The Ordovician history of the Iapetus Ocean in Britain: new palaeomagnetic constraints

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SHORT PAPER

The Ordovician history of the Iapetus Ocean in Britain: new palaeomagnetic constraints

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New late Tremadoc–early Arenig palaeomagnetic results from SW Wales imply that S Britain (part of Eastern Avalonia) occupied a southerly latitude of *c.* 60°S in early Ordovician times. When combined with Scottish Ordovician palaeomagnetic data, which indicate a 15°S latitude, the results indicate that the British sector of the Iapetus Ocean reached a latitudinal width of *c.* 5000 km in Tremadoc–Arenig times, which was reduced to *c.* 3300 km by Llanvirn–Llandeilo (mid-Ordovician) times.

The new data resolve two previous controversies in Palaeozoic palaeogeography. First, the high southerly palaeolatitude links Avalonia to Gondwana, marginal to W Africa, thus reconciling conflicting reconstructions based upon either palaeomagnetic or faunal/facies evidence alone. Second, reliable Llanvirn palaeomagnetic data imply that Avalonia had rifted northwards by Arenig time, whereas Armorica remained proximal to northern Africa throughout the Ordovician. The combined data therefore establish that Avalonia and Armorica formed separate micro-continents when rifting from Gondwana.

Palaeomagnetic, biogeographic and palaeoclimatic evidence are in agreement in establishing the existence of the Iapetus Ocean (Wilson 1966; Harland & Gayer 1972) in Ordovician times, but estimates of its size have varied substantially (Dewey 1969, 1971; McKerrow & Cocks 1976; Smith *et al.* 1981; Briden *et al.* 1984; McKerrow 1988; Torsvik *et al.* 1990*a*; Scotese & McKerrow 1990). In particular, biogeographic considerations have consistently been interpreted to represent wider oceanic separation than that indicated by palaeomagnetic data. This discrepancy is explicable in that early palaeomagnetic studies may not have employed sufficiently detailed demagnetization experiments to remove Late Palaeozoic secondary magnetizations of shallow inclination (see Briden & Mullan 1984, for discussion).

Recently, however, a palaeomagnetic result from the Shelve inlier (McCabe & Channell 1990), as well as a re-compilation of palaeomagnetic data from S Britain (Trench & Torsvik 1991), indicates that the British sector of the Iapetus Ocean covered approximately 30° of latitude in mid-Ordovician (Llanvirn–Llandeilo) times (N Britain 15°S, S Britain 45°S). Prior to the Llanvirn however, no reliable palaeomagnetic data exist for Southern Britain.

In early Ordovician times (Tremadoc–Arenig), faunal evidence indicates Iapetus to have reached its maximum extent (McKerrow & Cocks 1976, 1986), and early Ordovician sedimentary facies suggest a provenance link with the Armorican Massif (Fortey & Owens 1987; Noblet *et al.* 1990), from which palaeomagnetic data indicate high southerly latitudes (Perroud & Van der Voo 1985; Perroud *et al.* 1986). Therefore, although several palaeogeographic reconstructions depict S Britain as a peri-Gondwanan block in early Ordovician time (Pickering *et al.* 1988; Scotese & McKerrow 1990), no palaeomagnetic data have been available to quantify its palaeo-position. Similarly, palaeomagnetic data have been insufficient to discriminate whether S Britain (part of Eastern Avalonia; Soper *et al.* 1987; McKerrow 1988) formed a constituent of the Armorican plate (Armorican and Iberian Massifs: Van der Voo 1979; Perroud *et al.* 1984) during the Ordovician period.

To address these uncertainties, 15 sites were sampled within a sequence of late Tremadoc–early Arenig andesitic lavas and volcaniclastic sediments at Treffgarne, Dyfed, SW Wales (Traynor 1988). This sequence dips on average 30° to the north. Low-grade metamorphism (Oliver 1988) and tectonism is most likely Acadian (Woodcock *et al.* 1988), although Hercynian deformation cannot be excluded (Hancock *et al.* 1981).

Palaeomagnetic results. Stepwise-thermal demagnetization experiments (161 samples) identify two magnetization components. The lower unblocking-temperature component (200–500°C) has sub-horizontal to shallow negative inclination due south. We interpret this component, termed *S*, as the Permo-Carboniferous (Hercynian) overprint observed elsewhere in Wales (McClelland-Brown 1983; Briden & Mullan 1984; McCabe & Channell 1990). The higher unblocking-temperature component (>500°C, Fig. 1a), termed *T*, is primary, and has the following remanence properties.

(1) Reversely-magnetized polarity (tilt-corrected declination = 298°, inclination = 75°, alpha 95 = 5.5°, observed in 10 sites; Fig. 1b: Pole N56°, E306° & dp/dm = 9/10).

(2) Clasts from an intra-formational conglomerate (Thomas & Cox 1924) reveal high-unblocking magnetizations which are directionally-consistent within, but differ between, individual boulders (Fig. 1c). These magnetizations have equivalent unblocking temperatures to component *T*. Conversely, component *S* displays consistent directions within the boulders.

