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The palaeogeographic evolution of Southern Britain during early Palaeozoic times: a reconciliation of palaeomagnetic and biogeographic evidence

A. Trench [a], T.H. Torsvik [a] and W.S. McKerrow [b]

[a] *Norwegian Geological Survey, P.B. 3006, Lade N-7002, Trondheim, Norway*
[b] *Department of Earth Sciences, University of Oxford, Parks Road, Oxford, OX1 3PR, UK*

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ABSTRACT

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Palaeomagnetic, biogeographic and palaeoclimatic evidence together suggest that, in the Early Ordovician, Southern Britain lay off the west African margin of Gondwana at around 60 ° S. The combination of these disciplines reduces latitude uncertainties to around 5 to 10 degrees.

Rifting of Avalonia from Gondwana was followed, during most of the Ordovician, by northward drift as Avalonia and Baltica converged with subduction of Tornquist Sea crust. Both continents had similar moderate northward drift rates (3–6 cm/yr), so their convergence probably had a considerable longitudinal component.

Silurian and early Devonian data indicate that northward drift of Avalonia and Baltica continued after their collision, and that Southern Britain reached a latitude of around 20 ° S by c. 400 Ma.

Introduction

In the absence of marine magnetic anomalies, palaeomagnetic, biogeographic and palaeoclimatic data form the basis for Palaeozoic plate reconstructions. Reconstruction utilises the latitudinal dependence of well-dated samples using these geological sub-disciplines, i.e. the inclination of the Earth's magnetic field, the division of faunal communities into climatic belts and geographically isolated provinces, and the climatic restriction of particular sedimentary facies. Additionally, the direction of the magnetic field constrains the orientation of continents at a given latitude. Under favourable circumstances, the above methods may position former plates to within 5 degrees of latitude. Within this "error", studies of sedimentary provenance, stratigraphic overstep, timing of collisional/rifting events or comparable structural/metamorphic histories may further delineate the proximity of crustal blocks.

In this account, we review geological evidence bearing on the Palaeozoic drift history of Southern Britain, which formed a part of the Avalonian terrane. Avalonia constituted England, Wales and southern Ireland, the Ardennes of Belgium and northern France, the Avalon peninsula of Newfoundland, much of Nova Scotia, southern New Brunswick and coastal New England (McKerrow, 1988a; Scotese and McKerrow, 1990).

Previous reconstructions for Southern Britain based upon either faunal provincialism (Cocks and Fortey, 1982, 1990; McKerrow and Cocks, 1986) or palaeomagnetic data alone (Smith et al., 1973, 1981; Torsvik et al., 1990a) have differed significantly. Furthermore, little discussion jointly addressed the apparently contrasting datasets. The present contribution seeks to remedy this point.

Biogeographic versus palaeomagnetic consensus

Biogeography

Distinctive Early Ordovician platform benthic faunas are characteristic of each of the palaeocontinents: Laurentia, Baltica and Southern Europe. They are interpreted in terms of latitude and oceanic separation of these continents (Cocks and Fortey, 1982, 1990; McKerrow and Cocks, 1986). Southern and Central Europe lay proximal to Gondwana (Cocks and Fortey, 1988), which covered the geographic south pole. Avalonian shelf faunas also display close affinity with those of Gondwana (McKerrow and Cocks, 1976, 1986; Fortey et al., 1989), and Avalonia therefore lay near to the Gondwanan margin in high southerly latitudes (Cocks and Fortey, 1990). By contrast, Laurentia (with Scotland attached to its southern margin) was positioned in equatorial to low southerly latitudes (Cocks and Fortey, 1982, 1990).

