Palaeozoic palaeomagnetic studies in the Welsh Basin – recent advances

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Abstract – In the last two years, new palaeomagnetic data from Wales have resulted in radical revision of the Ordovician palaeogeography of Eastern Avalonia, part of the southern margin of the Iapetus Ocean. Combined with Palaeozoic palaeomagnetic data from Laurentia and Gondwana, these data suggest that Eastern Avalonia was a peri-Gondwanide high latitude continental fragment during at least part of Ordovician time, with a palaeolatitude of about 62° S and 51° S in Arenig and Llanvirn time, respectively. This implies a latitudinal width of the early Ordovician Iapetus Ocean between Eastern Avalonia and Laurentia of at least 30°. Geological evidence for the proximity of Eastern Avalonia and Laurentia suggests that the intervening Iapetus Ocean closed during Silurian time, from late Llandovery to early Ludlow. Recent palaeolatitude data from the Iapetus bordering continents are consistent with closure by middle to late Silurian time. New pre-Acadian early Devonian palaeomagnetic data from the Old Red Sandstone places the Welsh Basin at about 17° S, consistent with a palaeogeography in which Laurentia, Baltica, Avalonia, Armorica, and possibly Gondwana, were part of a single supercontinent. Pervasive late Carboniferous/early Permian remagnetization affects the Welsh Basin. The remagnetization is probably associated with fluids emanating from the Variscan thrust front. We do not observe remagnetization associated with Acadian orogeny and the remagnetizations, which have been studied in more detail in North America, appear to be a unique feature of the Variscan–Hercynian–Alleghenian orogeny.

1. Introduction

During the last few years, the recognition of widespread remagnetization of Palaeozoic rocks in Europe and North America has led to radical re-evaluation of existing palaeomagnetic data, and new efforts to isolate magnetization components where the ages of these components can be constrained by fold tests and conglomerate tests. In addition, analytical methods for resolving magnetization components have become more rigorous in the last few years. It is now widely accepted that blanket demagnetization methods, which were common practice up to about ten years ago, are unlikely to accurately resolve single magnetization components. More recent studies use fine-scale incremental thermal demagnetization with principal component analysis as a means of resolving magnetization components. In addition, the more useful recent studies include field (fold or conglomerate) tests which tightly constrain the age of the magnetization components. Without such constraints, Palaeozoic palaeomagnetic data are generally uninterpretable due to uncertainties in the age of the magnetization components. This uncertainty is particularly critical in the case of Eastern Avalonia due to the rapid Siluro–Ordovician latitudinal drift of this continental unit.

Briden, Turnell & Watts (1984) concluded that existing palaeomagnetic data were compatible with a latitudinal width of 10° for the Llanvirn Iapetus Ocean between Laurentia and Eastern Avalonia. With the exception of the Briden & Mullan (1984), data from the Builth Volcanics (discussed in detail below), the eight Ordovician poles from Eastern Avalonia cited in the Briden, Turnell & Watts (1984) analysis used blanket demagnetization techniques. Several of these poles, such as those from the Shelve Volcanics (Piper, 1978), are supported by positive fold tests. However, recent data from Ordovician rocks from Wales (e.g. McCabe & Channell, 1990; Trench *et al.* 1992) have given significantly different results, implying that although a pre-folding component of magnetization is present in the Shelve data of Piper (1978), single component magnetizations were not completely resolved by the blanket demagnetization techniques.

Until recently, Silurian and Devonian palaeomagnetic data from Eastern Avalonia were restricted to those from Silurian lavas in Somerset and Gloucestershire (Piper, 1975) and data from the Old Red Sandstone in Wales (Chamalaun & Creer, 1964). In both studies, there is evidence of a pre-folding magnetization component, but we now know that the demagnetization procedures in these early studies are unlikely to have resolved single component magnetizations. These poles are significantly different from all the Ordovician poles, and they define a hairpin in the apparent polar wander path (APWP) for Eastern Avalonia (see Briden, Turnell & Watts, 1984; Trench & Torsvik, 1991*a*).

In the present paper, we summarize the results of a number of new palaeomagnetic studies carried out within the Welsh Basin since 1989. In all these studies, contemporary demagnetization and analytical procedures have been applied and palaeomagnetic field tests performed. Collectively, the new data confirm some key features of the previously published APW paths, provide increased resolution for critical intervals and offer a reliable framework for the Ordovician to Devonian drift history of the Welsh Basin.

2. Recent palaeomagnetic data from Wales (Eastern Avalonia)

2.a. New Ordovician data

The recent Ordovician palaeomagnetic data have come from the Shelve and Builth inliers and from the Treffgarne Volcanics (Dyfed) (Fig. 1). The Builth and Shelve inliers are particularly well suited for palaeomagnetic study because they offer fold tests which tightly constrain the age of the magnetization components. The two inliers are situated between the Hercynian and Acadian deformation fronts. The Upper Llandovery to Wenlock cover of the inliers is relatively undeformed, and unconformably overlies Ordovician rocks which were more strongly deformed,