(3) Laboratory unblocking temperatures cover both magnetite and hematite ranges, but generally display discrete unblocking between 520–550°C (Fig. 1a), which indicates the dominance of low-Ti titanomagnetite formed during high-temperature deuteric oxidation in volcanic rocks.

Discussion. The new palaeomagnetic data imply that Southern Britain occupied a latitude of *c.* 60°S in late Tremadoc–early Arenig times (Fig. 2). Compared with Ordovician data from the Scottish terranes (*c.* 15°S, Torsvik *et al.* 1990*a*), this implies that the intervening Iapetus Ocean reached a latitudinal width of near 5000 km (Fig. 2).

A comparison with Ordovician palaeomagnetic data from Gondwana (Van der Voo 1988; Bachtadse & Briden 1990), which allow the reconstruction of the west Gondwanan margin, suggests Eastern Avalonia to have been positioned close to west Africa, possibly in the vicinity of Mauritania (Fig. 2) while Armorica was attached to NW Africa (Torsvik *et al.* 1990*a*). This scenario attributes late

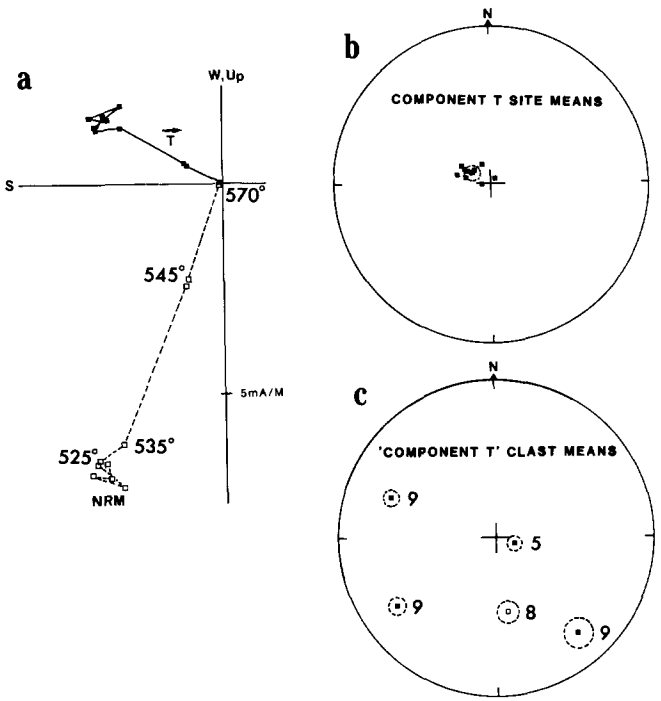

Fig. 1. (**a**) Representative orthogonal projection: Andesite lava. Primary (T) magnetization component is indicated. Open (Closed) squares refer to projection in the vertical (horizontal) plane. In-Situ co-ordinates. Component S not resolved in this example.

(**b**) Site-mean component (T) directions after structural tilt correction. Cone of 95% confidence about the total mean direction is dotted. Equal-angle projection.

(**c**) Clast-mean component (T) directions from an intra-formational volcanic conglomerate. Cones of 95% confidence are indicated for each clast. Number of samples from each clast is shown. In (b) and (c), solid (open) squares represent lower (upper) hemisphere directions.

Precambrian arc rocks in both Avalonia and Armorica (e.g. Scotese & McKerrow 1990) to a peripheral Gondwanan arc. At this time, Baltica was confined to southerly latitudes of 30–60° (Torsvik *et al.* 1990*b*), whereas Laurentia and Siberia (Mongolian margin facing north; Scotese & McKerrow 1990; Khramov *et al.* 1981) retained more equatorial latitudes (Fig. 2).

From this early Ordovician scenario, Eastern Avalonia then had rifted away from Gondwana into mid-southerly latitudes by mid-Ordovician (late Llanvirn–early Llandeilo) times (Fig. 3). This movement history is clearly recorded by palaeomagnetic data from volcanic rocks of the early Llanvirn Shelve (51°S: McCabe & Channell 1990) and the late Llanvirn Builth inliers (35°S: Briden & Mullan 1984; Trench *et al.* 1991) respectively. Conversely, the African Gondwanan margin and Armorica remained in high

