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Palaeomagnetic constraints on the distribution of continents in the late Silurian and early Devonian

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Silurian and Devonian palaeomagnetic data are reviewed and used to orient continental fragments in a global map-frame. In some cases longitude separations have been estimated from palaeontological data. The resulting maps show a possible evolution of the continents in Silurian and Devonian time. A 10° present-day latitude–longitude grid has been rotated to past positions and the extent of areas involved in subsequent deformation are shown. Two internally consistent alternatives are presented for the Silurian–Devonian boundary reconstruction. The first draws on North American and Baltic data, mostly from cratonic sediments; the second uses British data obtained mostly from igneous rocks, and admits poles from SE Australia in positioning Gondwanaland. Choosing between these alternatives depends on having better data from Gondwanaland and on evaluating the hypothesis of large-scale remagnetization of red beds.

INTRODUCTION

Evolution and environment in the middle Palaeozoic must depend in part on the relative positions and palaeolatitudes of the continents at that time. This paper reviews the palaeomagnetic data available for making global palaeocontinental reconstructions for three time intervals: Caradoc–Wenlock (= late Ordovician to middle Silurian); Ludlow–Emsian (= late Silurian to early Devonian); and Eifelian–Tournaisian (middle Devonian to early Carboniferous). These reconstructions can be regarded as refinements of previously published maps (Smith *et al.* 1973; 1981). They are intended to show the confidence with which such maps can be drawn, as well as providing a base on which palaeogeographic and other data can be plotted. The Chicago group have produced similar maps (Scotese *et al.* 1979; Bambach *et al.* 1980; Scotese 1984 and this symposium), to some of which they have added generalized geological data (Ziegler *et al.* 1977*a*, *b*). Less detailed series of maps have been published by Kanasewich *et al.* (1978); Morel & Irving (1978); Turner & Tarling (1982); Zonenshayn & Gorodnitskiy (1977*a*, *b*).

As discussed at length by Smith *et al.* (1973) there are at least five major problems associated with the construction of Palaeozoic palaeocontinental maps, none of which has been solved in the intervening decade. The first is simply a lack of reliable pole positions from many continents, especially for the Silurian and Devonian periods. This means that continuous apparent polar wander (a.p.w.) paths are difficult to draw, even for very large areas such as Gondwanaland, with doubt as to the correct polarity of some early Palaeozoic results.

The second problem is that it is now clear that many samples have more than one component of magnetization, each of uncertain age. Different evaluations of these uncertainties may lead to the rejection of some poles by one group of workers and their acceptance as reliable by another, or to different ages being assigned to the same pole, in turn leading to quite different conclusions, as in the case of the proposed displacement on the Great Glen Fault, discussed below.

Thirdly, many of the available poles are from red beds or similar sediments whose biostratigraphic ages are uncertain. Others are from beds whose biostratigraphic age is well known but is difficult to relate precisely to the isotopic time-scale. Thus even magnetically well-defined polar wander paths may lack good age control, so that large errors are associated with the palaeomagnetic estimates of the closure time of oceans and subsequent continental suturing.

Fourthly, because no Palaeozoic ocean-floor is preserved, other than as ophiolitic fragments, magnetic anomalies and fracture zone trends cannot be used to reposition continents relative to one another. Relative longitudes can be inferred only by using tectonic, palaeontological or some other data. For much of Palaeozoic time, we can draw only composites, that is, we can project each continental fragment onto a global map-frame so as to place it in its inferred palaeolatitude and orientation in a geologically plausible relationship with its neighbours. Though these constructions are, strictly, distinct from true maps, we shall for simplicity use the terms map and composite interchangeably.

The longitude uncertainty has been emphasized by all makers of palaeomagnetically based Palaeozoic maps. Ideally the palaeontologist would use his data to change the published maps, by sliding continents along latitude lines, without change of orientation, to obtain the best match of the two datasets. This can readily be done when the maps are cylindrical or polar projections, but requires more work for other projections. The published 'maps' cannot be criticized, as they have been by Boucot & Gray (1983), on the grounds that the oceanic currents implied by the 'maps' are inconsistent with the faunal distributions, until all possible longitudinal permutations have been considered. Because of the misunderstandings about longitudinal indeterminacy, we have, in contrast to all our previous maps, used some palaeontological estimates of relative longitude separation to reposition some continental fragments. However, we have not drawn upon any palaeoclimatic indicators as used in the Devonian map of Heckel & Witzke (1979).

Fifthly, a significant proportion of the Silurian and Devonian continental crust has been deformed during orogeny. This has two effects: it may be impossible to obtain reliable palaeomagnetic data from such areas and, secondly, stable areas separated from each other by Silurian or younger orogenic belts must be individually sampled before they can be repositioned palaeomagnetically. For example, much of China and SE Asia lack any reliable Silurian or Devonian palaeomagnetic data and cannot yet be repositioned even though now sutured on to Siberia.

The existence of strong non-dipole components in the Earth's magnetic field, regarded as a possibility a few years ago (Briden *et al.* 1970), now seems less likely, although a small quadrupole component such as that observed for the Cenozoic could give rise to errors of several degrees in individual palaeopoles (Livermore *et al.* 1983, 1984). For present purposes, however, the geocentric dipole field appears to be an adequate model for analysing Palaeozoic palaeomagnetic data.

Plate tectonics

(a) *Pangaea*

The assumptions of plate tectonics are fundamental to current interpretations of Palaeozoic palaeomagnetic data and to drawing Palaeozoic composites. We assume that all Silurian and younger orogenic belts contain sutures where two or more crustal fragments have been welded together. The stable areas outside the orogenic belts are assumed to have been parts of rigid plates, each of which can be oriented independently by palaeomagnetic data. In theory, one reliable pole position from any part of such a plate is sufficient to orient the entire plate. Fortunately, all the major continents can be repositioned for late Triassic and early Jurassic time to form Wegener's (1912) Pangaea. The only continental fragments that cannot be repositioned readily for that time are those involved in Mesozoic and Cenozoic orogeny.

This reassembly, known as Pangaea-A (Morel & Irving 1981), has been quantified by least-squares continental fitting methods (for example, Bullard *et al.* 1965; Smith & Hallam 1970) and independently confirmed by extrapolating the ocean-floor data back to continental closure (for example, Le Pichon *et al.* 1977; Norton & Sclater 1979). Pangaea-A has been the conventional starting point for discussions of Palaeozoic world maps. However, early Triassic and older palaeomagnetic data from Laurasia and Gondwanaland do not coincide on this reconstruction. They can be brought into much better agreement by rotating the northern continents by about 20° anticlockwise about a pole in NW Sahara along a plate margin lying within the Appalachian–Hercynian orogenic belt (Van der Voo & French 1974; Van der Voo *et al.* 1976; 1984). This reconstruction (figure 1) has been referred to as Pangaea-A2 (Morel & Irving 1981; Hallam, 1982). Other configurations (for example, Morel & Irving 1981) have been proposed to reconcile Permo-Carboniferous poles, but do not satisfy the geological constraints (Hallam 1982).

Like Pangaea-A, Pangaea-A2 can then be broken into its major stable Palaeozoic continental components along the Appalachian–Hercynian–Uralian orogenic belts to give rise to three Carboniferous and Devonian continents: Gondwanaland, Laurentia–Baltica (the 'Old Red Continent') and Siberia. Laurentia and Baltica must be broken into two along the Caledonian belt in Silurian and earlier Palaeozoic time.

The remaining areas to be repositioned are any microcontinents caught up in Silurian or younger orogenic belts, the orogenic zones themselves and microcontinents separated by younger orogenic belts from the major stable Palaeozoic continents. Several of these micro-continents, together with parts of the orogenic zones, have been intensively studied in the past decade (for example, Britain, central Europe, E N America). Some of them yield stable pole positions that allow them to be oriented in a Palaeozoic composite, while for others the palaeomagnetic data are still enigmatic. Most of these remaining areas have not been studied in detail and still cannot be oriented by palaeomagnetic data.

Pangaea-A is an excellent geometrical fit. Since oceans vanish by subduction, which in turn causes significant orogenic deformation within Pangaea, then the last phase of orogenic deformation must be the same age as or younger than the final stage of continental suturing. If the palaeomagnetic data suggests some post-collisional movement between two sutured continents, then that movement can only be transcurrent motion. The last phase of orogenic deformation in the Caledonides is late Silurian in age; in the Appalachian–Hercynian–Uralian belt it is early Permian. Thus if the palaeomagnetic data suggest that Laurentia and Baltica

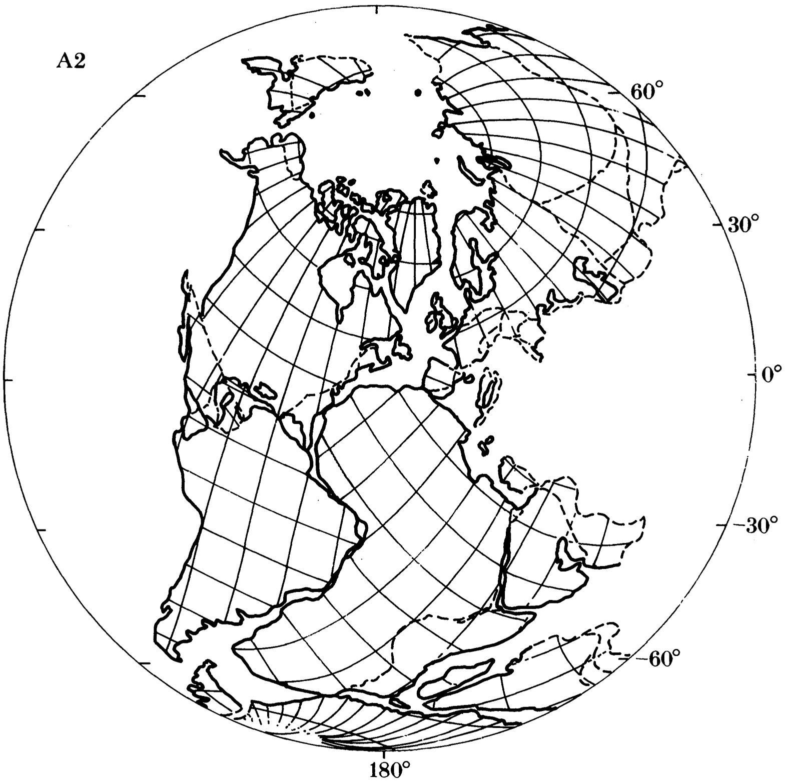

FIGURE 1. Pangaea-A2 reconstruction for early Carboniferous time oriented by using the global mean pole for the interval 280–260 Ma, after Livermore *et al.* (1985). Dashed lines show important Phanerozoic sutures. Mollweide Elliptic projection.

were in relative motion in Devonian or younger time, then there must be large Devonian or younger strike–slip faults between them. Similarly, if Gondwanaland and Laurentia–Baltica appear to be in relative motion in late Permian or later time, then there must be large Permian or younger strike–slip faults between them. If such faults do not exist then discrepancies between contemporaneous palaeomagnetic poles for any of these blocks are likely to be due to errors in the data.

For some reconstructions of the Gulf of Mexico, Pangaea-A2 gives a better alignment of the Palaeozoic orogenic belts around the Gulf (Walper 1980). However, if the gaps in the Gulf of Mexico region in Pangaea-A did not exist, then the transition from Pangaea-A2 to Pangaea-A must have involved a further reorganization of Mexico and central America (A. G. Smith, unpublished). As shown in figure 1, without such a reorganization, S America would, before the transition, have overlapped onto them and parts of N America. The youngest orogenic deformation to affect Pangaea-A is early Permian in age. Late Carboniferous deformation includes important strike–slip faults (Arthaud & Matte 1977). Thus the geological evidence suggests that the transition from Pangaea-A2 to Pangaea-A was essentially complete by the end of early Permian time. The disagreement between Permian and early Triassic poles on Pangaea-A is discussed elsewhere (Livermore *et al.* 1985).

Although the adoption of Pangaea-A2 as a base map can be regarded as a matter of convenience only, if it did in fact exist it suggests that some form of Pangaea may have persisted throughout the Carboniferous. Thus the map for the Eifelian–Tournaisian interval would be a form of Pangaea (Boucot & Gray 1983; Scotese 1984). This possibility may be important for understanding the nature of the Appalachian–Hercynian belt (Livermore *et al.* 1985).

(*b*) *Continental collisions*

It is not yet clear what physical parameters govern the collision of continents. However, the closure of Tethys is unique in that it can be determined from the Atlantic ocean-floor magnetic anomalies. These allow Eurasia and Africa to be repositioned, in turn permitting the closure to be examined. New magnetic anomaly data (Klitgord & Schouten 1982), and new geological and magnetic anomaly time scales (Harland *et al.* 1982) suggest that this motion has the following properties (Livermore & Smith 1984): the area of the Tethys is progressively reduced; the a.p.w. paths of Africa and Europe during closure are not simple paths, though they lack hairpin bends; the closure approximates to a pivoting motion between Africa and Europe about the end of the wedge-shaped Tethys.

