Channell <i>et al.</i> (1992a)
Mill Cove Redbeds	MC	424	7.9	-18	310	11 ± 5	This paper
Mendips Volcanics	MV	430	8.8	13	271	13 ± 5	Torsvik <i>et al.</i> (1993)
Tortworth Lavas	TL	435	4.7	-07	304	16 ± 3	Torsvik <i>et al.</i> (1994)
Browgill Redbeds	BR	435	12.4	-14	314	13 ± 7	Channell <i>et al.</i> (1993)
Borrowdale Volcanics	BoV	445?	6.9	8	006	43 ± 7	Channell & McCabe (1992)
Tramore Volcanics*	TV	460	8.5	11	018	40 ± 12	Deutsch (1980)
Builth Volcanics/Intrusives	BV	468	7.6	-03	005	35 ± 8	Trench <i>et al.</i> (1991)
North Builth Seds/Volcs/Intr	NB	468	10.0	18	013	54 ± 15	McCabe <i>et al.</i> (1992)
Stapley Volcanics	SV	473	4.9	27	036	51 ± 7	McCabe & Channell (1990)
Treffgarne Volcanics	TrV	490	5.5	56	306	62 ± 10	Trench <i>et al.</i> (1992)
<i>West Avalonia</i>							
Springdale and Wigwam†	SW	428	-	-	-	23 ± 9	Stamatakis <i>et al.</i> (1995)
Cape St. Mary Sills	CSM	440	8.9	-10	320	32 ± 8	Hodych & Buchan (1998)
Dunn Point	DP	450?	4.1	-2	310	41 ± 5	Johnson & Van der Voo (1990)

\* Recalculated from the original by Trench & Torsvik 1991.

† Based on inclinations only. The Springdale and Wigwam Formations represent an overstep sequence across the Central Mobile Belt.



**Figure 8.** Palaeolatitudes for the Avalonian plate, compared with the palaeolatitudes expected if Avalonia had collided with Laurentia. The expected palaeolatitudes are calculated for a reference location of 349.6°E, 52.1°N (the location of this study) and based on the reference APW path for Laurentia of Mac Niocaill & Smethurst (1994). Note the good agreement between the actual and predicted palaeolatitudes from mid-Silurian times onwards. Timescale after Tucker & McKerrow (1995).



**Figure 9.** Reference palaeopoles from eastern Avalonia compared to the reference APW path for Laurentia of Mac Niocaill & Smethurst (1994). The two black dots on the APW path for Laurentia (labelled Llan and Wen) are the predicted pole positions for Avalonia if there was no motion relative to Laurentia for early and mid-Silurian times, respectively. The Silurian pole positions from southern Britain (BR, TL, MV and MC) clearly do not correspond in longitude with those from Laurentia, indicating either that these sites have undergone local tectonic rotations or that the Avalonian microplate rotated some 30°–40° clockwise with respect to Laurentia during terminal closure of the Iapetus Ocean.

and Laurentia had narrowed to below the limits of palaeomagnetic resolution by the Wenlock. There is still, however, a discrepancy between the declinations recorded by similar-aged sequences to the north and south of the Iapetus Suture. These point to either an approximately 30° clockwise rotation of the entire Avalonian microcontinent relative to Laurentia during closure, or local vertical-axis rotations of the sampling sites in southern Britain.

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