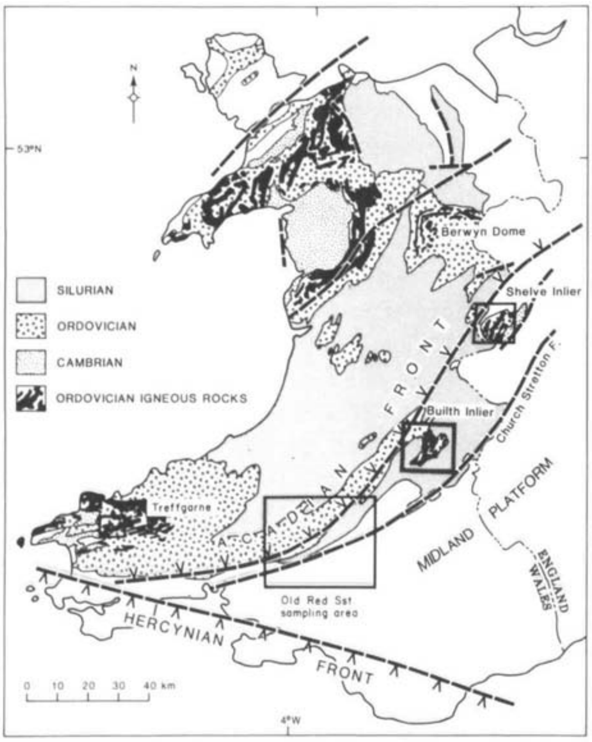

Figure 1. Location of Shelve, Builth, Treffgarne and Old Red Sandstone sampling areas (base map after Kokelaar *et al.* 1984).

probably in Ashgill time (Woodcock, 1984, 1987; Woodcock & Gibbons, 1988; Lynas, 1988). As a result, fold tests from Llanvirn rocks exposed in the two inliers can potentially constrain the age of magnetization to the Llanvirn–Ashgill interval, an unusually tight constraint particularly for Palaeozoic palaeomagnetic data. In addition, both in Builth and in Treffgarne, boulder beds associated with the volcanic sequences offer the possibility of a conglomerate test which can also tightly constrain the age of the magnetization.

The Stapeley Volcanics of the Shelve Inlier, first studied palaeomagnetically by Piper (1978), have been recently restudied by McCabe & Channell (1990). In the recent study, a high blocking temperature magnetization component was resolved from eleven sampling sites and the site mean directions pass a regional fold test at the 99% confidence level. The overall mean direction (Declination: 116.4°, Inclination: 67.9°, α_{95}: 4.9°) is significantly different from that given in the earlier study (Dec: 167.3°, Inc: 30.9°, α_{95}: 11.8°) of Piper (1978). As the earlier data pass the regional fold test at the 95% confidence level, we attribute the discrepancy to the inadequacy of blanket alternating field demagnetization to resolve a single magnetization component in these rocks. Fold tests indicate the presence of a pre-folding magnetization component but do not necessarily imply that the magnetization directions represent single (as opposed to multi-) components. The shallower inclination and the more southerly declination in the earlier study relative to the recent result, are probably due to the influence of late Carboniferous/Permian remagnetization (discussed below) which is ubiquitous throughout the Welsh Basin. The southerly and shallow magnetization direction which is characteristic of this 'Hercynian' magnetization component, when superimposed on the primary Llanvirn direction, could have produced the mean direction resolved in the Piper (1978) study. The implication of the new result from the Stapeley Volcanics (McCabe & Channell, 1990) is that it increases the latitudinal width of the Llanvirn Iapetus between Eastern Avalonia and Laurentia from about 10° to at least 30°, and it places Eastern Avalonia at about 51° S at this time, in the vicinity of the rim of Gondwana.

The palaeomagnetism of the Llanvirn spilitic lavas exposed in the Llanelwedd quarry, located in the southwest corner of the Builth Inlier, have been studied by Piper & Briden (1973) and Briden & Mullan (1984). The latter study used modern analytical techniques to resolve a high blocking temperature magnetization component. The component was believed to be primary (Llanvirn in age) based on a conglomerate test from a volcanic agglomerate exposed in the quarry. McCabe & Channell (1990) noted that the mean direction resolved by Briden & Mullan (Dec: 181.7°, Inc: 54.5°, α_{95}: 4.4°) is significantly different from the mean direction resolved from rocks of close to the same age from the Shelve Inlier (Dec: 116.4°, Inc: 67.9°, α_{95}: 4.9°).

This discrepancy has been the subject of a lively debate, summarized below. McCabe & Channell (1990) suggested that the Builth result may be contaminated by late Palaeozoic remagnetization and contended that the conglomerate test was based on too few samples. Trench & Torsvik (1991*b*), however, argued that the conglomerate test was valid and that the lower inclination data from Builth should not be considered subordinate to the higher inclination data from Shelve. They supported their argument by reanalysing the data of Piper (1978) from dolerite and andesite intrusions in Shelve and noted that, after structural tilt correction (not applied in the original study as the intrusions were then thought to postdate folding), the mean inclination (Dec: 119°, Inc: 52°, α_{95}: 8.8°) is similar to that resolved at Builth by Briden & Mullan (1984). McCabe & Channell (1991) documented conglomerate tests from Builth that demonstrate the presence of primary magnetization in the spilites from the quarry and in the overlying keratophyres, but again argued that the demagnetization data from the quarry indicate a mixing of magnetization components, consistent with the influence of a late Palaeozoic remagnetization. McCabe & Channell (1991) supported their argument by quoting data from two sites from the northern part of the Builth Inlier which give steep inclinations, similar to those observed at Shelve by McCabe & Channell (1990).

This debate instigated two additional independent studies of palaeomagnetism in the Builth Inlier (Trench *et al.* 1991; McCabe, Channell & Woodcock, 1992). The combined results of these studies shed further light on the magnetization history of the inlier and, in the following paragraphs, we present a consensus view of the entire dataset.