During the Middle–Late Ordovician (Llandeilo–Caradoc), the commoner benthic faunas (trilobites and brachiopods) of Southern Britain show increasing similarity with those of the Baltic continent (Whittington and Hughes, 1972), a trend which is also observed in ostracodes (Vannier et al., 1989). By contrast, faunal links with Gondwana decline over this time interval (Vannier et al., 1989; Romano, 1990, p. 490) and the faunas display "mixed parentage" suggesting increased separation from Gondwana across the Rheic Ocean (McKerrow and Ziegler, 1972; McKerrow and Cocks, 1986; Cocks and Fortey, 1990). By Ashgill time, platform trilobites and brachiopods from Southern Britain and Baltica formed a single faunal province suggesting narrowing of the intervening Tornquist Sea (Cocks and Fortey, 1982). By the Early Silurian, the benthic ostracodes, which probably (like their modern equivalents) were unable to cross even a narrow ocean, are assigned to the same Baltic–British Province. This suggests closure of the Tornquist Sea before the start of the Silurian. A northward movement of Southern Britain into mid-southerly latitudes (c. 40 ° S) is therefore required during the Ordovician period (McKerrow and Cocks, 1986).

Silurian marine faunas with pelagic spat, do not exhibit provincialism between Laurentia and Southern Britain/Baltica (Aldridge, 1986; Cocks and Fortey, 1990). This reflects a narrowing of the Iapetus Ocean to around 1000 km (McKerrow and Cocks, 1986). The timing of final closure of Iapetus is determined from the age of the Acadian folding as around the Early–Middle Devonian boundary (Emsian–Eifelian) (McKerrow, 1988b). Freshwater fish cross both the Iapetus and Tornquist sutures after this time.

In summary therefore, the faunal evidence from Southern Britain requires an Early Ordovician link with Gondwana, followed by increasing proximity firstly to Baltica and then to Laurentia during late Ordovician to Devonian times. This can be accommodated by the rifting of Avalonia from Gondwana and a subsequent northward drift (McKerrow, 1988a; Scotese and McKerrow, 1990, 1991; Cocks and Fortey, 1990). Docking of Avalonia and Baltica probably followed by the end of the Ordovician. Subsequently, there were collisions between Baltica and Laurentia in the late Silurian and between Avalonia and Laurentia in the Devonian (McKerrow, 1988a, b).

Palaeomagnetism

Palaeomagnetic data from Palaeozoic Southern Britain have been reviewed by Briden et al. (1973, 1984, 1988), Piper (1987) and by Torsvik et al. (1990a). The addition of new studies during the period since 1973 has led to a continuously evolving palaeomagnetic database. As a consequence, the inferred drift history of Southern Britain, and the scale of its oceanic separation from Northern Britain (Laurentia) and Baltica has varied.

Palaeomagnetic data from Laurentia indicate an east–west trend for the Ordovician southern Laurentian margin in low southerly latitudes (Van der Voo, 1988). Conversely, new and re-interpreted data from Baltica indicate that it was positioned in temperate southerly latitudes at this time, but was "inverted" with respect to its present orientation (Torsvik et al., 1990b; Torsvik and Trench, 1991a).

Briden et al. (1973) concluded that "little or no closure has taken place across the British Caledonides since early Ordovician time" as palaeomagnetic studies throughout Britain had yielded a common Ordovician palaeopole (e.g. Briden and Morris, 1973; Piper and Briden, 1973). The subsequent revision of some data using updated laboratory techniques (Briden and Mullan, 1984), when combined with new data from northern Britain (Turnell and Briden, 1983) produced a recognisable offset in Ordovician poles across the Iapetus suture however. The "offset" indicated a higher southerly palaeolatitude for Southern Britain than Northern Britain and "established the width of the Iapetus Ocean as c. 1000 kilometres in mid-Ordovician time" (Briden et al., 1984). Torsvik et al. (1990a) presented time-calibrated apparent polar wander paths (APWP's) for Northern and Southern Britain which confirmed continental separation for Caradoc–Ashgill times (c. 450 Ma) in the order of 1000–1500 km (N. Britain c. 20° S, S. Britain c. 30–35° S). Northern Britain lay close to the east–west trending Laurentian margin at this time.