While it is unwise to generalize from one example, we speculate that Palaeozoic oceans may have had similar closure patterns. Thus, if it could be established that two Palaeozoic continents collided at a particular point, bringing into existence a wedge-shaped ocean, then the subsequent history of closure could be modelled kinematically by pivoting the continents about the collision point.

The problem with applying this kinematic model is that of identifying the first collisional event between major continents, as opposed to a collisional event between a microcontinent and a major continent. Probably the best present guide to the time of earliest collision is given by the time when fresh water and terrestrial faunas from previously separated continents start to mix. By using the fossils as a guide to timing, the palaeomagnetically determined composites can be adjusted longitudinally to bring about a collision at the appropriate time, with subsequent evolution of the oceanic region between the two continents being guided by the kinematic model.

PALAEOMAGNETIC POLES

Table 1 lists the poles used as the basis of our palaeomagnetic maps. The present data base is in contrast to that by Smith *et al.* (1973) where only 18 poles were available for a 'Lower Devonian' map, nearly two-thirds of which were actually from Carboniferous rocks. We have selected results considered reliable in terms of their sampling, magnetic cleaning and dating, although in only a few cases has the precise age of magnetization been demonstrated (cf. review by Briden & Duff 1981). As the quality of available poles differs from fragment to fragment, we have not attempted to apply rigorous selection criteria to every pole; rather we have sought the most reliable data available for each continental fragment.

From table 1 we have attempted to construct Silurian to Devonian a.p.w. paths for the four major continents (Gondwanaland, Laurentia, Baltica and Siberia). We also discuss in more detail palaeomagnetic results from Britain, Avalonia and Armorica. All the poles have been rotated from their present-day positions to Pangaea-A2 and then sampled in three windows. These windows are, referring to the time-scale of Harland *et al.* (1982) and table 2, Caradoc–Wenlock (439.5 ± 18.5 Ma), Ludlow–Emsian (404.0 ± 17.0 Ma) and Eifelian–Tournaisian (369.5 ± 17.5 Ma).

TABLE 1. PALAEOMAGNETIC DATA

formation	site lat. (°N)	site lon. (°E)	pole lat. (°N)	pole lon. (°E)	A_{95}§ or dp/dm	age Ma	reference†
GONDWANALAND							
Antarctica							
Sor Rondane intrusives	−72.0	24.0	−28.0	10.0	5/6	482	10/140
Taylor Valley Lampro. Dykes	−77.6	163.4	−9.3	26.7	5.5/10.9	482	16/175
Australia							
Mulga Downs Gp	−32.8	143.5	−54.0	96.0	11	367	16/153
Ross River Overprint	−23.6	134.5	−60.2	68.1	7.1/4.8	374	16/161
Housetop Granite (NRM)	−41.3	145.9	−67.0	94.0	28	375	9/123
Browning Group Volcs	−34.5	148.8	−64.0	45.0	9	387	14/369
Mereenie Sandstone	−23.8	133.0	−41.5	40.5	19.0/10.5	425	14/376
Stairway Sandstone	−23.8	133.0	−2.0	50.5	8.5	463	14/393
Tumblagooda Sandstone	−27.7	114.5	−30.0	31.0	9	482	14/405
Jinduckin Formation	−14.1	131.7	−13.0	25.0	10.1/11.0	482	14/395
SE Australia							
Mugga Mugga Porphry	−35.0	149.4	−63.2	7.9	6/9	420	8/127
Ainslie Volcs	−35.0	149.0	−71.0	353.0	10	425	14/368
Africa							
Msissi norite Morocco	30.9	355.3	−0.5	25.0	16.5	367	14/361
Gneiguira–Dikel Sediments	18.5	347.5	−35.3	43.5	3.0/5.6	374	KDS84
Blaubeker Formation	−24.0	16.5	51.0	352.0	19	471	KMGRS80
Table Mountain Series	−34.0	18.0	50.0	349.0	2	472	4/32
Ntonya Ring Structure	−15.5	35.3	27.0	345.0	1/2	477	9/137
South America							
Suri Formation	−27.8	291.9	−8.5	5.9	5.9	473	VVM80
SIBERIA							
Rybinsk Basin Redbeds	56.0	94.0	−24.0	331.0	6/3	367	OT5–93
Krasnoyarsk Redbeds	54.0	93.0	−23.7	324.2	7.1	370	OT5–136
Krasnoyarsk Redbeds	54.0	93.0	−26.3	331.3	6	374	OT5–137
Byskar Series	56.0	93.0	−32.0	342.0	5/5	374	OT5–42
Tungus Syncline Carbonates	68.0	89.0	−32.0	320.0	9/7	380	OT5–164
Manturovsk Suite Carbonates	69.0	88.0	−17.0	325.0	10/6	380	OT5–163
Krasnoyarsk Redbeds	54.0	93.0	−28.5	337.9	12	380	OT5–138
Rybinsk Basin Redbeds	53.0	95.0	−32.0	342.0	6/3	380	OT5–96
Krasnoyarsk Redbeds	54.0	93.0	−31.6	338.0	15.1	387	OT5–139
Byskar Series	55.0	93.0	−31.0	334.0	3/1	387	OT5–101
Krasnoyarsk Redbeds	54.0	93.0	−22.4	338.2	16.1	401	OT5–140
Kureisk and Zubovsk Suites	68.0	89.0	−43.0	330.0	6/5	401	OT5–166
Okler Series	55.8	93.2	−19.0	336.0	18.4/12.3	401	OT5–71
Chergaka Suite	52.0	94.0	13.0	312.0	15/9	414	OT4–14
Chinetinsk Suite	52.0	84.0	3.0	319.0	6/3	428	OT4–69
Lena River Aleurolites	61.0	116.0	−2.0	278.0	11/7	430	OT4–37
Lena River Red Sandstone	61.0	116.0	0.0	281.0	11/7	430	OT4–7
Dolbor Suite Redbeds	60.5	117.0	20.2	299.5	10	440	OT3–93
Bratsk Suite Redbeds	58.3	106.0	18.6	304.8	9.8	440	OT3–88
Bratsk and Makarovsk Suites	58.3	107.3	22.1	313.7	7.4	448	OT3–91
Mangazeika Suite Redbeds	59.0	113.0	22.5	313.5	10	450	OT3–92
BALTICA							
Kvamshesten O.R.S. Norway	61.4	5.6	−22.0	350.0	5/10	381	12/134
Roragen Red Sst. Norway	62.5	11.9	−19.0	340.0	8/15	398	8/124
Ringerike Sst. Norway	60.0	10.0	−21.0	339.0	—	418	10/129
Sulitjelma Gabbro Norway	67.2	15.4	−14.0	360.0	15/30	448	14/389
IBERIA							
Atienza Andesite, Spain	41.0	357.0	−36.0	23.0	6/12	360	9/126
Almaden Volcanics, Spain	39.0	355.0	−21.0	48.0	6/11	418	9/127
ARMORICAN MASSIF							
Diabases E Germany	51.7	11.0	−35.5	321.9	26.0	384	14/374
Jersey Lamprophyre Dykes	49.0	358.0	16.0	322.0	31/38	404	D80
Jersey Group B Dolerites	49.0	358.0	−1.0	339.0	9/12	404	D80
Armorican Redbed Comp. C	49.0	359.0	11.0	325.0	9/11	404	D79
SOUTHERN BRITAIN							
Carboniferous Lst., Ireland	52.7	352.4	−43.0	341.0	7/13	356	15/121
Bristol U. O.R.S. and L. Carb. Lst.	51.4	357.5	−32.0	338.0	5/10	360	14/359
Hendre and Blodwell Intrusives	52.8	356.8	−32.2	346.8	14.9	384	16/162

TABLE 1 (*cont.*)

	site		pole		A_{95}§		
formation	lat. (°N)	lon. (°E)	lat. (°N)	lon. (°E)	or dp/dm	age/Ma	reference†
Old Red Sandstone, Wales	52.0	357.0	3.0	298.0	12/.14	398	8/126
Lavas Somerset and Gloucester	51.5	355.5	8.1	308.7	11.5/17.7	400	15/131
Builth Intrusives	52.1	356.7	2.0	2.0	11/16	446	14/390
Carrock Fell Gabbro Complex	54.7	356.9	−19.0	4.0	8/15	448	FBM77
Breidden Hill	52.5	357.0	−4.0	13.0	15/22	453	PS75
Grampian Highlands							
Cheviot Lavas	55.5	357.9	11.0	320.0	18	393	14/370
Cheviot Granite	55.5	357.9	4.0	337.0	17	398	14/371
Lorne Plateau Volcs	56.5	354.5	2.0	321.0	5/8	405	14/377
O.R.S. Lavas, Midland Valley	57.0	357.0	−4.0	320.0	4/7	408	14/379
Garabal Hill–Glen Fyne complex	56.3	355.2	−5.0	326.0	18/30	415	12/138
Arrochar Complex and aureole	56.2	355.2	−8.0	324.0	4/6	418	12/139
Aberdeen Gabbros	57.4	357.5	−3.0	345.0	20.0	445	WB84
Northern Highlands							
Moine Metasediments Int. Tb	57.0	354.5	−1.0	309.0	9.5	408	W82
Moine Metasediments High Tb	57.0	354.5	−6.0	313.0	6.0	408	W82
Ratagan Complex	57.2	354.5	−15.0	347.0	5/10	415	T82
Borrolan Ledmorite	58.1	355.0	−10.0	19.7	5.0/7.3	430	TB83
Caledonian Microdiorites	57.0	355.0	−16.5	346.4	3.8/6.9	435	EP84
Caledonian Dolerites	57.0	355.0	−14.7	347.5	6.4/11.4	435	EP84
Borrolan Pseudoleucite	58.0	355.1	−23.6	358.0	8.3/16.2	448	TB83
Borrolan Syenite	58.0	355.1	−18.4	326.9	4.1/7.9	448	TB83
Loch Loyal Complex	58.4	355.6	− 4.2	358.0	13.4/20.1	448	TB83
Loch Ailsh Complex	58.1	355.2	−15.6	321.3	4.3/8.1	448	TB83
Achmelvich Dyke	58.2	354.7	−16.5	330.6	1.8/3.2	448	TB83
Assynt Dykes	58.2	355.0	−15.5	324.5	5.6/10.4	448	TB83
LAURENTIA							
North American Craton							
Catskill Redbeds	40.0	282.0	−43.5	304.2	4.5	374	VFF79
Martin Formation, Arizona	33.5	249.0	−55.7	289.2	1.1/2.2	374	16/158
Catskill Redbeds	42.0	285.5	−46.8	296.6	4.4	374	16/157
Temple Butte Grand Canyon	36.0	248.0	−52.6	294.9	0.9/1.8	374	16/159
Columbus Limestone	40.0	277.0	−45.0	300.0	1.6/2.9	381	14/366
Delaware Limestone	40.0	277.0	−48.2	298.0	2/4	381	14/365
Peel Sound Formation, Canada	73.8	261.8	−25.0	279.0	9	398	D82
Bloomsburg Redbeds, Appalach	40.0	282.0	−32.0	282.0	6/10	418	9/125
Rose Hill Fm., Appalachians	38.0	280.0	−19.0	309.1	5.8	423	FV79
Beemerville Alkaline Complex	41.2	285.3	−35.0	306.0	9/18	443	14/392
Juniata Fm., Appalachians	40.0	282.0	−31.5	294.4	4.8	448	16/173
Moccasin-Bays Fm., Tennessee	36.0	276.5	−33.0	327.0	3/6	453	WV79
Chapman Ridge Fm., Tennessee	36.0	276.0	−27.0	292.0	12/19	453	WV79
Acadia							
Perry Formation New Brunswick	45.0	293.0	−32.0	298.0	8/16	367	10/126
Perry Formation Sediments	45.0	293.0	−35.0	301.0	5/9	367	8/121
Perry Lavas Maine	45.0	292.0	−24.0	308.0	—	367	9/120
Perry Formation Volcanics	45.0	293.0	−26.0	289.0	10/17	367	8/120
Massachussetts Metavolcanics	42.4	288.8	−23.0	306.0	10.0	377	SBHMK76
Belchertown pluton	43.2	287.6	−48.1	326.7	6.5/12.7	380	16/160
Hersey Formation	44.9	292.8	−19.8	308.8	4.7/7.7	408	KO80
Eastport Formation	44.9	292.9	−23.7	293.7	6.6/11.1	412	KO80
Eastern Newfoundland							
Terrenceville Formation	47.7	305.3	−27.4	303.5	6.1/11.1	367	K82
Clam Bank Group	48.0	301.0	−28.0	326.0	6/12	398	8/123
Botwood Group Sandstone‡	49.0	305.0	−25.0	293.0	9.3/14.3	423	L79
Botwood Group Rhyolite‡	49.0	305.0	−13.0	305.0	9.2	430	L79

† Numbers refer to *Geophysical Journal* lists, except those prefixed by 'OT', which refer to the Ottawa catalogue (Irving *et al.* 1976), and those referenced individually as follows: D82, Dankers (1982); D79, Duff (1979); D80, Duff (1980); EP84, Esang & Piper (1984); FBM77, Faller *et al.* (1977); FV79, French & Van der Voo (1979); K82, Kent (1982); KDS84, Kent *et al.* (1984); KO80, Kent & Opdyke (1980); KMGRS80, Kroner *et al.* (1980); L79, LaPointe (1979); PS75, Piper & Stearn (1975); SBHMK76, Schutts *et al.* (1976); T82, Turnell (1982) TB83, Turnell & Briden (1983); VVM80, Valencio *et al.* (1980); VFF79, Van der Voo *et al.* (1979); W82, Watts (1982); WB84, Watts & Briden (1984); WV79, Watts & Van der Voo (1979).