Although the demagnetization data from the spilites in the Llanelwedd quarry open the question of late Palaeozoic overprints, no such argument can be made for the overlying keratophyres which appear to be characterized by a single magnetization component, and conglomerate tests in the beach facies keratophyre boulders indicate the presence of a primary (Llanvirn) component (McCabe & Channell, 1991; Trench *et al.* 1991; McCabe, Channell & Woodcock, 1992). Trench *et al.* (1991) used the attitude of the overlying Newmead Sandstone to tilt-correct their magnetization data, in order to negate the effects of local volcano-tectonic tilting and flow folding which are documented by failed fold tests in the keratophyres and dolerites. The mean direction resulting from this study (Dec: 171°, Inc: 54°, α_{95}: 7.5°) is close to that obtained by Briden & Mullan (1984). A similar but shallower mean direction (Dec: 173°, Inc: 43°, α_{95}: 4.5°) was obtained by McCabe, Channell & Woodcock (1992), again using the dip of the Newmead Sandstones to untilt the volcanic pile to the horizontal (Fig. 2). McCabe, Channell & Woodcock (1992) have shown that the data from the vicinity of the Llanelwedd quarry are anomalous *not only* relative to Shelve *but also* relative to data from the rest of the Builth Inlier. Six sites from the northern and central parts of the Builth Inlier collected from dolerite sills, marine sediments (*D. bifidus* zone), tuffs and keratophyres yield a mean magnetization direction which passes the fold test at the 95% confidence level (McCabe, Channell & Woodcock, 1992). The mean inclination (69.8°) is close to that resolved from the Shelve Inlier (67.9°) but significantly different from those resolved in the region of the Llanelwedd quarry (43° and 54°) (Figs 2–4).

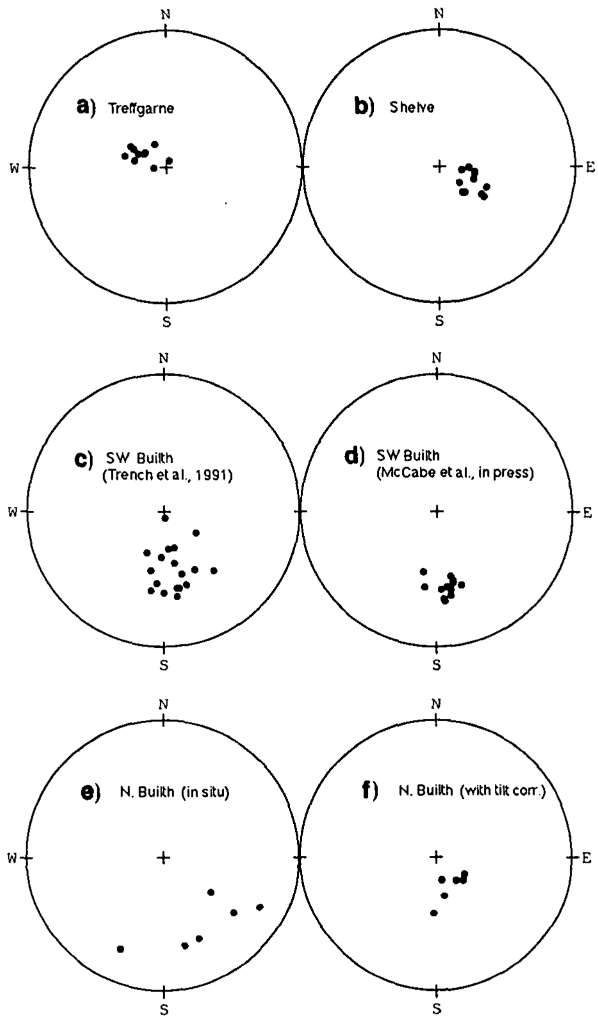

Figure 2. Site mean directions with structural tilt correction for: (a) Treffgarne (Trench *et al.* 1992); (b) Shelve (McCabe & Channell, 1990); (c) southwest Builth (Trench *et al.* 1991); (d) southwest Builth (McCabe, Channell & Woodcock, 1992). For northern Builth (McCabe, Channell & Woodcock, 1992) site mean directions are given *in situ* (e) and with structural tilt correction (f). All inclinations are downward (positive). Equal area projection.

There are four solutions which could account for the apparently anomalous palaeomagnetic data from the Llanelwedd quarry (SW Builth):

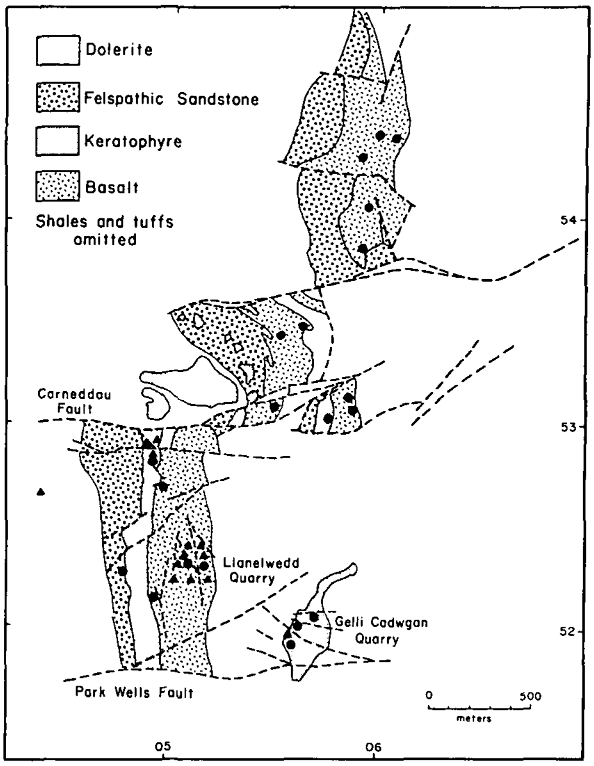

Figure 3. Site locations of Trench *et al.* (1991) (circles) and McCabe, Channell & Woodcock (1992) (triangles) in the vicinity of the Llanelwedd quarry (southwest Builth). Base map after Trench *et al.* (1991).