Most recently, the structural re-interpretation of existing Southern British mid-Ordovician data (see below) together with new data from mid-Ordovician volcanics (McCabe and Channell, 1991), yields a further updated APWP for Palaeozoic Southern Britain (Trench and Torsvik, 1991). The poles incorporated in this revised treatment are listed in Table 1. Notable revisions to published poles are as follows:

(1) The tectonic correction of site-mean data from the Shelve Intrusions of mid-Wales (Piper, 1978), which are now thought to pre-date Ashgill deformation (Lynas et al., 1985). Tilt correction of the original data yields a positive fold test at the 95% confidence level (Trench and Torsvik, 1990).

(2) Structural correction of palaeomagnetic sites from the Carrock Fell Gabbro of North England (Briden and Morris, 1973). As new radiometric studies are best satisfied by a Llanvirn intrusion age for the gabbro (Rundle, 1981; Thirlwall and Fitton, 1983), post-Llanvirn tectonism should be accounted for if a primary remanence has been preserved. When corrected for post-Ordovician folding (Roberts, 1971; McKerrow, 1988b), a revised pole is produced at 17° N 31° E. Tectonic correction also restores a primary igneous layering within the gabbro to a near-horizontal attitude (Harris and Dagger, 1987).

The new path implies more substantial mid-Ordovician (Llanvirn) separation across the

TABLE 1

Ordovician to Devonian palaeomagnetic poles from Southern Britain

	Age	Lat.	Long. (° E)	dP,dM	Reference
Stapely Volcanics	Lv	27	36	7,8	[1]
Shelve Intrusions	?Lv	10	46	8,12	[2]
Binsey Formation	Lv	3	345	9,13	[3]
Builth Volcanics and lower intrusions	Lv	−3	5	7,11	[4]
Carrock Fell Gabbro	Lv	17	31	16,20	[3]
High Ireby Formation	Lv	−12	357	6,10	[3]
Tramore Volcanics	L.Car	11	18	10,13	[3,5]
Borrowdale Volcs	L.Car	0	23	7,11	[6]
Builth Upper Intrusions	?Ld–Car	2	2	11,15	[7]
Breidden Hills	Car	0	17	12,17	[3,8]
Somerset/Gloucester lavas	Lld–Wen	8	309	12,18	[9]
Old Red Sandstone, Wales	L.Dev	3	298	9,15	[10]

Abbreviations to ages are as follows: Lv = Llanvirn, Ld = Llandeilo, L.Car = Lower Caradoc, Lld = Llandovery, Wen = Wenlock, L.Dev = Lower Devonian. References: [1] McCabe and Channell, 1990; [2] Trench and Torsvik, 1991a; [3] Trench and Torsvik, 1991b; [4] Trench et al., 1991; [5] Deutsch, 1980; [6] Faller et al., 1977; [7] Piper and Briden, 1973; [8] Piper and Stearn, 1975; [9] Piper, 1975; [10] Chamaulaun and Creer, 1964.

British sector of the Iapetus Ocean (c. 3300 km, N. Britain 15° S, S. Britain 45° S). It is this latest APWP, in conjunction with the outlined faunal constraints, which forms the basis for the present contribution.

Sedimentary facies indicators

During Early Ordovician times, a shallow-marine sandstone facies (Armorican Quartzite) characterises Armorica, the African margin of Gondwana, and probably extends into Avalonia as the Stiperstones Quartzite and equivalents (Noblet and Lefort, 1990; Fortey and Owens, 1990). Armorica and Avalonia were therefore most probably positioned proximal to northern Africa, in high southerly latitudes near to the South Pole at this time (Scotese and Barrett, 1990).

Sedimentary provenance studies also support this hypothesis as neodymian–samarium isotopic ratios suggest that, prior to the Arenig and after the Ashgill, Avalonia was receiving sediments from a large continent (Thorogood, 1990).