‡ Not used owing to doubts as to which tectonic fragment this pole corresponds.

§ A_{95} (dp/dm) denotes the radius (semi-axes) of the circle (oval) of 95% confidence about the mean palaeomagnetic pole.

Table 2. Middle Palaeozoic time scale of Harland *et al.* (1982)

period	epoch	age	Ma
Carboniferous			352
	Tournaisian		
			360
		Famennian	
	D_3		367
		Frasnian	
			374
		Givetian	
Devonian	D_2		380
		Eifelian	
			387
		Emsian	
			394
	D_1	Siegenian	
			401
		Gedinnian	
			408
	Přídolí		
			414
	Ludlow		
Silurian			421
	Wenlock		
			428
	Llandovery		
			438
Ordovician	Ashgill		
			448
	Caradoc		

GONDWANALAND

Gondwanaland is shown with Madagascar closed up against Somalia, though with a slightly looser fit (Segoufin & Patriat 1981) than the usual least-squares fit (Smith & Hallam 1970). The two parts of New Zealand have been restored to their positions at the time of magnetic anomaly 13, and returned to Australia by closure of the Tasman Sea, assuming western New Zealand was fixed to Lord Howe Rise. The misfit in this procedure is represented as a displacement of Marie Byrd Land from East Antarctica (Molnar *et al.* 1975). The Antarctic Peninsula is positioned according to Jurassic palaeomagnetic information presented by Longshaw & Griffiths (1983). The Ellsworth and Thurston Island blocks appear to have moved independently during Jurassic and earlier time, but have been omitted for the time being as these motions are still very uncertain. Florida is tucked into the space between S America and Africa, while Spain and other Mediterranean fragments are placed on the northern edge of Gondwanaland, along with Turkey, Iran, Afghanistan, Tibet and parts of SE Asia. Since all these fragments are affected by post-Ordovician orogenesis, their location around the N edge of Gondwanaland must be regarded as somewhat arbitrary.

Despite its being the largest continent during the early Palaeozoic, Gondwanaland is only sparsely represented palaeomagnetically. Not only is there doubt about the dating of its polar path, but several quite different paths have been suggested.

Apart from SE Australia, none of the components of Gondwanaland gives sufficient poles for Palaeozoic a.p.w. paths to be drawn with confidence. Unfortunately, SE Australia lies in the Tasman orogenic zone in which subduction is inferred to have taken place throughout most of Cambrian to Devonian time (Packham & Leitch 1974). Poles from such an area cannot be used with any confidence to orient a stable continent until after the final deformation. Many of the SE Australian poles lie in the Lachlan province of the Tasman belt where the final folding did not take place until mid-Devonian time (Rutland 1976). McElhinny & Embleton (1974) believed SE Australia to have been separated from the remainder of that continent before the Devonian. Hence, they ignored data from this region, to compile a path for Gondwanaland in which the Ordovician S pole lay to the north of Africa, migrating to a Devonian–Carboniferous position off the SE coast of Mozambique (figure 2*a*).

A quite different Gondwana a.p.w.p. was proposed by Schmidt & Morris (1977). They interpreted early Palaeozoic poles as representing opposite polarity and drew a path which joined nearly all available poles (figure 2*b*). Their path included poles from SE Australia, but placed some of them out of chronological order and required periods of very rapid polar wander.

In another attempt to reconcile the Australian results with those from the rest of Gondwanaland, Morel & Irving (1978) proposed a similarly tortuous path which required two hairpin bends between Ordovician and Devonian time (figure 2*c*).

By using a larger set of poles from SE Australia, Goleby (1980) has constructed a fourth Gondwana a.p.w.p. (figure 2*d*), which in the Silurian deviates sharply to the west to include many results based on both primary and secondary magnetization of Australian sediments.

Until the deviations suggested by these SE Australian poles are substantiated by results from other areas of Gondwana, or until there is geological evidence for an absence of significant movement between SE Australia relative to the remainder of Australia, we prefer not to apply them to Gondwana as a whole. However, the paucity of well-dated results leads to ambiguity in the timing of the southward migration of the palaeopole across Africa. There are two possible interpretations which differ substantially in their implications for global palaeogeography and tectonics during Silurian and Devonian time (Kent *et al.* 1984).

In the first, the pole from the Msissi Norite (Hailwood 1974) suggests that the Gondwana pole crossed the present-day equator in Famennian time (about 365 Ma). This pole position is supported by the rotated pole from the Australian Mereenie Sandstone which is, however, dated only as Silurian?–Devonian. A preliminary pole from the Beja Gabbro of southern Portugal (Perroud *et al.* 1982) also gives a similar position, and may suggest continuity with Gondwana in late Devonian time. Alternatively, a group of poles from Australia (Housetop Granite, Mulga Downs and Ross River Overprint) indicate that the pole had already passed off SE Africa by that time. A more southerly position is also supported by a result from the Gneiguira–Dikel sediments of NW Africa (Kent *et al.* 1984), but the age of this magnetization is not well constrained.

Although the age of the Msissi Norite is recorded as reliable, we suggest a compromise solution in which the Msissi–Mereenie position is assigned an age corresponding to the Silurian–Devonian boundary, while the more southerly position is taken as the late Devonian–Tournaisian pole. This still requires fairly rapid closure of the Rheic Ocean, but less so than otherwise, while not dismissing apparently reliable results.

Since poles for the Caradoc–Wenlock interval are too few to define the Gondwana pole adequately, we have had to interpolate between older and younger data. A fairly precise ($A_{95} = 15°$) mean was calculated from 13 Arenig to Llandeilo poles from Antarctica, Africa, Australia and South America (table 1). The Caradoc–Wenlock pole has then been found by

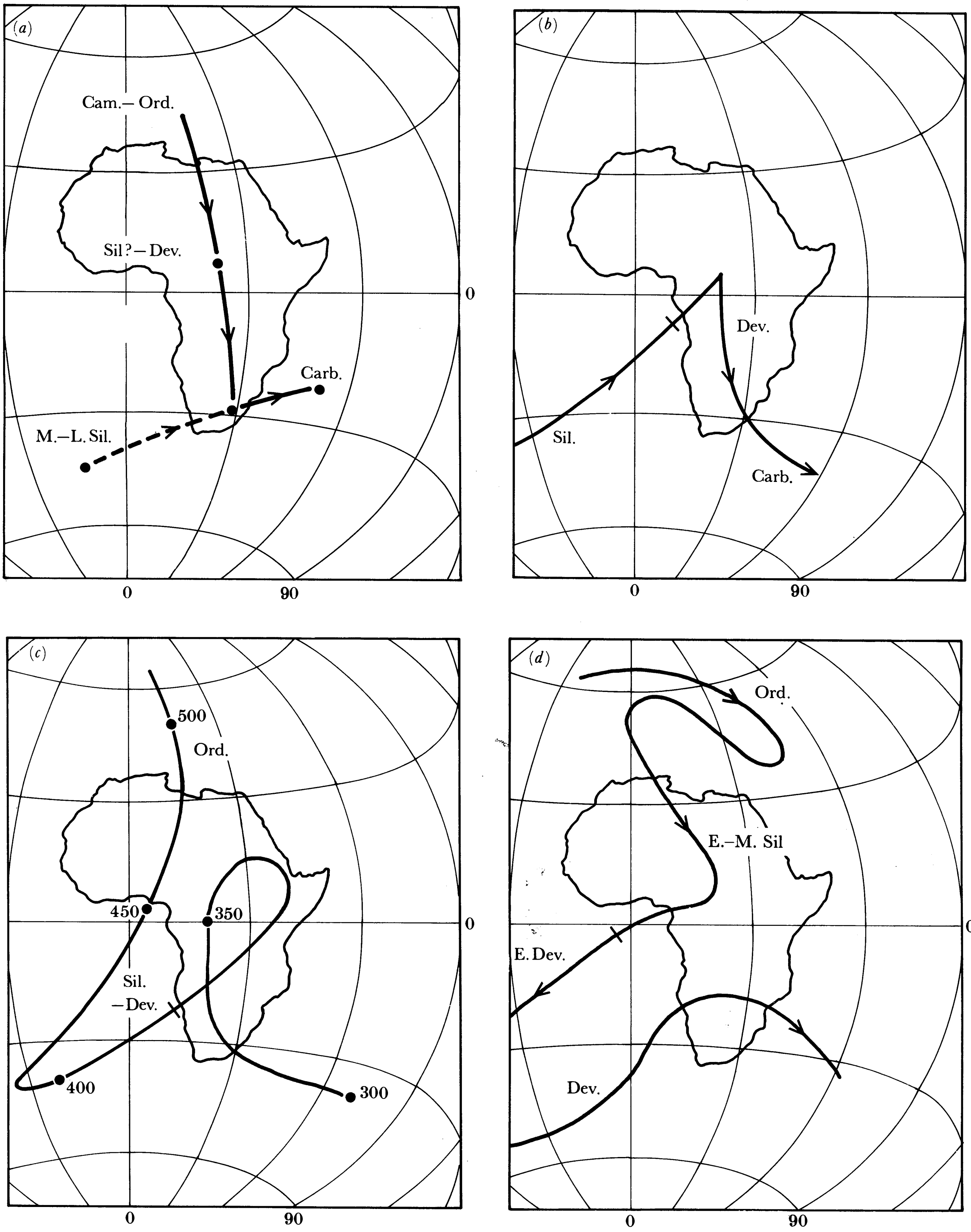

FIGURE 2. Proposed Palaeozoic a.p.w. paths for Gondwanaland. (*a*) McElhinny & Embleton (1974); (*b*) Schmidt & Morris (1977); (*c*) Morel & Irving (1978); (*d*) Goleby (1980).

interpolating between this position and that inferred for Silurian–Devonian time. Thus our preferred a.p.w. path for Gondwana is one in which the pole migrates southwards essentially along the 25° E meridian (figure 3*a*), similar to the path of McElhinny & Embleton (1974).

Laurentia

Laurentia consists of most of N America to which are attached Greenland, W Spitsbergen, Rockall and Scotland north of the Great Glen Fault in their pre-rifting positions. Alaska and Chukotka have been rotated to close up the Laurentian Basin of the Arctic Ocean (A. G. Smith, unpublished), leaving Kamchatka and Kolyma which are arbitrarily attached to N America in their present-day relative positions though these are likely to have been different at this time. Baja California has been joined to Mexico, as have Yucatan and Honduras. Mexico has been slid along a presumed transform into a postulated Jurassic position (A. G. Smith, unpublished), but no attempt has been made to introduce further modifications for Palaeozoic time.

While precise, the mean poles for North America differ systematically from those of the European fragments on Pangaea-A and -A2, *prime facie* implying that, in pre-Visean time, North America was situated further north relative to the other parts of Laurasia than it was during Permo-Carboniferous and later time. This would imply a phase of sinistral transcurrent motion during the early Carboniferous, yet no major fault systems of that age have been identified to date.

Van der Voo & Scotese (1981) have suggested that the Great Glen may mark the site of this displacement, amounting to approximately 2000 km. They assume, often in contrast to the conclusions of the original investigators, that the magnetizations of various Orcadian Old Red Sandstone (O.R.S.) rocks (for example, the Caithness and John O'Groats Sandstones) are of primary origin. They show that the mean of these poles on Pangaea-A or -A2, agrees extremely well with the mid to late Devonian mean for the North American craton, while poles from southern Britain and Acadia indicate lower palaeolatitudes.

Briden *et al.* (1984) criticize this interpretation because the magnetizations of the Stornoway Beds and Duncansby Volcanic Neck are clearly Permian in age. They also present data favouring a much smaller or zero offset on the Great Glen Fault since Ordovician time. These conclusions imply either that a major fault lies undiscovered to the NW of Scotland, or that the dating of the magnetization of the North American Devonian poles is in error, a possibility discounted by Van der Voo & Scotese (1981).

Briden *et al.* (1984) also point out that the pole of rotation implied by the Great Glen Fault is incompatible with that required to reconcile the palaeomagnetic data. Geological arguments against Carboniferous megashear on the Great Glen Fault are advanced by Winchester (1982), Donovan & Meyerhoff (1982), Parnell (1982) and Smith & Watson (1983).

Irving & Strong (1984) have considered palaeomagnetic evidence in favour of a Permian overprinting of the North American cratonic poles during the Kiaman reversed magnetic interval, which they associate with a period of very hot surface conditions following burial and uplift in the Hercynian–Appalachian orogeny. Such conditions are thought to have caused the creation of haematite carrying a stable remanence. Irving & Strong (1984) also point out that the primary magnetization in W Newfoundland rocks puts N America further south than implied by the 'Kiaman' poles.