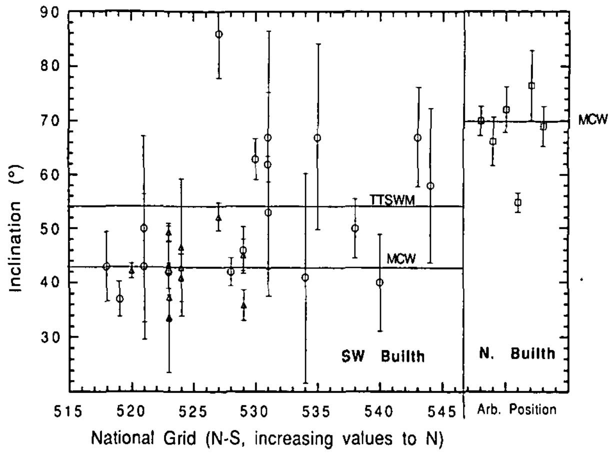

Figure 4. Site means inclinations from southwest Builth (circles: data from Trench *et al.* 1991; triangles: data from McCabe, Channell & Woodcock, 1992) and from north Builth (squares: data form McCabe, Channell & Woodcock, 1992). Horizontal lines represent overall mean inclinations from Trench *et al.* (1991) [TTSWM] and from McCabe, Channell & Woodcock (1992) [MCW]. Site locations for southwest Builth given in Figure 3.

(1) The sampling region around the Llanelwedd quarry (area of a few km^2) (Fig. 3) has undergone a volcano-tectonic tilt history such that the region was tilted, magnetized and then tilted back to close to the horizontal prior to the deposition of the Newmead Sandstone.

(2) The volcanic pile accumulated too rapidly for geomagnetic secular variation to be averaged out. The approximately 200 m thick section of spilites and keratophyres could have been deposited very rapidly, on the order of decades by analogy with some recent andesitic volcanoes (e.g. Pacaya in Guatemala).

(3) The overlying Newmead Sandstone was deposited on a surface characterized by a primary dip. A primary dip of 25° is necessary to reconcile the data with those from northern Builth (McCabe, Channell & Woodcock, 1992). Primary dips in excess of 10° in the Newmead Sandstone are extremely unlikely in view of the recognition of bipolar 'herring-bone' cross-bedding.

(4) The Stapeley Volcanics at Shelve are early Llanvirn (*D. bifidus* Zone) whereas the volcanics in southwest Builth are late Llanvirn (*D. murchisoni* Zone). The discrepancy between the Shelve and the southwest Builth results may indicate rapid continental drift of Eastern Avalonia in Llanvirn time (Trench *et al.* 1991). This would require drift rates of at least 20 cm/yr. This alternative is now considered unlikely in view of the steep inclinations found in marine sediments of early Llanvirn age (*D. bifidus* Zone) from northern Builth (McCabe, Channell & Woodcock, 1992) (Figs 2 and 4).

Whereas the McCabe, Channell & Woodcock (1992) study in southwest Builth was restricted to the immediate vicinity of the Llanelwedd quarry, the study of Trench *et al.* (1991) extended several kilometres to the north (Fig. 3). In the vicinity of the Llanelwedd quarry, the site mean magnetizations tend to have lower inclinations than those from further north (Fig. 4) and this may therefore account for the discrepancy between the mean directions obtained from this area by Trench *et al.* (1991) and McCabe, Channell & Woodcock (1992) (Fig. 2). The difference in scatter of site mean directions for the two studies (Fig. 2) probably reflects the difference in dispersion of site locations (Fig. 3). These observations imply that the area is affected by variable amounts of volcano-tectonic tilting which *both* predated *and* postdated the thermal remanent magnetization. The volcano-tectonic tilting which predated the magnetization is documented by negative fold tests (Trench *et al.* 1991) and that which postdated the magnetization is documented by the significantly different site mean *inclinations* from different blocks in the vicinity of the Llanelwedd quarry (Fig. 4). A local angular unconformity in the vicinity of the quarry, between the Newmead Sandstone and the overlying Llandeilo marine shales (Jones & Pugh, 1949), indicates further tilting subsequent to Newmead deposition.

Although we do not yet have a definitive explanation for the apparent anomalous nature of the magnetization of the Llanelwedd quarry, we prefer option (1) (above) to explain the discrepancy. The palaeolatitudes implied by the mean directions from southwest Builth, 35° S for both the Trench *et al.* (1991) and Briden & Mullan (1984) data, and 25° S for the McCabe, Channell & Woodcock (1992) data, are not only significantly lower than palaeolatitudes implied by data from the same aged rocks from northern Builth and the slightly younger rocks from Shelve, they are also considerably lower than the palaeolatitudes (42° S and 43° S) inferred from late Ordovician results from Western Avalonia in Nova Scotia (Van der Voo & Johnson, 1985) and from the English Lake District (Channell & McCabe, 1992). Although the Western Avalonian data are compatible with those from Eastern Avalonia, the coherence of Eastern and Western Avalonia in Ordovician time is not proven.