Tropical carbonate facies dominate Laurentia (Webby, 1984), including warm-water reefs and stromatolites. The Laurentian margin was therefore oriented approximately east–west in low latitudes during Early Ordovician times (Cocks and Fortey, 1990).

Carbonates were also prevalent on the Baltic platform in Early Ordovician times, but do not show evidence for a warm climate until the Late Ordovician (Jaanusson, 1973, 1976; Webby, 1980), suggesting northward movement of Baltica throughout the Ordovician period. The African Gondwanan margin, on the other hand, remained close to the South Pole throughout Ordovician time as indicated by an abundance of Late Ordovician tillites (Caputo and Crowell, 1985; Scotese and Barrett, 1990).

Climate-controlled-facies evidence from the major continents therefore provides a framework within which the movement of the Avalonian terrane can be constrained. In summary, Southern Britain was initially marginal to Gondwana in high southerly latitudes, but moved northward in Ordovician times, as it tracked Baltica towards the low-latitude Laurentian margin.

A combined palaeomagnetic, faunal and facies model

If one assumes the premise of an axially geocentric dipole during Palaeozoic times, palaeomagnetic studies provide the most quantitative method for the calculation of palaeolatitudes. Movements inferred through faunal and climate-related facies evidence (see above) can then be given a mathematical basis if sufficient palaeomagnetic data are available.

Our strategy has therefore been to position Southern Britain using palaeomagnetic evidence when sufficiently reliable data exist. Unfortunately, this is not the case prior to the Llanvirn. However, as faunal and sedimentary links suggest affinity of Southern Britain to Gondwana in the early Ordovician, a movement history becomes discernable when these constraints are combined with Gondwanan palaeomagnetic data.

The Armorican massif and much of Avalonia include widespread late Precambrian arc rocks (600–570 Ma). These indicate an arc developed on the margin of Gondwana, and it is probable that these terranes were spread out along the continental margin. In Early Cambrian facies, archaeocyathans are present in France and Morocco (Brasier and Cowie, 1989) while only clastic facies occur in Mauritania, Senegal and Florida. It thus seems likely that Armorica lay close to Morocco while Avalonia, with its clastic Cambrian facies, was perhaps sited next to Mauritania and Florida. As Gondwana has a reliable Early Ordovician palaeomagnetic dataset (Van der Voo, 1988; Bachtadse and Briden, 1990), the former orientation of its margin can be reconstructed with confidence. It is also noteworthy that palaeomagnetic and facies indicators for the position of the South Pole over Gondwana concur for Early Ordovician times (cf. Bachtadse and Briden, 1990; Scotese and Barrett, 1990).

A summary of the methods adopted in our analysis is as follows:

(1) Palaeozoic palaeomagnetic poles from Southern Britain were compiled, graded (criteria

of Van der Voo, 1988), and assigned "magnetic ages" after consideration of available stratigraphic constraints. Whenever absolute age determinations were available, these were used directly. A smoothed spherical spline was then fitted to these data using the method described by Jupp and Kent (1987) to produce a time-calibrated APWP (Trench and Torsvik, 1991b).

(2) Latitudinal reconstructions for Southern Britain were created using mean palaeomagnetic poles from the APWP for intervals of 10 million years (Fig. 1). Mean APWP poles can only be calculated back to approximately 470 Ma as no reliable earlier data exist for the Ordovician period.

(3) Faunal and sedimentary facies evidence suggest the proximity of Avalonia to Gondwana during Early Ordovician times. A latitudinal estimate was therefore generated by suturing Southern Britain to the Mauritania–Florida margin of Gondwana (Fig. 1, Gondwanan pole listed by Van der Voo, 1988).

(4) Latitudinal drift velocities (Fig. 2) were calculated from the APWP for mid-Ordovician to Devonian times (470–400 Ma). We note that these are minimum estimates of true velocity as no account is taken of possible longitudinal drift over this period. Velocities prior to 470 Ma were not calculated given the uncertainty in the precise position of Southern Britain on the Gondwanan margin.