We note, however, that any such process must be capable of producing remagnetization of rocks from the Appalachians to Arizona while only partly affecting formations in the Avalon and Acadian regions. Also, the Catskill red beds, from which key poles have been obtained (Kent & Opdyke 1978; Van der Voo *et al.* 1979), contain both normal and reversed polarities and so are unlikely to have been totally remagnetized during the Kiaman interval. However, recent reinvestigation of the Carboniferous Mauch Chunk Formation (Kent & Opdyke 1984), formerly thought to carry a pure primary remanence, suggests a dual component remanence, one of probable Permian age as suggested by Roy & Morris (1983). These problems could best be resolved by careful palaeomagnetic analysis of isotopically dated Devonian extrusive igneous rocks, if such can be found.

It now seems clear that late Devonian poles from most other fragments are in agreement with Pangaea-A2 (figure 3), while some of the North American cratonic poles lie about 20° to the south. If it could be substantiated, remagnetization would provide a much simpler explanation for this difference than would large-scale transcurrent motion.

It is not clear whether large-scale strike–slip occurred during earlier time. There appear to be three groupings of Silurian–Devonian poles. The late Silurian Bloomsburg and the early Devonian Peel Sound (table 1) poles are the only ‘reliable’ results currently available for cratonic North America. These are distinct from poles from the Hersey and Eastport Formations of Acadia, and also from poles from what has been dubbed the ‘Traveler Terrane’ (Spariousu & Kent 1983).

The late Ordovician–early Silurian pole for the craton is reasonably well defined by five poles generally from modern studies with careful demagnetization. Silurian poles from sedimentary

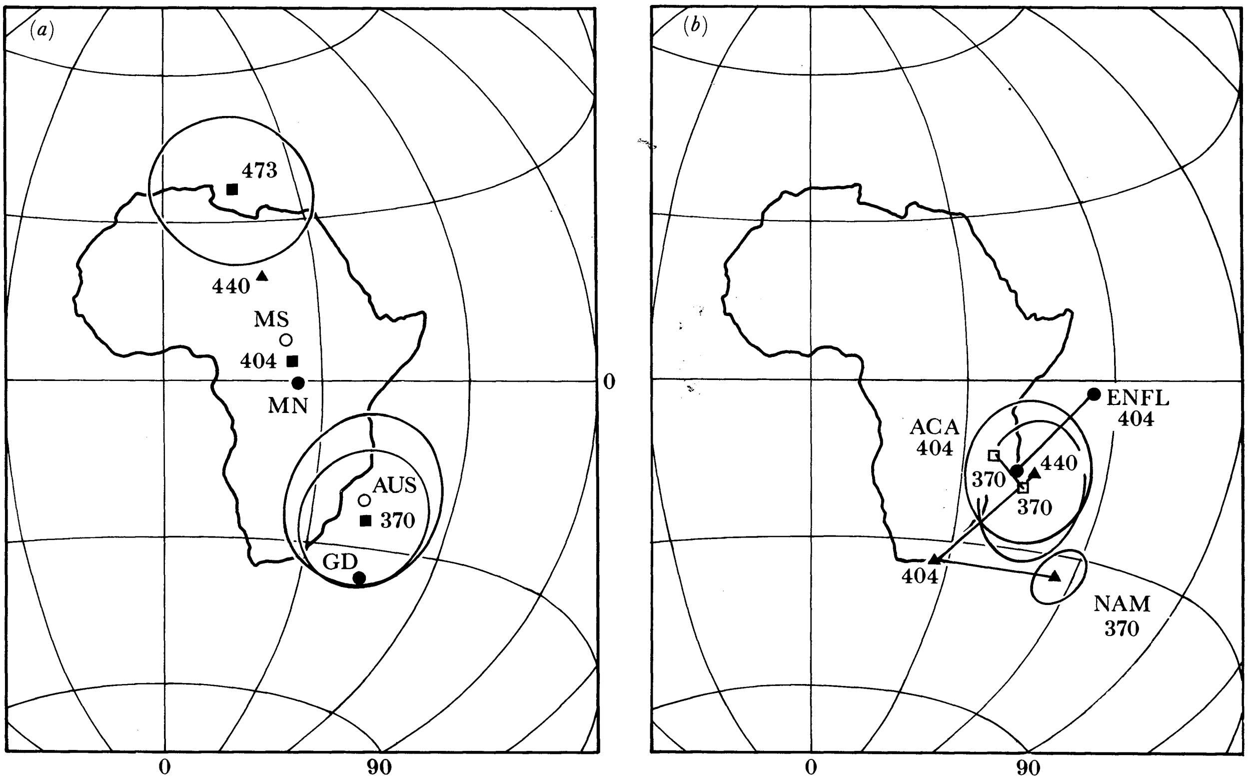

FIGURE 3*a*, *b*. For caption see opposite.

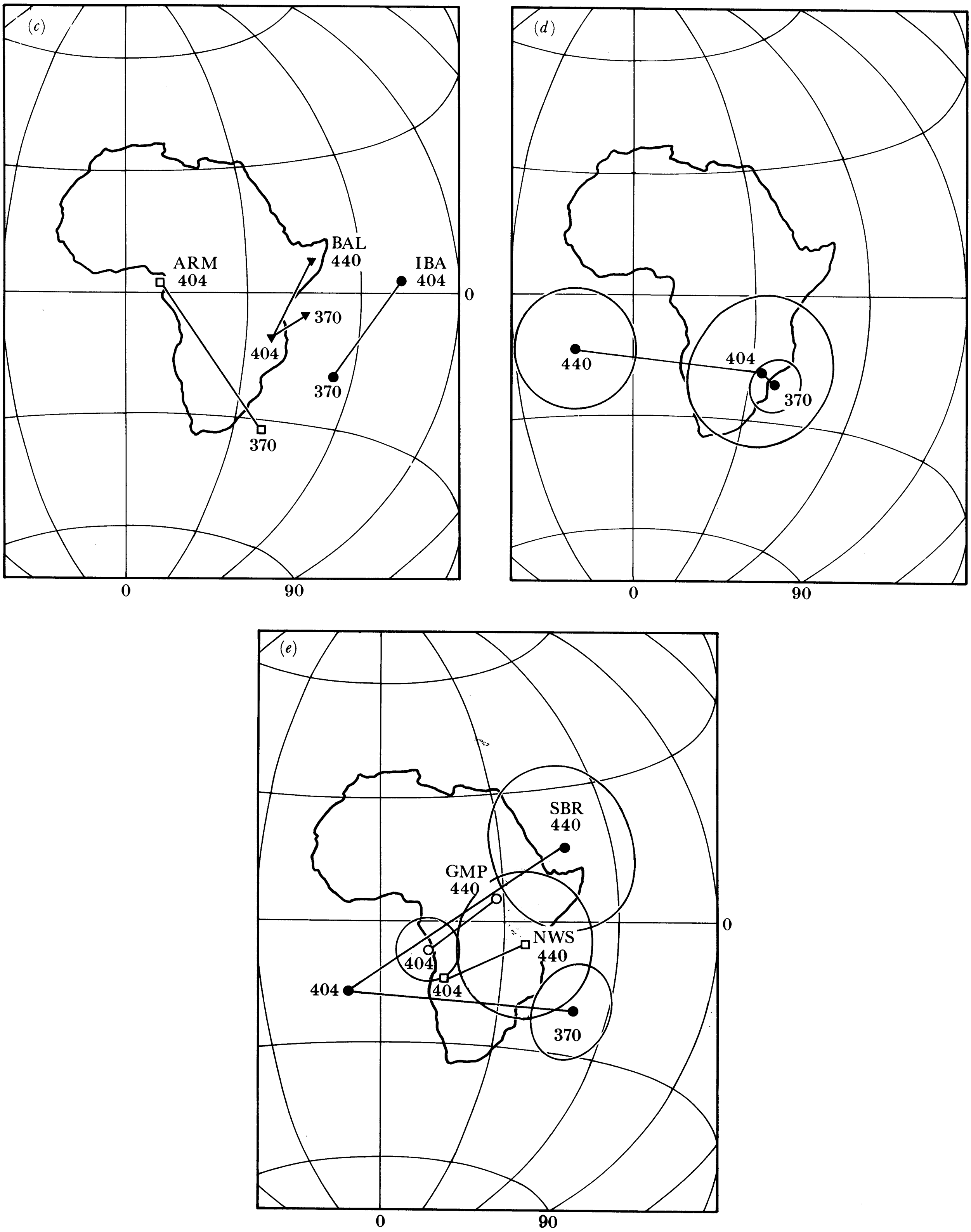

FIGURE 3. Mean fragment poles calculated from data in Table 1. Confidence limits of 95% are shown where appropriate. (*a*) Gondwanaland: symbols as follows: solid squares: computed mean used to orient maps, ages correspond to mid-point of sampling intervals; solid circles: African poles, MN, Msissi Norite, GD, Gneiguira–Dikel; open circles: Australian poles, MS, Mereenie Sandstone, AUS, Mean of Housetop Granite, Mulga Downs and Ross River Overprint; solid triangle: Caradoc–Wenlock pole interpolated between 473 and 404 Ma poles. (*b*). North America: NAM, North American craton; ENFL, Eastern Newfoundland; ACA, Acadia. (*c*) Baltica, Iberia and Armorica (BAL, IBA and ARM). (*d*) Siberia. (*e*) Britain: SBR, South of Iapetus suture; GMP, North of Iapetus suture, south of Great Glen; NWS, North of Great Glen.

and igneous rocks at Botwood in the Central Mobile Belt of Newfoundland are in agreement with the Hersey–Eastport position, but also lie close to the Ordovician–Silurian mean for the craton. Since it is uncertain to which of these fragments, namely, North America or Avalon, the Central Belt was attached, we have omitted the Botwood poles for the time being.

BALTICA

Baltica consists of Scandinavia and the Russian platform, central and E Spitsbergen, Britain south of the inferred Iapetus suture and the Pontides in N Turkey. It is bounded by the Caledonide, Ural and Hercynian orogenic belts. None of the Scandinavian poles presently available for this interval may be said to be reliable. All four (table 1) are based on older studies and all have attendant doubts. The only late Ordovician pole is that from the Sulitjelma gabbro, which exhibits low magnetic stability and is from a tectonically complex area (Henley 1970).

Silurian–Devonian poles come from the Ringerike and Roragen sandstones, which, despite strong thermal overprinting, are in good agreement. A pole from the Kvamshesten O.R.S. is consistent with these poles and is therefore included.

A number of poles have been reported from Russian red beds of Silurian and Devonian age (see, for example, Khramov *et al.* 1981). These differ from the Norwegian results and lack evidence of the age of magnetization; they have not been considered here. The polar path for Baltica (figure 3*c*) shows limited wander, as noted by Morel & Irving (1978).

SIBERIA

A selection of poles for Siberia has been taken from the compilation of Soviet data by Irving *et al.* (1976). Referred to Pangaea-A2 and averaged, these give the path shown in figure 3*d*, which shows a Silurian eastward migration followed by a fairly consistent late Silurian to early Carboniferous position near the coast of Mozambique. The late Devonian–early Carboniferous poles are in accord with those from Britain, Baltica and Acadia, indicating that any separation of Siberia from Baltica was, by then, insignificant, at least in latitude. Unfortunately, this path is based largely on studies of red sediments lacking good age control. Moreover, the studies employ only minimal demagnetization and are not fully documented.

Kazakhstania, thought to be another independent Palaeozoic fragment, is scarcely represented palaeomagnetically. Devonian poles have been reported from limestones (OT5-88) and porphyrites (OT5-39), but as no details of these studies were available to us, we have not used them. Other workers (for example, Scotese *et al.* 1979) have attempted to locate Kazakhstania on the basis of such data but we prefer to leave the Asian fragments aside until a rather more firm data base is available.

ARMORICA

Van der Voo (1979) suggested that concordant palaeomagnetic directions, combined with geological evidence, indicate that several peri-Atlantic microblocks were joined together during much of Palaeozoic time to form Armorica. These blocks include the Avalonian terranes of North America (E Newfoundland, Acadia, Appalachian Piedmont), southern Britain and Ireland, the Armorican and Bohemian massifs, and parts of Iberia. As noted by Perroud *et al.* (1984), these fragments may instead have been part of a mosaic situated at similar palaeolatitudes, but disconnected. In the absence of information concerning their exact relative positions, they assume a single block.

Eocambrian–Cambrian poles from the Armorican and Bohemian Massifs and Iberia show good agreement with a.p.w. paths for Gondwana from about 600 Ma (Hagstrum *et al.* 1980). This may indicate that suturing was completed following the Cadomian orogeny (Perigo *et al.* 1983). Similarly, concordant palaeolatitudes have now been demonstrated for Ordovician time (Perroud *et al.* 1984), so that any latitudinal separation must have been confined to the Silurian and early Devonian.

Until further evidence of the integrity of this Armorican plate is forthcoming, we prefer not to incorporate southern Britain and Avalonia (Avalon Platform, Acadia, Appalachian Piedmont), treating these as a separate Palaeozoic fragment, while the rest of Armorica (that is, mid Europe and Armorican Massif), in the absence of data allowing independent post-Ordovician orientation, is kept fixed to the northern margin of Africa.