The debate over the validity of the high inclination palaeomagnetic data from Llanvirn rocks in the Shelve and Builth inliers has to some extent been settled by new data from the early Arenig Treffgarne Volcanic Formation in Dyfed, near Haverfordwest (Trench *et al.* 1992). A conglomerate test in andesitic boulders indicates that the characteristic magnetization component is Arenig in age. The overall mean direction (Dec: 298°, Inc: 75°, α_{95}: 5.5°) indicates a palaeolatitude of about 62° S, consistent with the high palaeolatitudes from Llanvirn rocks in Shelve and north Builth.

A recent result from the Borrowdale Volcanic Group of the English Lake District (Channell & McCabe, 1992) yields a palaeolatitude for late Ordovician time (~ 450 Ma) of 43° S, implying progressive closure of the Iapetus Ocean between Eastern Avalonia and Laurentia during Llandeilo and Caradoc time. A higher palaeolatitude (52°) is implied by the early work of Thomas & Briden (1976) from late Ordovician volcanic and plutonic rocks from North Wales; however, the analytical procedures used at that time were such that it is not possible to determine whether the site mean directions denote single magnetization components.

2.b. New Siluro-Devonian data

The two palaeomagnetic studies which have defined the Siluro-Devonian hairpin in the polar wander paths for Eastern Avalonia are those of Piper (1975) from Llandovery volcanics of the Mendip Hills and Tortworth Inlier, and the data of Chamalaun & Creer (1964) from the Old Red Sandstone of South Wales (Fig. 5). These poles lie close to Siluro-Devonian poles from Scotland and therefore imply closure of the intervening Iapetus by this time. Although both these early studies quote fold tests indicating the existence of a pre-Hercynian magnetization component, the lack of detailed demagnetization and modern component analysis cast doubt on whether single magnetization components were resolved, and hence on the validity of the data. With this in mind, the Old Red Sandstone of South Wales and the volcanic rocks of the Mendip Hills have been restudied by Channell, McCabe & Woodcock (1992) and Torsvik & Trench (1992), respectively.

For the recent study of the Old Red Sandstone in Wales, the sampling area (Fig. 1) is located north of the Hercynian front but overlaps the Acadian deformation front, the intention being to more tightly constrain the age of the magnetization by sampling in folds of Acadian (mid-Devonian) rather than Variscan (late Carboniferous/Permian) age. Particular attention was focused on a major monoclinal fold at the Acadian front, comprising the southeast younging Myddfai Steep Belt and the low-dipping rocks of the platform to the southeast. Intensive sampling was carried out along the Sawdde Valley transect across this structure. The fold is considered to be Acadian because it affects Lower Devonian but not Upper Devonian rocks, and its cleavage is contiguous with the main Acadian cleavage of central Wales. The magnetization of these samples is dominated by a magnetization component which postdates both Acadian and Hercynian folding. This component is considered to be a late Carboniferous/Permian overprint because the pole positions plot on the late Carboniferous/Permian part of the polar wander path for southern Britain (Fig. 5). Of the 39 sampled sites, 13 sites contain a dual polarity high blocking temperature magnetization component which predates Acadian folding. The depositional age of the Lower Old Red Sandstone sites range from Ludlow to Emsian (House *et al.* 1977) and the Acadian folding is considered to be late early to mid-Devonian in age (Soper, Webb & Woodcock, 1987; Woodcock *et al.* 1988). The overall mean direction of the pre-Acadian component (Dec: 232.2°, Inc: 31.9°, α_{95}: 8.5°) therefore has a late Silurian–early Devonian age. The resulting pole position lies close to those of Chamalaun & Creer (1964) and Piper (1975) confirming the existence of the Siluro-Devonian hairpin in the polar wander path for Eastern Avalonia (Fig. 5, Table 1).

The recent pole from mid-Silurian volcanic rocks of the Mendip Hills (Torsvik & Trench, 1992) is supported by conglomerate and fold tests but does not coincide with the earlier result of Piper (1975) derived partly from the same rocks, or with the poles from the Old Red Sandstone of Wales (Fig. 5, Table 1). The discrepancy with the Piper (1975) result is considered to be due to the inadequacy of the blanket demagnetization techniques used in the earlier work. The discrepancy with the poles from the Old Red Sandstone are considered to be partly due to clockwise tectonic rotation of the sampling area (Torsvik & Trench, 1992). The new mean inclination from the Mendip Hills (−24°) yields a palaeolatitude (13° S) which is comparable to the palaeolatitude obtained from the recent study of the Old Red Sandstone (17° S) (Channell, McCabe & Woodcock, 1992).