The latitudinal reconstructions for Southern Britain record its northward movement throughout Early Ordovician to Early Devonian times, as Avalonia moved towards the southern margin of Laurentia (Figs. 1, 2a). Suturing Southern Britain to Mauritania/Florida implies a palaeolatitude of approximately 60°S in earliest Ordovician times (Fig. 2a). Continual northward drift is indicated approaching 20°S by end-Silurian times (Figs. 1, 2a). Post-400 Ma latitudes are not depicted as the British sector of Iapetus had effectively closed by the Emsian/Eifelian (c. 395 Ma).

The early Tremadoc (basal Ordovician) initiation of calc-alkaline igneous activity in Wales indicates the onset of subduction which may have closely followed the rifting of Avalonia from Gondwana. The transit of Avalonia from Gondwana to Baltica corresponds in time to the calc-alkaline igneous activity in Southern Britain (Kokelaar et al., 1984) and the Ardennes (André et al., 1986). It appears that these Tremadoc to Caradoc igneous rocks are related to the subduction of Tornquist oceanic crust, and it can be concluded that a trench lay NE of England and the Ardennes at this time. This indicates that the convergence of Avalonia and Baltica involved a considerable longitudinal component.

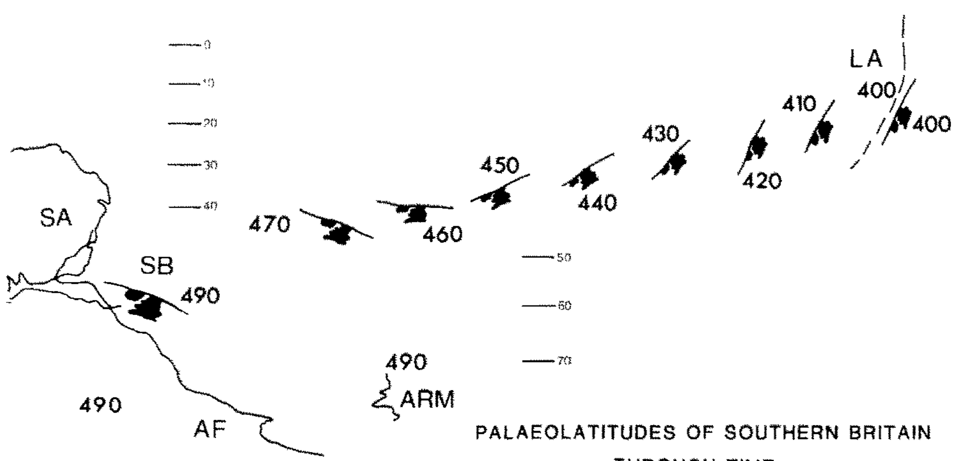

Fig. 1. Latitudinal drift history for Southern Britain for Early Ordovician–Early Devonian times. Galls projection. (Latitudes plot as horizontal lines. Distortion minimised in mid-latitudes.) The margin of Western Gondwana is shown at c. 490 Ma (*AF* = Africa, *SA* = South America). The Armorican massif (*ARM*) is also shown at 490 Ma. Southern Britain (*SB*) is sutured to the Mauritania/Florida margin of Gondwana in Early Ordovician times (c. 500–490 Ma). The orientation of the Laurentian margin (*LA*) is depicted at 400 Ma. Horizontal scale indicates palaeolatitudes in intervals of 10 degrees.