The mean poles shown in figure 3*d* indicate that, by middle Devonian time, Armorica was in low latitudes similar to those of Laurentia and Baltica. If Gondwana remained in mid latitudes, as suggested by results from the African Msissi Norite (see above) and the Beja gabbro from southern Portugal (Perroud *et al.* 1984), then a mid European Ocean is indicated, existing from Silurian to mid Devonian time.

A pole from the Monmartin Syncline (Jones *et al.* 1979), formerly thought to have a late Devonian age, now appears more likely to represent a late Carboniferous magnetization (Perroud *et al.* 1984), and is therefore excluded.

Earlier poles are unreliable and are included for interest only. In particular, the Silurian–Devonian mean for Armorica is based on three results (Duff 1979, 1980) with very unreliable ages, and which are grouped only on the basis of their concordance. A new late Devonian pole (Perroud & Bonhommet 1984) is in agreement with poles from elsewhere in Europe, but is based on rather uncertain tectonic corrections and has not been included.

Britain

Britain is a key area in the study of the formation of the so-called Old Red Continent. Fortunately there are a number of poles now available from each of the three structural units into which it has been divided. These divisions are: (i) north of the Great Glen Fault; (ii) south of the Great Glen Fault but north of the Iapetus suture through Solway Firth; and (iii) south of the Iapetus suture. A thorough review of British data is given in Briden *et al.* (1984).

No reliable results are available for the two northernmost fragments for late Devonian–Tournaisian time, but reasonably precise means have been obtained for the two older intervals. The Caradoc–Wenlock mean for northern Scotland is based on nine new poles (table 1) published by Turnell & Briden (1983) and Esang & Piper (1984). Silurian–Devonian poles, apart from that from the Ratagan complex, are in fair agreement, including two averaged results from the Moine metasediments (Watts 1982).

Only one pole was used for the Grampian highlands for Ordovician–Silurian time. This comes from the Aberdeenshire gabbros and represents an average of the youngest group calculated from new data (Watts & Briden 1984). The Silurian–Devonian pole for this fragment is based on results from the Newer Granites (Garabal Hill–Glen Fyne and Arrochar), reliable results from the O.R.S. of the Midland Valley and from the Lorne Plateau lavas (category

B of Briden & Duff 1981), and two less reliable results from Cheviot lavas and granites which are, however, in broad agreement.

Taken at face value, the poles from the Grampian Highlands seem to lie systematically north of those from the NW Highlands. To reconcile them requires closure rather than transcurrent displacement along the Great Glen which is unacceptable. However, the Grampian pole for the Caradoc–Wenlock period depends critically on the magnetization age of a few localities in the Aberdeen gabbros and could well lie WSW of the position we have computed. For the Ludlow–Emsian interval, the more northerly located poles for the Grampian Highlands are much less precise; hence the computed pole may be too far north. Thus the discrepancy between the a.p.w. paths for the Grampian and NW Highlands (figure 3*e*) may not be real: Briden *et al.* (1984) reached the same conclusion on the basis of matching a.p.w. paths, on data from a wider age range, with the implicit assumption that radiometric age and magnetization age are in many cases not identical.

Hence, although our Grampian a.p.w. path in figure 3*e* lies close to the path from southern Britain, we argue that in reality it is different, and indistinguishable from the path for the NW Highlands. We regard this last discrepancy, between the a.p.w. paths for S Britain and the NW Highlands as plotted on figure 3*e*, as indicative of closure at the Iapetus suture, possibly related to the oblique closure model of Phillips *et al.* (1976) which predicts more than 1000 km of dextral shear along the suture during collision.

Southern Britain is represented by a grade B pole from the Builth Inlier intrusives, plus a grade C pole from the Breidden Hills (Piper & Stearn 1975), and a further pole from the Carrock Fell gabbro (Faller *et al.* 1977) which falls somewhat to the south of the other two.

Doubts similar to those raised about the Silurian–Devonian poles from Scandinavia may be raised about the data from S Britain: those from the Upper O.R.S. or from the early Carboniferous limestones are based on small collections and limited demagnetization data. Finally, the most thorough study of the Anglo-Welsh O.R.S. did not yield a very precise pole position.

Maps

(*a*) *Caradoc–Wenlock map*

The maps shown in figures 4–7 were constructed by placing the major fragments in the palaeolatitudes and orientations suggested by their mean palaeomagnetic poles for each interval. In certain cases, data were either lacking or in conflict with other mean poles. The positioning of these fragments is described below.

Baltica and Laurentia are separated by the Caledonian (Iapetus) ocean. From the similarity of the a.p.w. paths on the opposite sides of the ocean Piper (1979) and Briden *et al.* (1984) estimate its mid Ordovician width to be about 1000 km. McKerrow & Cocks (1976) used faunal evidence to estimate a width of about 1000 km in late Ordovician–early Silurian time. A somewhat wider separation (*ca.* 2000 km) is shown in figure 4, where we have attached N Britain to N America rather than position it as a separate microblock, in which case it would lie much further south, as discussed by Morris (1976).

The relationship of Gondwana to Laurentia or Baltica is also uncertain, in particular the question of which part of Gondwana lies closest to Laurentia and Baltica. By late Devonian time we assume continental collision had occurred (see below), probably between S America and N America. We therefore minimize the motion between Gondwana and the two northern continents throughout the Silurian and Devonian periods by placing S America opposite N America in the late Ordovician–early Silurian map (figure 4). Some support for this position is provided by the distribution of Venezuelan Silurian brachiopods, which, in the Ludlow are very similar to those in Nova Scotia and Gaspe (E N America), Wales, Scotland, Norway, Sweden, as well as Siberia (Boucot 1972).

Boucot & Gray (1983) suggest that a form of Pangaea existed in Early Devonian time; if so, then the pivot-point oceanic closure model based on the Mesozoic and Cenozoic closure of the Tethys would be applicable to all three time intervals for which maps have been made. We do not apply this model explicitly, but it is implicit in the attempt to keep northern S American and southern N America close together in the maps for all three time intervals.

During Caradoc–Wenlock time (figure 4), we have assumed that Iberia and the Armorican Massif were fused to Gondwanaland in their Permo-Triassic relative positions. If an ocean existed between Armorica and Gondwana in the Silurian as suggested by Perroud *et al.* (1984), then the earlier configuration may well have been rather different (cf. Scotese *et al.* 1979), with the components of Armorica perhaps separated as microcontinents.

Siberia, rotated by about 90° W about a local pole to bring its orientation into conformity with its palaeomagnetic data, is shown a small distance E of the Russian platform.

Although later Palaeozoic and younger sutures exist in China, SE Asia and adjacent regions, only qualitative data are currently available for orienting these areas with respect to the poles or to neighbouring continents. For example, Boucot & Gray (1983) suggest that not all sutures

TABLE 3. MEAN PALAEOMAGNETIC POLES AND EULER ROTATIONS USED IN CONSTRUCTING PALAEOGEOGRAPHIC MAPS

(Rotation 1 brings the mean pole into agreement with the south geographic pole, rotation 2 adjusts longitude to avoid overlap and give agreement where possible with independent information. These poles and rotations apply after returning all continents to Pangaea-A2 with Africa fixed. A positive rotation angle indicates a clockwise rotation when viewed from outside the Earth.)

		south pole				rotation 1			rotation 2		
fragment	age/Ma	°N	°E	N	A_{95}	°N	°E	angle/deg	°N	°E	angle/deg
Baltica	370†	−19.1	46.0	13	6.0	0.0	316.0	−70.9		—	
Baltica	404	−12.4	36.1	4	7.2	0.0	306.1	−77.6		—	
Baltica	440	14.1	47.1	4	12.7	0.0	317.1	−104.1		—	
Gondwana	370	−24.9	41.1	4	12.4	0.0	311.1	−65.1		—	
Gondwana	404	3.6	23.1	2	—	0.0	294.1	−93.6	−90.0	0.0	−45.0
Gondwana	404‡	−19.4	3.6	2	—	0.0	273.6	−70.6		—	
Gondwana	440	19.6	19.3	§	—	0.0	289.3	−109.6	−90.0	0.0	−45.0
Gondwana	473¶	36.4	15.3	9	14.5	0.0	285.3	−126.4		—	
Laurentia	404	−32.7	27.5	2	—	0.0	297.5	−57.3		—	
Laurentia	404‖	−10.8	9.3	11	8.8	0.0	279.3	−79.2		—	
Laurentia	440	−16.7	44.1	5	13.0	0.0	314.1	−73.3		—	
Siberia	370	−20.8	36.9	8	6.2	0.0	306.9	−69.2	−90.0	0.0	−30.0
Siberia	404	−18.2	33.2	6	18.1	0.0	303.2	−71.8	−90.0	0.0	−30.0
Siberia	440	−13.1	345.6	7	14.9	0.0	255.6	−76.9	−90.0	0.0	−120.0

† Mean poles for Baltica include data from Avalonia, southern Britain as described in the text. 370 Ma mean also includes poles from Armorica–Iberia.

‡ Mean of Ainslie Volcanics and Mugga Mugga Porphyry poles.

§ No poles available: interpolated.

¶ Used to interpolate 440 Ma position.

‖ Based on mean of British poles.

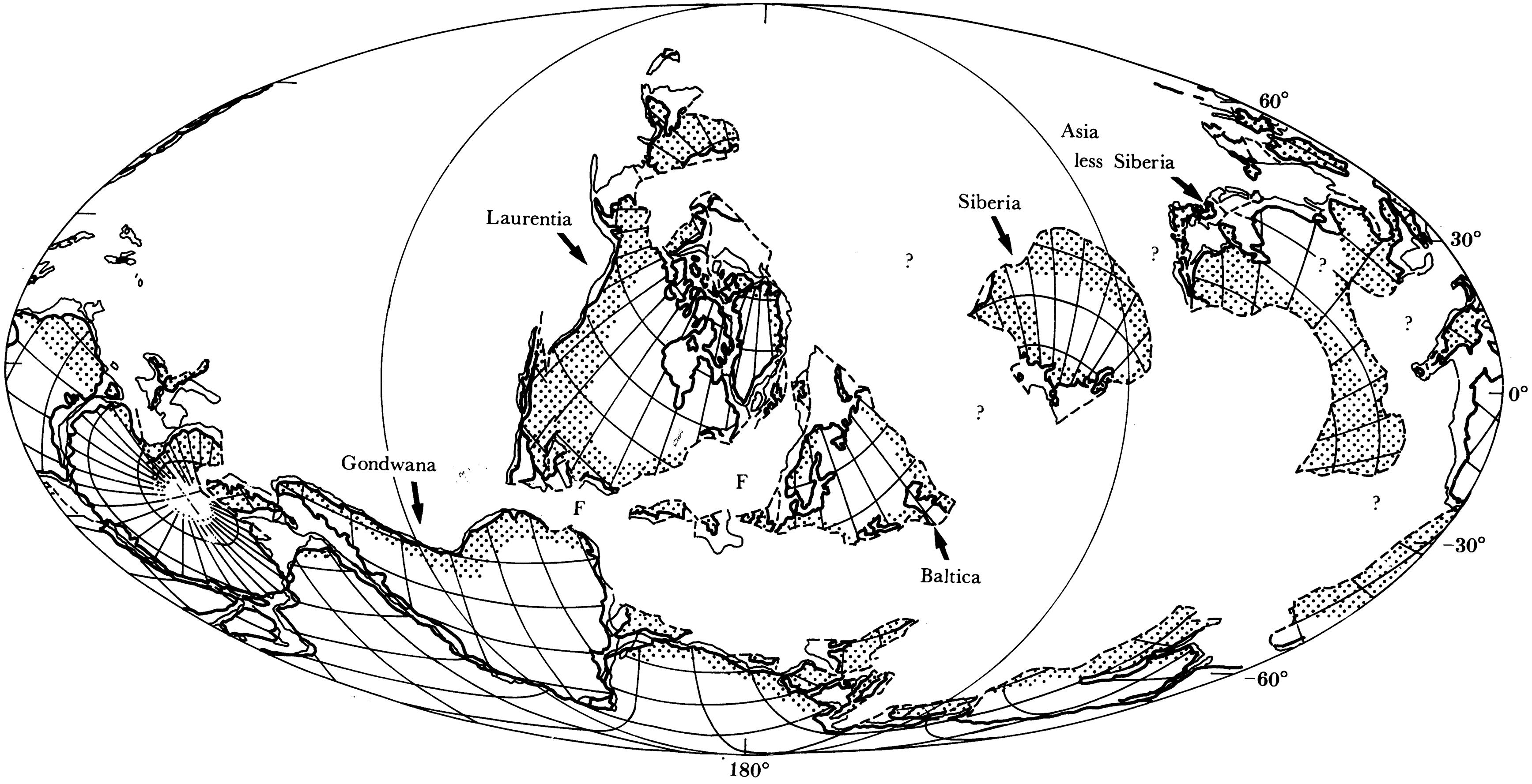

Figure 4. Global reconstruction for Caradoc–Wenlock time (458–421 Ma). Stippled areas denote the approximate extent of orogenic deformation of the same age as the map or younger. F indicates that longitude separation is based on fossil evidence; ?, in oceanic regions indicates uncertain longitudinal separation; ?, in continental regions indicates that no palaeomagnetic data are available. Mollweide Elliptic projection.