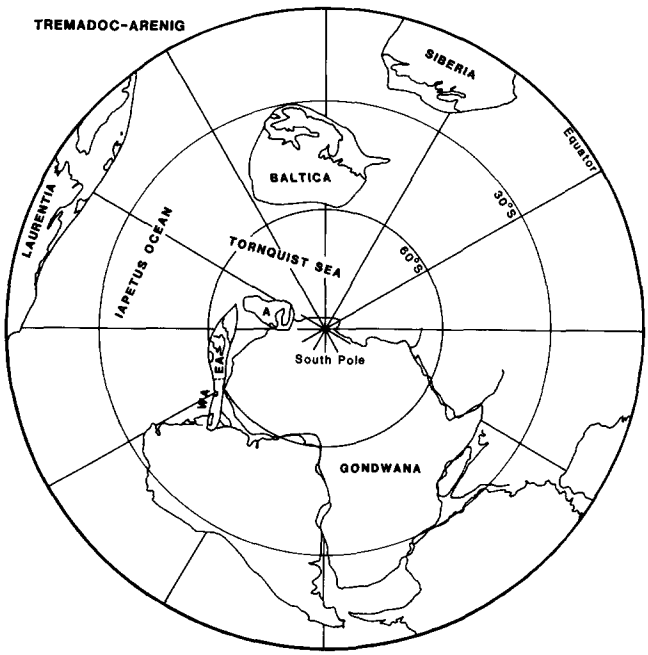

Fig. 2. Continental reconstruction for early Ordovician (late Tremadoc–early Arenig) times based on palaeomagnetic data (optional longitude). Southern Britain and other Avalonian segments positioned in *latitude* according to the Treffgarne pole. A preferred palaeo-orientation has been used to maintain the facing of the Iapetus margin in Britain. In Figs 2 & 3, Western Avalonia (WA) is positioned according to data from Eastern Avalonia (EA) in a Bullard *et al.* fit (1965), since no structurally reliable early and mid-Ordovician data exist for Western Avalonia. Gondwana positioned according to Van der Voo (1988) (pole: 34°N, 007°E, African co-ordinates), Laurentia and Northern Britain combined (Torsvik *et al.* 1990*b*, pole: 13°S, 29°E, European co-ordinates in a Bullard *et al.* fit (1965)), Baltica (Torsvik *et al.* 1990*b*, pole: 31°N, 086°E), Armorica (A) (Torsvik *et al.* 1990*a*, table 7, 490 Ma pole: 30°N, 334°E), Siberia according to a mean pole of 30°N, 330°E (Torsvik *et al.* 1990*a*). Equal-area polar projection.

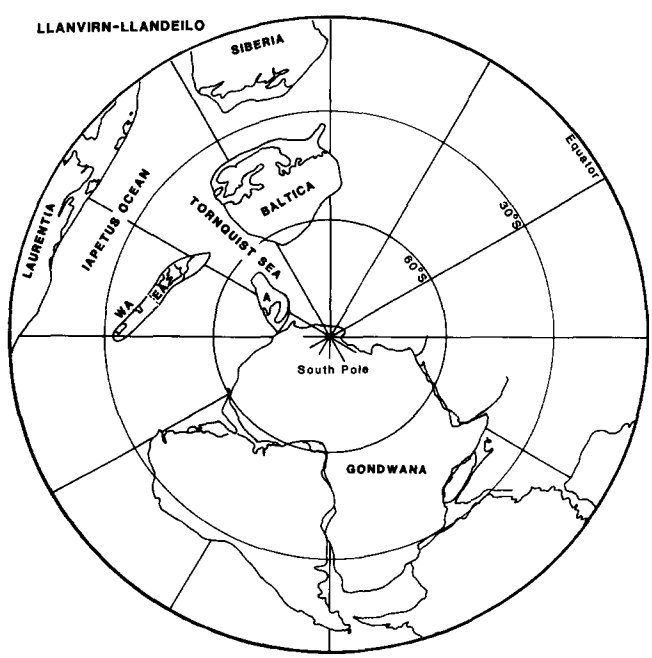

Fig. 3. Continental reconstruction for mid-Ordovician (late Llanvirn–early Llandeilo) times. Latitudinal positioning of Gondwana and Siberia as Fig. 2. Avalonia from Trench & Torsvik (1991, table 2, 470 Ma pole: 12°N, 23°E), Baltica (Torsvik *et al.* 1990*b*, combined path *X* and *Y*, 470 Ma pole: 21°N, 32°E), Armorica (Torsvik *et al.* 1990*a*, table 7, 470 Ma pole: 33°N, 345°E), Laurentia and Northern Britain (Torsvik *et al.* 1990*b*, pole: 22°S, 19°E, European co-ordinates). Equal-area polar projection.

southerly latitudes throughout the Ordovician period as implied by palaeomagnetic data (Perroud & Van der Voo 1985; Perroud *et al.* 1986; Van der Voo 1988; Bachtadse & Briden 1990) and the presence of Ordovician tillites (Scotese & Barrett 1990).

Conclusions.

(1) Avalonia, Armorica (Armorican–Iberian Massifs) and probably other European Massifs formed marginal parts of Gondwana in the vicinity of NW Africa in early Ordovician times, separated by the Iapetus Ocean and the Tornquist Sea from Laurentia and Baltica respectively,

(2) Latitudinal separation across the British sector of Iapetus was approximately 5000 km in late Tremadoc–early Arenig times, reduced to *c.* 3300 km by Llanvirn–Llandeilo times,

(3) Avalonia rifted away from Gondwana late in the early Ordovician, Arenig, and later collided with Baltica and Laurentia, ultimately forming Euramerica by late Silurian–early Devonian times. Conversely, Armorica remained attached to Gondwana until at least late Ordovician–early Silurian times.

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