Table 1. Key to Figure 5: selected Palaeozoic poles from Eastern Avalonia

	Stratigraphic age	Pole position		dp/dm
		Latitude (°)	Longitude (°)	
1: Treffgarne Volcanics* (Trench *et al.* 1992)	E. Ordovician	56 N	306 E	9/10
2: Stapeley Volcanics (Shelve)* (McCabe & Channell, 1990)	M. Ordovician	27 N	36 E	7/8
3: N. Builth seds/volc/intrusives* (McCabe, Channell & Woodcock, 1992)	M. Ordovician	18 N	13 E	15/17
4: Tramore Volcanics (Ireland) (Deutsch, 1980)	M. Ordovician	11 N	18 E	10/13
5: Borrowdale Volcanics (Channell & McCabe, 1992)	L. Ordovician	8 N	6 E	8/11
6: Somerset/Gloucester. volcanics (Piper, 1975)	Silurian	8 N	309 E	12/17
7: East Mendip Inlier (Torsvik & Trench, 1992)	M. Silurian	13 N	271 E	5/9
8: Old Red Sandstone* (Chamalaun & Creer, 1964)	L. Sil/E. Dev	3 N	298 E	9/15
9: Old Red Sandstone* (Channell, McCabe & Woodcock, 1992)	L. Sil/E. Dev	7 S	307 E	5/10
10: Portishead Red Beds (Morris *et al.* 1973)	E. Carboniferous	32 S	338 E	5/10
11: Old Red Sandstone overprint* (Channell, McCabe & Woodcock, 1992)	L. Carb/E. Perm	40 S	338 E	4/8
12: Builth overprint* (Trench *et al.* 1991)	L. Carb/E. Perm	44 S	351 E	4/8
13: Builth overprint* (McCabe, Channell & Woodcock, 1992)	L. Carb/E. Perm	48 S	354 E	3/6
14: Exeter Lavas (Zijderveld, 1967)	E. Permian	50 S	329 E	2/4

* Poles from Wales. Prefixes E, M, L refer to early, middle, late respectively.

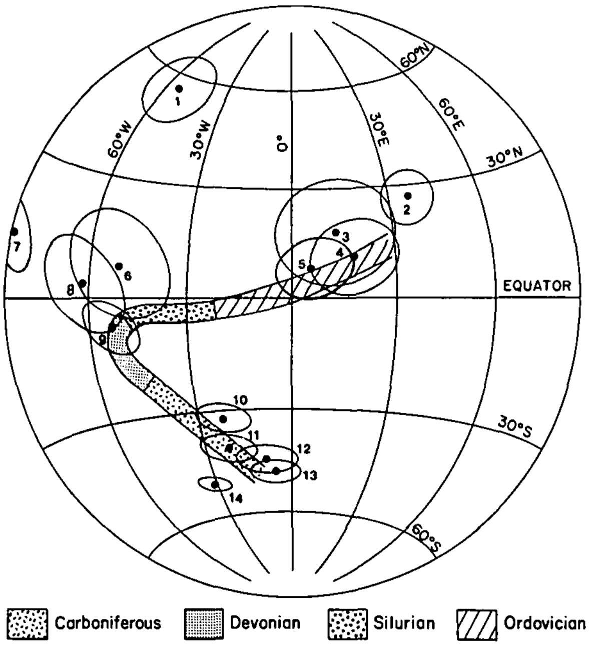

Figure 5. Selected Palaeozoic palaeomagnetic poles for Eastern Avalonia (key: Table 1) superimposed on the apparent polar wander path for Eastern Avalonia of Trench & Torsvik (1991*a*).

2.c. Remagnetizations associated with Variscan orogeny

Creer (1968) was the first to recognize the widespread partial or total remagnetization in late Carboniferous/early Permian time of Palaeozoic rocks in Britain and North America. For the Welsh Basin, the palaeomagnetic pole positions given by the secondary (overprint) magnetizations lie close to other late Carboniferous/early Permian poles (Fig. 5, Table 1) indicating that the remagnetization occurred at this time.

Widespread remagnetization of this age in North America affects not only the Appalachians, but is also recognized throughout much of central and eastern cratonic North America. The North American remagnetizations have been associated with new growth of hematite and magnetite triggered by fluids migrating from the Appalachians during the Alleghenian orogeny (see McCabe & Elmore, 1989). The nature of such fluids is unclear and must be reconciled with the observations that the same fluids are apparently responsible for new hematite growth in red beds *and* new magnetite growth in limestones. Blocking temperatures of the remagnetizations are more consistent with authigenic growth of new magnetic minerals rather than thermal remagnetization of pre-existing mineral phases.

Late Carboniferous/early Permian remagnetizations are recognized in Llanvirn volcanics at Builth (Briden & Mullan, 1984; Trench *et al.* 1991; McCabe, Channell & Woodcock, 1992), in Llanvirn rocks in Shelve (McCabe & Channell, 1990), in Arenig volcanics at Treffgarne (Trench *et al.* 1992), and in the Old Red Sandstone where this component dominates the magnetization of the sediment (McClelland-Brown, 1983; McClelland, 1987; Stearns & Van der Voo, 1987; Channell, McCabe & Woodcock, 1992). In South Wales the remagnetization of the Old Red Sandstone predates some Variscan structures (Stearns & Van der Voo, 1987) and postdates others (McClelland-Brown, 1983), suggesting that remagnetization is coeval with Variscan deformation. Primary magnetizations in the Old Red Sandstone have been recognized in the Myddfai Steep Belt and at other locations well north of the Variscan front (Channell, McCabe & Woodcock, 1992). The upper part of the Lower Old Red Sandstone is generally more pervasively remagnetized, perhaps due to the predominance of coarser-grained, high permeability sandstones in this part of the sequence. The Variscan-aged remagnetization is carried by hematite in the case of the Old Red Sandstone, and by magnetite in the some volcanic rocks, such as those at Builth.