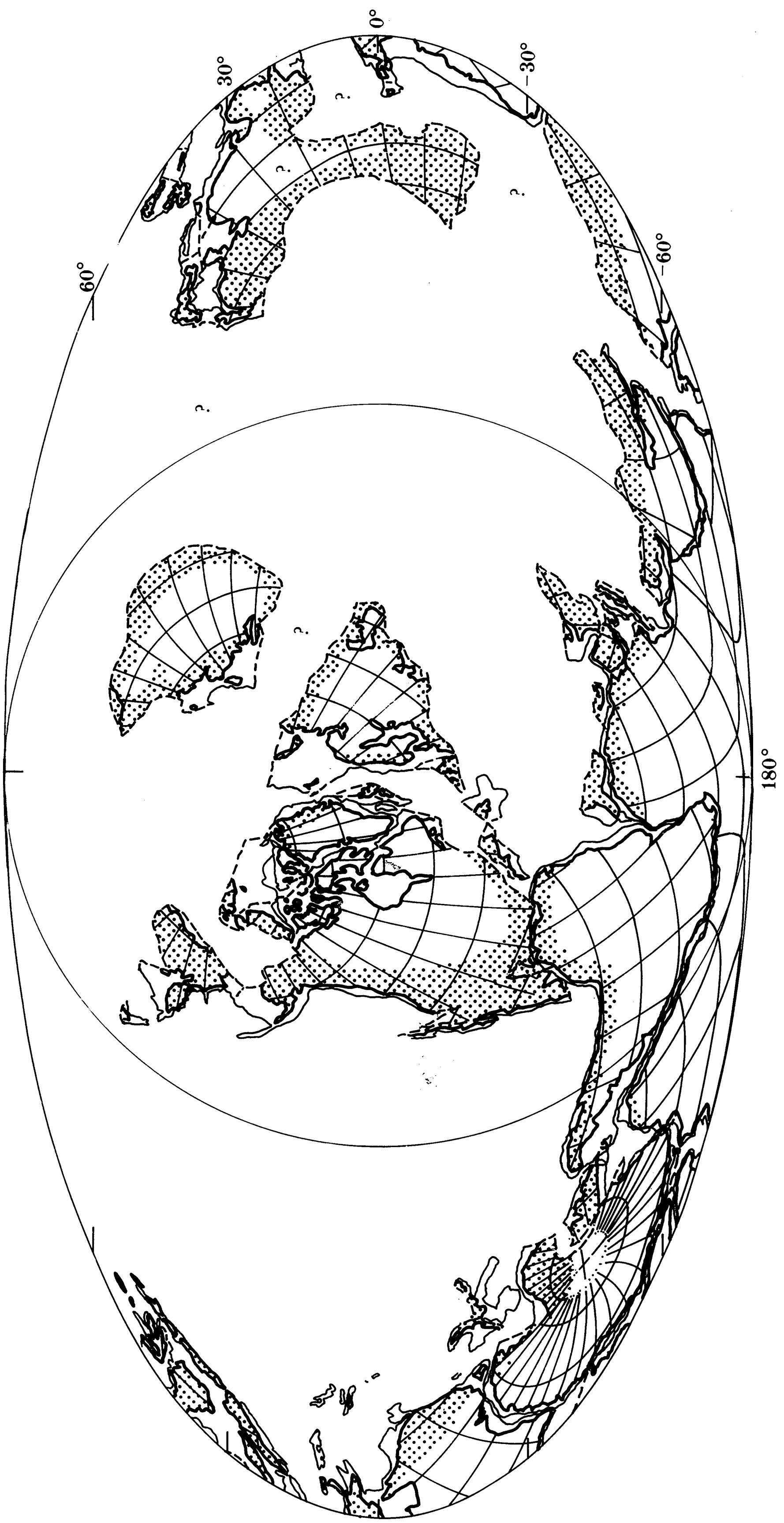

FIGURE 5. Global reconstruction for Ludlow–Emsian time (421–387 Ma). Symbols and projection as figure 4.

another, but may represent the closure of relatively small oceans. By using lithofacies evidence, they suggest that Siberia, China and SE Asia was a single continent in much of Palaeozoic time, a configuration compatible with the distribution of their fossil data. More recently, Wang Yu *et al.* (1984) suggest that Silurian and Devonian faunas from South China differ significantly from most other regions, implying that it was geographically isolated from other regions. For convenience only we have arbitrarily attached these continents to Gondwanaland north of Australia, while recognizing that they may well have been one or more discrete fragments during late Ordovician–early Silurian time.

Details of all map parameters are given in table 3.

(*b*) *Ludlow–Emsian maps*

Because of the differences in the N American and British late Silurian–early Devonian pole positions, it is not possible to draw a definitive map for this period. We show two alternatives. In the first (figure 5), Laurentia and Baltica are oriented separately. Gondwanaland is placed in a position relative to Laurentia and Baltica in accordance with the pivot-point closure model. Siberia is moved closer to Baltica. Armorica is attached to the northern margin of Africa.

The second Silurian–Devonian map (figure 6) uses the British data to orient Laurentia–Baltica. This is possible only if it is assumed that suturing was already complete by this time. The British pole moves Laurentia–Baltica so far S as to cause overlap onto Gondwanaland for any reasonable point along the preferred polar path for Gondwana. We have therefore positioned Gondwana using poles from SE Australia (Ainslie volcanics, Mugga Mugga porphyry, table 1) which imply a westward diversion in the Gondwana a.p.w. path. Loops such as those shown by Morel & Irving (1978) and Goleby (1980) require a phase of Silurian closure followed by renewed opening during the Devonian between Gondwana and the northern continents.

The resulting reconstruction is interesting in that it is virtually a Pangaea-A2 fit, the overlap, represented by the mismatch between Meguma and Newfoundland, is well within the errors. However, the latitude is much higher than any previous reconstruction requiring a phase of rapid northward motion during the Devonian. For the sake of clarity, we have adjusted the position of Iberia–Armorica to avoid the overlap with Baltica by using their Pangaea-A positions relative to Africa.

If valid, such a map would mean that Pangaea may have had a much longer lifetime than previously supposed. This should be testable by using palaeontological and palaeoclimatic data. Faunal information suggests widening across a Rheic Ocean after Wenlock time (Cocks & Fortey 1982), but probably does not support the high latitudes shown in figure 6.

Both reconstructions are unsatisfactory in some respects. Structural evidence suggests that Laurentia was sutured to Baltica in late Silurian time, with no evidence for strike–slip motions larger than about 200 km in later time. This means that the Caledonian (Iapetus) ocean had been eliminated by this time. This conclusion is not compatible with the palaeomagnetic data even if the confidence limits are taken into account. Figure 5 shows Laurentia and Baltica in contact, but not fully sutured. Relative to Laurentia, Baltica lies more than 1500 km S of its position on figure 4. Thus the palaeomagnetic data imply large sinistral transform faults of Devonian age, probably within the Caledonian suture. Though such faults exist, for example, the Great Glen Fault in NW Scotland, the present concensus is that displacements are only about 100 km. The more southerly position of figure 6 is, however, in agreement with Harland's (1965) views that the stratigraphy of E Greenland closely resembles that of parts of Spitsbergen at this time, in turn implying the existence of large strike–slip faults in the region.

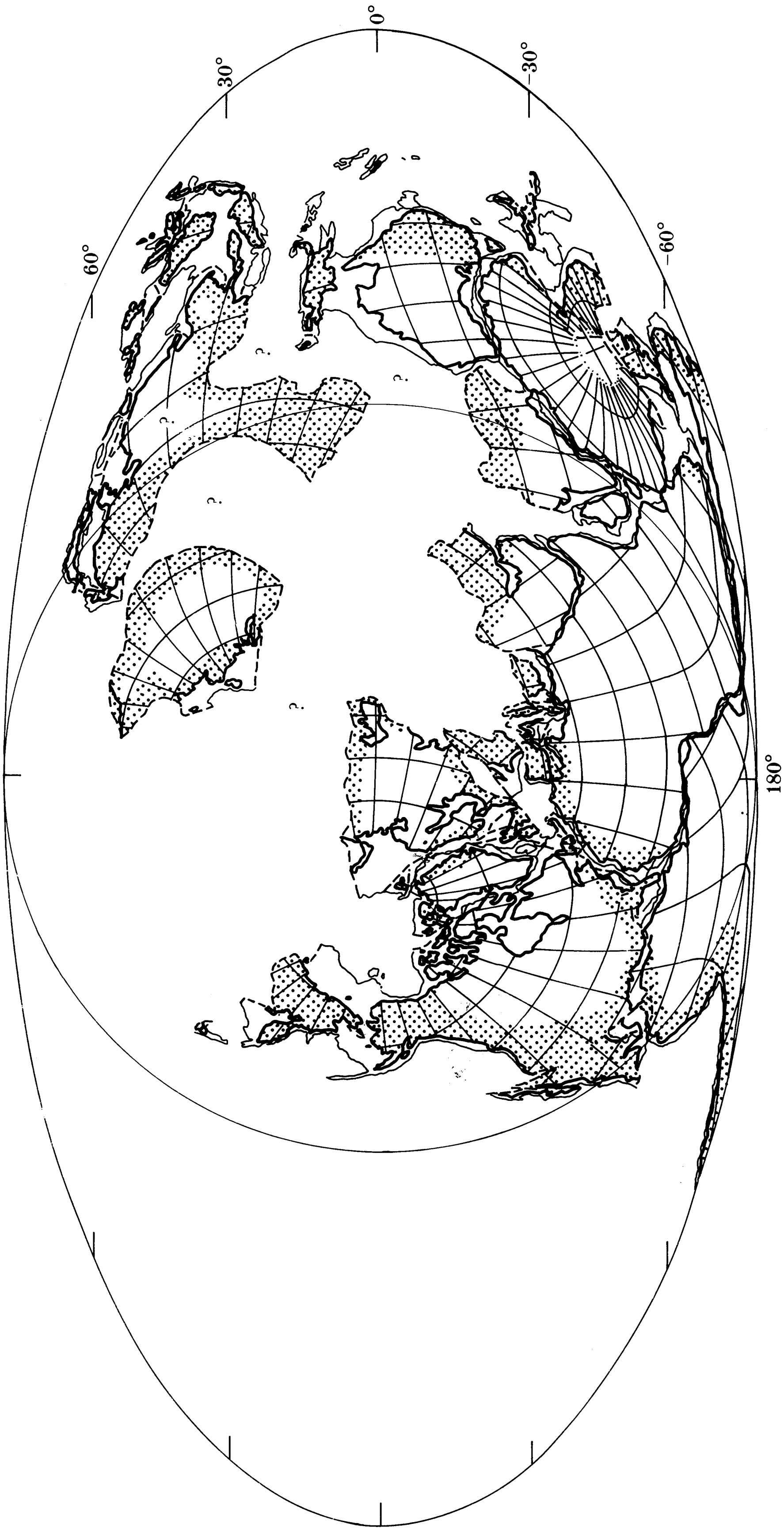

Figure 6. Alternative reconstruction for Ludlow–Emsian time (421–387 Ma) based largely on British poles. Symbols and projection as figure 4.

The distributions of Devonian vertebrates support the view that collision had taken place between Laurentia and Baltica by this time in that a period of biotic dispersal took place between Laurentia and Baltica at the end of Silurian time to bring about a Euramerican faunal province (Young 1981). Five faunal provinces existed in Early Devonian time: Euramerica, Siberia, S Siberia (Tuva), S China and Gondwana (Young 1981), but it is not clear whether such provinces were due to the presence of oceans or merely of shelf seas that could isolate provinces of presumed freshwater fish.

The relative positions of Gondwanaland and Laurentia–Baltica in both maps is supported by the need for reproductive communication between the shallow marine 'Eastern Americas' faunal realm (Boucot & Gray 1983). This realm includes NW S America and much of E N America. It is not clear from either of the two Silurian–Devonian maps how this realm was isolated biogeographically from the 'Old World' province of N Africa, Arabia and the Rhenish–Bohemian region of Europe.

The contrast between figures 5 and 6 can be regarded as reflecting the poles provided predominantly by sediments (N America and Baltica) and by igneous rocks (Britain). It is unfortunate, though inevitable in the present state of knowledge, that the data from an area as small as Britain largely determine the form of one of the global Silurian–Devonian maps.

(*c*) *Eifelian–Tournaisian map*

During the late Devonian a second dispersal of Devonian invertebrates brought into being a single faunal province (Young 1981). The late Devonian dispersal suggests that collisions had taken place among all the major continents giving rise to a late Devonian form of Pangaea.

We assume that the N American late Devonian poles have been remagnetized, possibly in Permian time. As noted above, the alternative is to postulate motions of *ca.* 2000 km on as yet unidentified transform faults. Thus Laurentia–Baltica has been positioned by using poles from Britain, Avalonia, Central Europe and Iberia. By using this fragment as a reference, we have positioned Gondwana palaeomagnetically, adjusting the longitude relative to Laurentia–Baltica so that the two continents are close to their Pangaea-A2 configuration (figure 7).