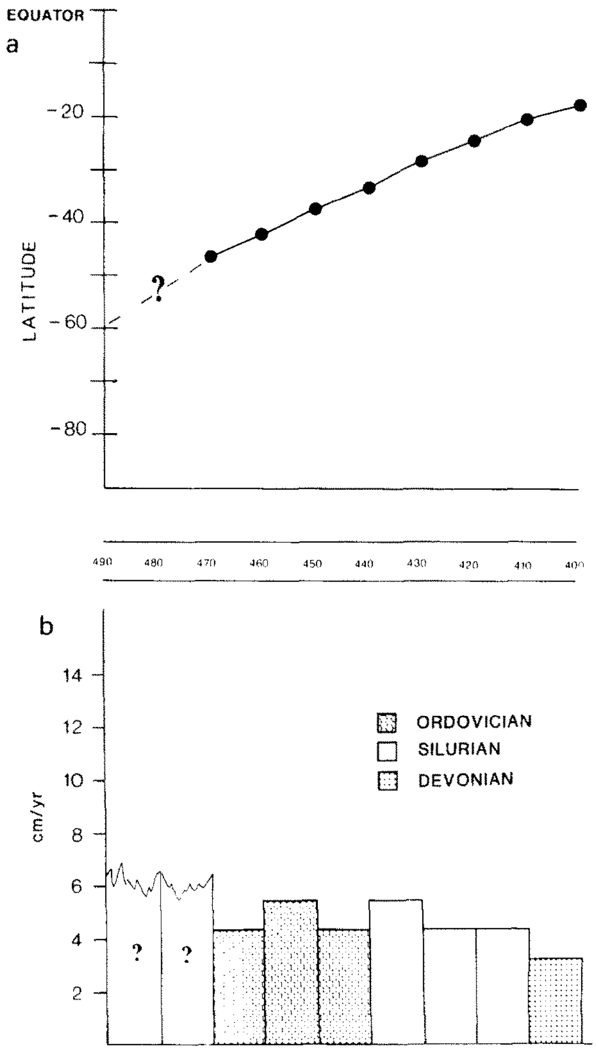

Fig. 2. (a) Plot of palaeolatitude versus time for Greenwich, London over the interval 470–400 Ma. Dashed line indicates uncertainty prior to 470 Ma. (b) Histogram displaying drift-rate of Southern Britain at 10 million year intervals (470–400 Ma). Ordovician, Silurian and Devonian periods are shaded. Ordovician–Silurian and Silurian–Devonian period boundaries have been indicated at 440 and 410 Ma for simplicity.

Calculated latitudinal drift-rates for Southern Britain are between 3 and 6 cm/yr for Llanvirn to Early Devonian times (470–400 Ma) (Fig. 2b). This rate is comparable to that of Baltica which also drifted northward at between 1 and 6 cm/yr over this time interval (Torsvik et al., 1991) confirming that there was a large longitudinal component in the closure of the Tornquist Sea.

The northward movement of Avalonia was accompanied by a counter-clockwise rotation of approximately 55° over the 470–400 Ma interval (calculated as the modelled change in magnetic declination at Greenwich, London). Baltica also rotated counter-clockwise over the same time. There must therefore have been considerable dextral shear across one or both margins of the Tornquist Sea.

Concluding remarks

The above model reconciles previously contrasting palaeogeographies proposed on either palaeomagnetic or faunal/facies grounds alone. Apparent differences in previous studies are related to: (1) gradual changes in the palaeomagnetic dataset due to revision of earlier studies and the performance of new studies; and (2) the fact that biogeographic reconstructions necessarily indicate palaeolatitudes although the technique is somewhat qualitative when used in isolation.

Uncertainties remain, however, which call for a testing of the present model. Most notably, palaeomagnetic data from Lower Ordovician rocks in Southern Britain are required to more precisely determine its position along the Gondwanan margin as suggested by the biogeographic evidence.

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Note added in proof

A Lower Ordovician (Tremadoc/ Arenig) palaeomagnetic result from Wales has recently been reported (Torsvik and Trench, 1991b). This new result places Southern Britain in southerly latitudes of c. 60°, closely in correspondence with the position of Southern Britain indicated in Fig. 1 which is based on the faunal/sedimentary evidences.

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