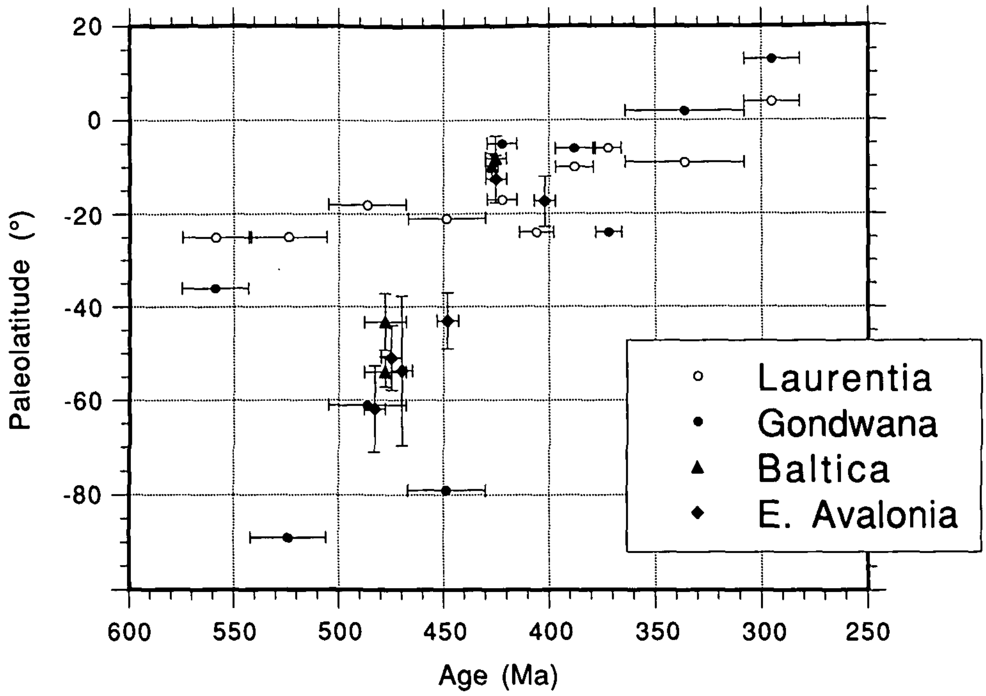

Figure 6. Palaeolatitudes for a reference point in southern Britain assuming that this region was a part of Laurentia (open circles) or part of Gondwana (closed circles) (after Van der Voo, 1992). Other palaeolatitude data are from Baltica (Claesson, 1978; Douglass, 1988; Torsvik & Trench, 1991; Trench & Torsvik, 1992) and Eastern Avalonia. The data for Eastern Avalonia are from Wales (McCabe & Channell, 1990; Trench *et al.* 1992; Channell, McCabe & Woodcock, 1992; McCabe, Channell & Woodcock, 1992) apart from the mid-Silurian result from the Mendip Inlier (Torsvik & Trench, 1992) and the late Ordovician determination from the English Lake District (Channell & McCabe, 1992).

Remagnetization in the Welsh Basin is presumably the result of its proximity to the Variscan front, and may be due to fluids emanating from the Variscan thrust belt, similar to those affecting North American Palaeozoic rocks. In North America, where the remagnetization has been more thoroughly studied, it is generally believed that the process is essentially a chemical rather than thermal process, and is associated with authigenic growth of magnetic minerals (hematite and magnetite) from pyrite and clay mineral precursors (see McCabe & Elmore, 1989). We do not recognize extensive remagnetization associated with Acadian orogenic events, either in Wales or in North America, indicating that such widespread remagnetizations are not a characteristic feature of orogenies in general, but a rather unique feature of the Variscan –Hercynian–Alleghenian orogeny.

3. Palaeogeography and Palaeolatitudes

The new palaeomagnetic results from Wales have resulted in modifications of the polar wander path for Eastern Avalonia. The polar wander path for Eastern Avalonia of Briden, Turnell & Watts (1984) has recently been superseded by that of Trench & Torsvik (1991 *a*) who incorporated the new Llanvirn data from Shelve (McCabe & Channell, 1990), data from the Shelve Intrusives (Trench & Torsvik, 1991 *b*) and modifications of the Ordovician Carrock Fell (Briden & Morris, 1973) and Tramore Volcanics poles (Deutsch, 1980). This polar wander path can now be augmented by the Treffgarne pole (Trench *et al.* 1992), the pole from northern Builth (McCabe, Channell & Woodcock, 1992), the Siluro-Devonian pole from the Old Red Sandstone (Channell, McCabe & Woodcock, 1992), the mid-Silurian result from the Mendip Hills (Torsvik & Trench, 1992) and the late Ordovician result from the English Lake District (Channell & McCabe, 1992) (Fig. 5). The Ordovician pole from Treffgarne (pole 1 in Fig. 5) and the Silurian pole from the Mendip Hills (pole 7 in Fig. 5) are considered to have been tectonically rotated away from the polar wander path. In spite of the tectonic rotation, the mean inclinations provide critical palaeolatitude data.