Siberia has now rotated into a more familiar orientation and is placed close to Baltica, though the longitude separation is arbitrary. Other fragments such as SE Asia are shown in the same arbitrary orientations as in the previous maps.

DISCUSSION

It is gratifying that maps of the Silurian and Devonian periods based on palaeomagnetic data are beginning to show a certain homoeomorphy: there are no serious disagreements between the present maps and those of Scotese (1984), though it must be said that both sets incorporate a number of far-reaching assumptions and signally fail to satisfy the growing body of British Silurian and early Devonian data, hence our 'alternative' Silurian–Devonian map. The very sparse distribution of palaeomagnetic data may be appreciated from figure 8, which shows the sampling sites used for each map rotated with the continents. These assumptions and deficiences must be clearly borne in mind by users of these maps.

The major problems are the a.p.w. of Gondwanaland and the interpretation of the palaeomagnetism of sediments (diagenetic magnetization) and igneous rocks whose original orientation cannot be determined from field geological data. Plausible longitudinal separations

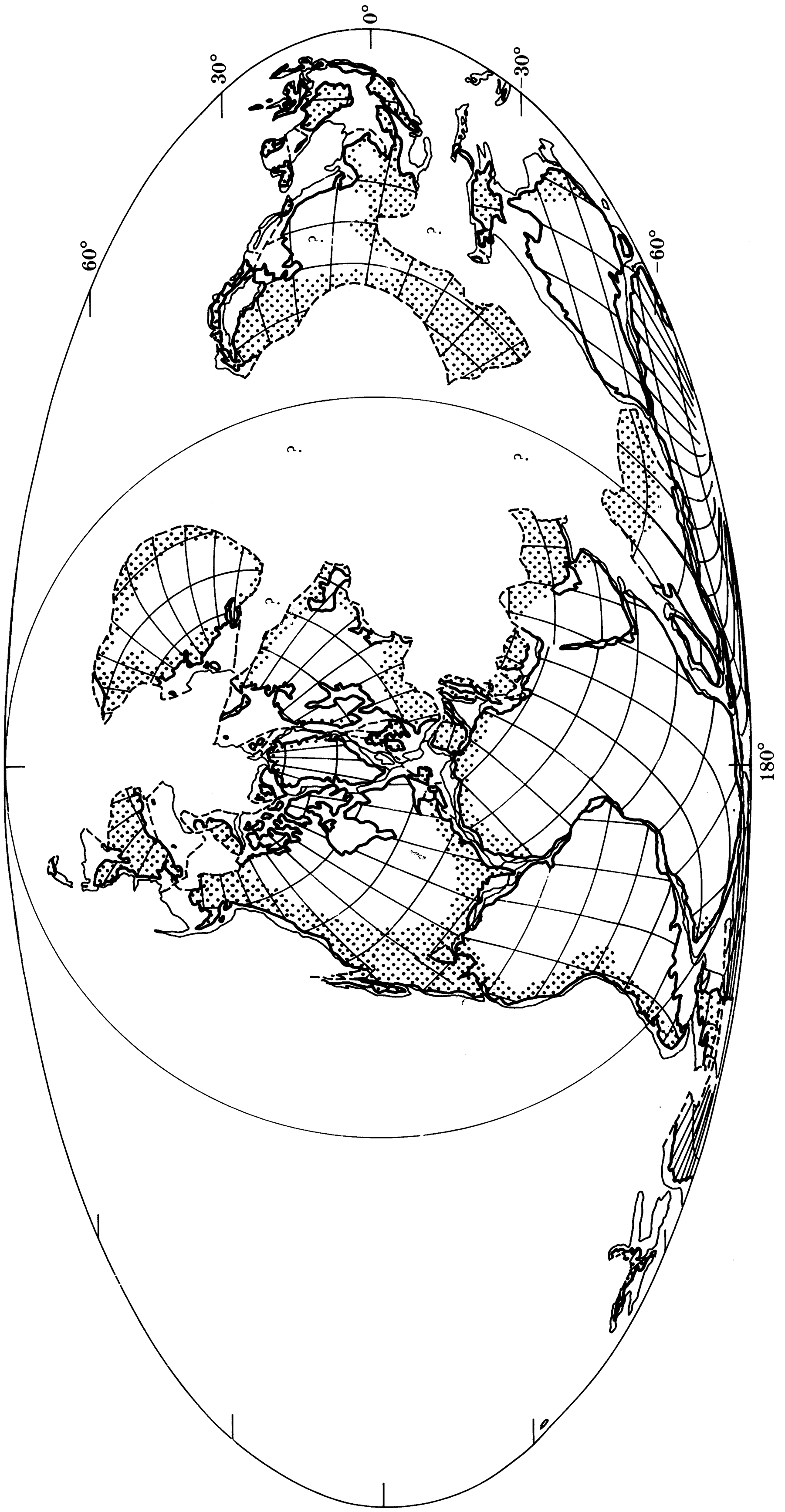

FIGURE 7. Global reconstruction for Eifelian–Tournaisian time (387–352 Ma). Symbols and projection as figure 4.

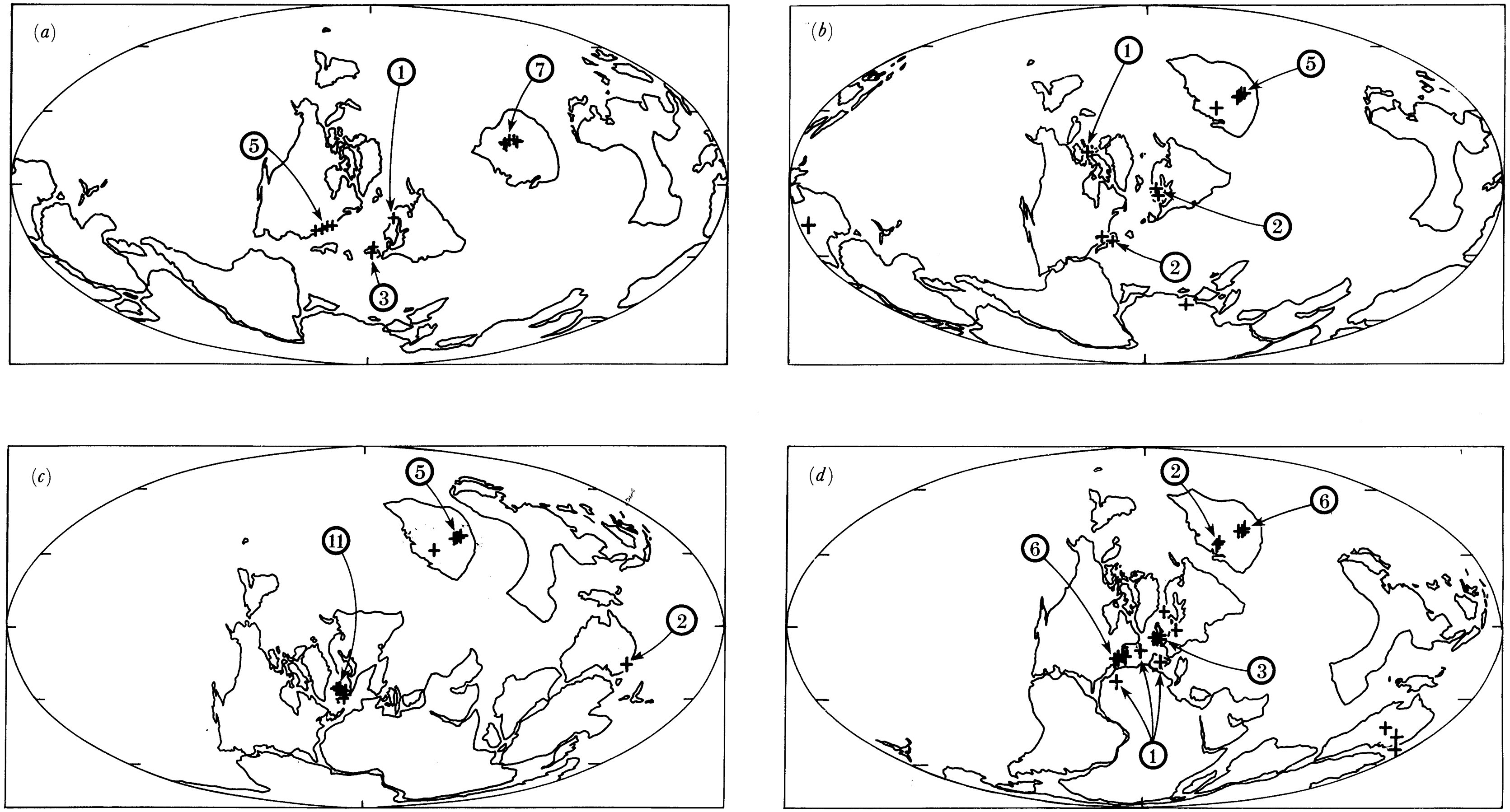

FIGURE 8. Distribution of sampling sites of palaeomagnetic results used in constructing maps shown in figures 4–7. Each cross represents a site; where they are so closely clustered they cannot be separated or where not easily distinguished, they are marked with an arrow and a circle containing the number of results. (*a*) Caradoc–Wenlock; (*b*) Ludlow–Emsian; (*c*) alternative Ludlow–Emsian; (*d*) Eifelian–Tournaisian. Mollweide Elliptic projection.

are emerging for the various continental fragments from fossil distributions: it would be interesting to try to quantify this problem in some way. Without such quantification, the longitudes are still highly uncertain and the present composites can be adjusted to give a wide range of 'maps'. Once these longitudinal uncertainties are minimized and the palaeomagnetic data give better latitudinal control, it may be possible to disentangle those factors of faunal distribution that are climatically controlled, and those that are not.

With regard to the emergence of land plants: we cannot detect any special arrangement of the continents at the Silurian–Devonian boundary, whichever of the alternative maps is chosen, that might have played a dominant role in this important step in biological evolution, other than the general convergence of fragments. However, although the configuration does not seem particularly unusual, it is possible that there may have been particularly favourable distributions of low-lying and coastal areas for this step in biological evolution. But it seems to us more likely that other factors such as atmospheric or oceanic circulation, or a particular stage in the chemical evolution of the atmosphere may have been more important.

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REFERENCES

Arthaud, F. & Matte, P. 1977 Late Palaeozoic strike–slip faulting in southern Europe and northern Africa: results of the right-lateral shear zone between the Appalachians and the Urals. *Bull. geol. Soc. Am.* **88**, 1305–1320.

Bambach, R. K., Scotese, C. R. & Ziegler, A. M. 1980 Before Pangaea: the geographies of the Palaeozoic world. *Am. Sci.*, **68**, 26–38.

Boucot, A. J. 1972 Silurian of Venezuela. In *Correlation of the South American Silurian rocks* (ed. W. B. N. Berry & A. J. Boucot), pp. 53–54. Spec. Paper Geol. Soc. America 133.

Boucot, A. J. & Gray, J. 1983 A Palaeozoic Pangaea. *Science, Wash.* **222**, 571–581.

Briden, J. C. & Duff, B. A. 1981 Pre-Carboniferous palaeomagnetism of Europe north of the Alpine orogenic belt. In *Palaeoreconstruction of the continents* (ed. M. W. McElhinny & D. A. Valencio), pp. 137–149. Geodynamics Series, vol. 2. Washington, D.C.: American Geophysical Union.

Briden, J. C., Morris, W. A. & Piper, J. D. A. 1973 Palaeomagnetic studies in the British Caledonides. VI. Regional and global implications *Geophys. J. R. astr. Soc.* **34**, 107–134.

Briden, J. C., Smith, A. G. & Sallomy, J. T. 1970 The geomagnetic field in Permo-Triassic time. *Geophys. J. R. astr. Soc.*, **23**, 101–117.

Briden, J. C., Turnell, H. B. & Watts, D. R. 1984 British palaeomagnetism, Iapetus Ocean and the Great Glen Fault. *Geology* **12**, 428–431.

Bullard, E. C., Everett, J. & Smith, A. G. 1965 The fit of the continents around the Atlantic. *Phil. Trans. R. Soc. Lond.* A **258**, 41–51.

Cocks, L. R. M. & Fortey, R. A. 1982 Faunal evidence for oceanic separations in the Palaeozoic of Britain. *J. geol. Soc. Lond.* **139**, 465–478.

Dankers, P. 1982 Implications of Lower Devonian poles from the Canadian Arctic Archipelago for the North American apparent polar wander path. *Can. J. Earth. Sci.* **19**, 1802–1809.

Donovan, R. N. & Meyerhoff, A. A. 1982 Comment and reply on 'Palaeomagnetic evidence for a large (~ 2000 km) sinistral offset along the Great Glen fault during Carboniferous time'. *Geology* **10**, 604.

Duff, B. A. 1979 The palaeomagnetism of Cambro-Ordovician red beds, the Erquy Spilite Series and the Tregastel–Ploumanac'h granite complex, Armorican Massif (France). *Geophys. J. R. astr. Soc.* **59**, 345–365.

Duff, B. A. 1980 The palaeomagnetism of Jersey volcanics and dykes, and the Lower Palaeozoic apparent polar wander path for Europe. *Geophys. J. R. astr. Soc.* **60**, 355–375.