In Figure 6, hypothetical palaeolatitudes for southern Britain, assuming that this region was part of Gondwana or part of Laurentia (from Van der Voo, 1992), are compared with palaeolatitudes from Baltica and Eastern Avalonia. The recent data from Eastern Avalonia (diamonds in Fig. 6) give Ordovician palaeolatitudes close to those predicted by assuming that southern Britain (Eastern Avalonia) was part of Gondwana during Mid-Ordovician time. The data from Eastern Avalonia are also close to those from Baltica (Fig. 6), suggesting that the Ordovician palaeolatitudes of the two units were similar. The mid-Ordovician Iapetus Ocean between Eastern Avalonia and Laurentia had a latitudinal width of at least 30°. The paucity of reliable palaeomagnetic data for late Ordovician and Silurian

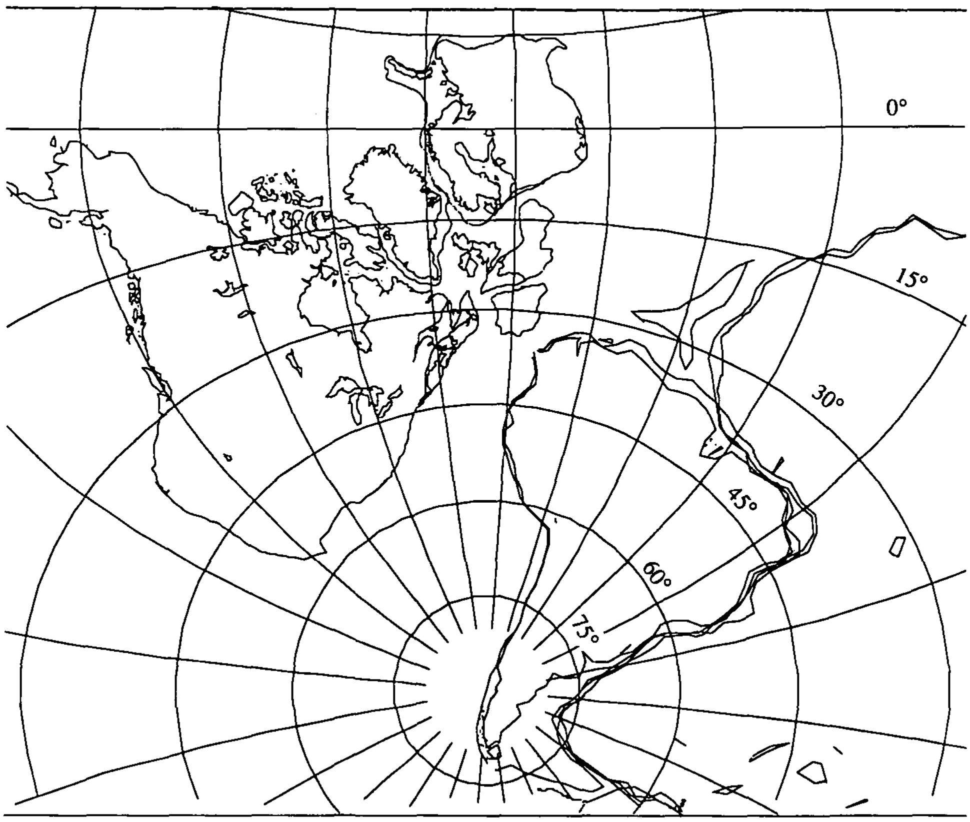

Figure 7. Siluro-Devonian reconstruction of the Old Red Continent (Laurentia, Avalonia, Baltica) and Gondwana. The Old Red Continent was assembled using the finite rotations of Bullard, Everett & Smith (1965) and positioned using: (1) the mean Siluro-Devonian palaeomagnetic pole for North America with quality index $Q \geqslant 3$ (Van der Voo, 1990), in European coordinates; (2) the mean Siluro-Devonian pole for stable Europe ($Q \geqslant 3$, Van der Voo, 1990); and (3) the Lower Old Red Sandstone pole from Wales (Channell, McCabe & Woodcock, 1992). Gondwana was positioned using the interpolated Siluro-Devonian pole for Gondwana given by Kent & Van der Voo (1990) (from Channell, McCabe & Woodcock (1992)).

time, not only from Eastern Avalonia but also from the other Iapetus bordering continents, is such that we have little information on the chronology of closure of the Iapetus Ocean. For Eastern Avalonia, the late Ordovician (~ 450 Ma) result from the English Lake District (Channell & McCabe, 1992) yielded a palaeolatitude of 43° S (Fig. 6) comparable to the latest Ordovician palaeolatitude (43° S) from Nova Scotia (Western Avalonia) obtained by Van der Voo & Johnson (1985).

Considerably lower palaeolatitudes are given by the new Siluro-Devonian palaeomagnetic data from Eastern Avalonia. The mid-Silurian result of Torsvik & Trench (1992) and the early Devonian result of Channell, McCabe & Woodcock (1992) yielded palaeolatitudes of 13° S and 17° S, respectively. The palaeolatitudes of Baltica and Eastern Avalonia, and the hypothetical palaeolatitudes for Laurentia and Gondwana (for a reference point in southern Britain) merge by mid-Silurian time (425 Ma) (Fig. 6), implying that the oceans which separated these units were more or less closed by this time. This is consistent with geological data for proximity of Eastern Avalonia and Laurentia by late Silurian time. The late Ordovician–Early Silurian closure of the Iapetus Ocean would require *minimum* subduction rates of about 8 cm/yr.

A compilation of late Silurian–early Devonian palaeomagnetic data from Iapetus bordering continents (including the new result from the Old Red Sandstone) is consistent with the existence at this time of a supercontinent comprising Gondwana, Laurentia, Baltica, Armorica and Eastern Avalonia (Fig. 7). Subsequent rifting of Gondwana may have initiated a late Devonian/early Carboniferous 'Iapetus' ocean which was closed during Hercynian orogeny, although the existence of this ocean has not been adequately documented.

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