Esang, C. B. & Piper, J. D. A. 1984 Palaeomagnetism of Caledonian intrusive suites in the Northern Highlands of Scotland: constraints to tectonic movements within the Caledonian orogenic belt. *Tectonophysics* **104**, 1–34.

Faller, A. M., Briden, J. C. B. & Morris, W. A. 1977 Palaeomagnetic results from the Borrowdale volcanic group, English Lake District. *Geophys. J. R. astr. Soc.* **48**, 111–121.

French, R. B. & Van der Voo, R. 1979 The magnetization of the Rose Hill Formation at the classical site of Graham's fold test. *J. Geophys. Res.* **84**, 7688–7696.

Goleby, B. R. 1980 Early Palaeozoic Palaeomagnetism in south east Australia. *J. Geomag. Geoelectr.* **32**, suppl. III, SIII 11–SII 21.

Hagstrum, J. T., Van der Voo, R., Auvray, B. & Bonhommet, N. 1980 Eocambrian–Cambrian palaeomagnetism of the Armorican Massif, France. *Geophys. J. R. astr. Soc.* **61**, 489–517.

Hailwood, E. A. 1974 Palaeomagnetism of the Msissi Norite (Morocco) and the Palaeozoic reconstruction of Gondwanaland. *Earth planet. Sci. Lett.* **23**, 376–386.

Hallam, A. 1982 Supposed Permo-Triassic megashear between Laurasia and Gondwanaland. *Nature, Lond.* **301**, 499–502.

Harland, W. B. 1965 Discussion in A symposium on continental drift. *Phil. Trans. R. Soc. Lond.* A **258**, 59–75.

Harland, W. B., Cox, A. V., Llewellyn, P. G., Pickton, C. A. G., Smith, A. G. & Walters, R. 1982 A geologic time scale. Cambridge: University Press.

Heckel, P. H. & Witzke, B. J. 1979 Devonian world palaeogeography determined from distribution of carbonates and related lithic palaeoclimatic indicators. In *The Devonian System* (ed. M. R. House, C. T. Scrutton & M. G. Bassett). Spec. Papers in Palaeontology no. 23. London: The Palaeontological Association.

Henley, K. J. 1970 The structural and metamorphic history of the Sulitjelma region, Norway, with special reference to the nappe hypothesis. *Norsk Geologisk Tidschrift*, **50**, 97–136.

Irving, E. & Strong, D. F. 1984 Palaeomagnetism of the Early Carboniferous Deer Lake Group, western Newfoundland: no evidence for mid-Carboniferous displacement of 'Acadia'. *Earth Planet. Sci. Lett.* **69**, 379–390.

Irving, E., Tanczyk, E. & Hastie, J. 1976 Catalogue of palaeomagnetic directions and poles, third issue, Palaeozoic results, *Geomag. Ser. no. 5*. Ottawa, Canada: Earth Physics Branch, Energy, Mines and Resources.

Jones, M., Van der Voo, R. & Bonhommet, N. 1979 Late Devonian to Early Carboniferous palaeomagnetic poles from the Armorican Massif, France. *Geophys. J. R. astr. Soc.* **58**, 287–308.

Kanasewich, E. R., Havskov, J. & Evans, M. E. 1978 Plate tectonics in the Phanerozoic. *Can. J. Earth Sci.* **15**, 919–955.

Kent, D. V. 1982 Palaeomagnetic evidence for post-Devonian displacement of the Avalon platform (Newfoundland). *J. geophys. Res.* **87**, 8709–8716.

Kent, D. V., Dia, O. & Sougy, J. M. A. 1984 Palaeomagnetism of Lower–Middle Devonian and Upper Proterozoic–Cambrian(?) rocks from Mejeria (Mauritania, West Africa). In *Plate reconstruction from Palaeozoic palaeomagnetism* (ed. R. Van der Voo, C. R. Scotese, and N. Bonhommet), pp. 99–115. Geodynamics Series vol. 12. Washington, D.C.: American Geophysical Union.

Kent, D. V. & Opdyke, N. D. 1978 Palaeomagnetism of the Devonian Catskill red beds: evidence for motion of the coastal New England–Canadian maritime region relative to cratonic North America. *J. geophys. Res.* **83**, 4441–4450.

Kent, D. V. & Opdyke, N. D. 1980 Palaeomagnetism of Siluro-Devonian rocks from eastern Maine. *Can. J. Earth Sci.* **17**, 1653–1665.

Kent, D. V. & Opdyke, N. D. 1984 A revised palaeopole for the Mauch Chunk Fm. of the Appalachians and its tectonic implications. *Eos Trans. Am. geophys. Un.* **65**, 200.

Khramov, A. N., Petrova, G. N. & Pechersky, D. M. 1981 Palaeomagnetism of the Soviet Union. In *Palaeoreconstruction of the continents* (ed. M. W. McElhinny & D. A. Valencio), pp. 177–194. Geodynamics Series vol. 2. Washington, D.C.: American Geophysical Union.

Klitgord, K. D. & Schouten, H. 1982 Early Mesozoic reconstructions from sea-floor spreading data. *Eos Trans. Am. geophys. Un.* **63**, 307.

Kröner, A., McWilliams, M. O., Germs, G. J. B., Reid, A. B. & Schalk, K. E. L. 1980 Palaeomagnetism of late Precambrian to early Palaeozoic mixtite-bearing formations in Namibia (South West Africa) – The Nama Group and Blaubeker Formation. *Am. J. Sci.* **280**, 942–968.

LaPointe, P. L. 1979 Palaeomagnetism and orogenic history of the Botwood Group and Mount Peyton batholith, central mobile belt, Newfoundland. *Can. J. Earth Sci.* **16**, 866–876.

LePichon, X., Sibuet, J. C. & Francheteau, J. 1977 The fit of the continents around the North Atlantic Ocean. *Tectonophysics* **38**, 169–209.

Livermore, R. A. & Smith, A. G. 1984 Some boundary conditions for the evolution of the Mediterranean region. *Proceedings of NATO-ARI*, Erice, Sicily, November, 1982. (In the press.)

Livermore, R. A., Vine, F. J. & Smith, A. G. 1983 Plate motions and the geomagnetic field. I. Quaternary and late Tertiary. *Geophys. J. R. astr. Soc.* **73**, 153–171.

Livermore, R. A., Vine, F. J. & Smith, A. G. 1984 Plate motions and the geomagnetic field. II. Jurassic to Tertiary. *Geophys. J. R. astr. Soc.* **79**, 939–962.

Livermore, R. A. *et al.* 1985 (In preparation.)

Longshaw, S. K. & Griffiths, D. H. 1983 A palaeomagnetic study of Jurassic rocks from the Antarctic Peninsular and its implications. *J. geol. Soc. Lond.* **140**, 945–954.

McElhinny, M. W. & Embleton, B. J. J. 1974 Australian palaeomagnetism and Phanerozoic plate tectonics of eastern Gondwanaland. *Tectonophysics* **22**, 1–29.

McKerrow, W. S. & Cocks, L. R. M. 1976 Progressive faunal migration across the Iapetus Ocean. *Nature, Lond.* **263**, 304–306.

Molnar, P., Atwater, T., Mammerickx, J. & Smith, S. M. 1975 Magnetic anomalies, bathymetry and the evolution of the South Pacific since the Late Cretaceous. *Geophys. J. R. astr. Soc.* **40**, 383–420.

Morel, P. & Irving, E. 1978 Tentative palaeocontinental maps for the early Phanerozoic and Proterozoic. *J. Geol.* **86**, 535–561.

Morel, P. & Irving, E. 1981 Palaeomagnetism and the evolution of Pangaea. *J. geophys. Res.* **86**, 1858–1872.

Morris, W. A. 1976 Transcurrent motion determined palaeomagnetically in the Northern Appalachians and Caledonides and the Acadian Orogeny. *Can. J. Earth Sci.* **13**, 1236–1243.

Norton, I. O. & Sclater, J. G. 1979 A model for the evolution of the Indian Ocean and the breakup of Gondwanaland. *J. geophys. Res.* **84**, 6803–6830.

Packam, G. H. & Leitch, E. C. 1974 The role of plate tectonics in the interpretation of the Tasman orogenic zone. In *The Tasman geosyncline*. A symposium in honour of Professor Dorothy Hill, Geol. Soc. Australia, Queensland Division, pp. 129–155. University of Queensland.

Parnell, J. 1982 Comment and reply on 'Palaeomagnetic evidence for a large (~ 2000 km) sinistral offset along the Great Glen fault during Carboniferous time'. *Geology* **10**, 605.

Perigo, R., Van der Voo, R., Auvray, B. & Bonhommet, N. 1983 Palaeomagnetism of late Precambrian–Cambrian volcanics and intrusives from the Armorican Massif, France. *Geophys. J. R. astr. Soc.* **75**, 235–260.

Perroud, H. 1983 Palaeomagnetism of Palaeozoic rocks from the Cabo de Peñas, Asturia, Spain. *Geophys. J. R. astr. Soc.* **75**, 201–215.

Perroud, H. & Bonhommet, N. 1984 A Devonian palaeomagnetic pole for Armorica. *Geophys. J. R. astr. Soc.* **77**, 839–845.

Perroud, H., Bonhommet, N., Desouches, V. & Ribeiro, A. 1982 Preliminary palaeomagnetic results for the Upper Devonian Beja gabbro, Southern Portugal (abstr.). *Eos Trans. Am. geophys. Un.* **63**, 308.

Perroud, H., Van der Voo, R. & Bonhommet, N. 1984 Palaeozoic evolution of the Armorica plate on the basis of palaeomagnetic data. (In the press.)

Phillips, W. E. A., Stillman, C. J. & Murphy, T. 1976 A Caledonian plate tectonic model. *J. geol. Soc. Lond.* **132**, 579–609.

Piper, J. D. A. 1979 Aspects of Caledonian palaeomagnetism and their tectonic implicatons. *Earth planet. Sci. Lett.* **44**, 176–192.

Piper, J. D. A. & Stearn, J. E. F. 1975 Palaeomagnetism of the Briedden Hill (Palaeozoic) Inlier, Welsh Borderlands. *Geophys. J. R. astr. Soc.* **43**, 1013–1016.

Roy, J. L. & Morris, A. 1983 A review of palaeomagnetic results from the Carboniferous of North America; the concept of Carboniferous geomagnetic field horizon markers. *Earth planet. Sci. Lett.* **65**, 167–181.

Rutland, R. W. R. 1976 Orogenic evolution of Australia. *Earth Sci. Rev.* **12**, 161–196.

Schmidt, P. W. & Morris, W. A. 1977 An alternative view of the Gondwana Palaeozoic apparent polar wander path. *Can. J. Earth Sci.* **14**, 2674–2678.

Schutts, L. D., Brecher, A., Hurley, P. M., Montgomery, C. W. & Krueger, H. W. 1976 A case study of the time and nature of palaeomagnetic resetting in a mafic complex in New England. *Can. J. Earth Sci.* **13**, 898–907.

Scotese, C. R. 1984 Palaeozoic palaeomagnetism and the assembly of Pangaea. In *Plate reconstruction from Palaeozoic palaeomagnetism* (ed. R. Van der Voo, C. R. Scotese & N. Bonhommet), pp. 1–10. Geodynamics Series vol. 12. Washington, D.C.: American Geophysical Union.

Scotese, C. R., Bambach, R. K., Barton, C., Van der Voo, R. & Ziegler, A. M. 1979 Palaeozoic base maps. *J. Geol.* **87**, 217–277.

Segoufin, J. & Patriat, P. 1981 Reconstructions of the western Indian Ocean at anomalies M21, M2 and 34 times. Palaeoposition of Madagascar. *Bull. Soc. geol. France* **23**, 603–607.

Smith, A. G., Briden, J. C. & Drewry, G. E. 1973 Phanerozoic world maps. In *Organisms and continents through time. Spec. Pap. Palaeont. Assoc.* **12**, 1–42.

Smith, A. G. & Hallam, A. 1970 The fit of the Southern continents. *Nature, Lond.* **225**, 139–144.

Smith, A. G., Hurley, A. M. & Briden, J. C. 1981 *Phanerozoic palaeocontinental world maps*. Cambridge: University Press.

Smith, D. I. & Watson, J. 1983 Scale and timing of movements on the Great Glen fault. *Geology* **11**, 523–526.

Spariousu, D. J. & Kent, D. V. 1983 Palaeomagnetism of the Lower Devonian Traveler Felsite and the Acadian orogeny in the New England Appalachians. *Bull. geol. Soc. Am.* **94**, 1319–1328.

Storetvedt, K. M. & Carmichael, C. M. 1979 Resolution of superimposed magnetisations in the Devonian John O'Groats Sandstone, North Scotland. *Geophys. J. R. astr. Soc.* **58**, 769–784.

Turnell, H. B. 1982 Palaeomagnetism of lower Palaeozoic intrusions in the Scottish Highlands. Ph.D. thesis, University of Leeds.

Turnell, H. B. & Briden, J. C. 1983 Palaeomagnetism of NW Scotland syenites in relation to local and regional tectonics. *Geophys. J. R. astr. Soc.* **75**, 217–234.

Turner, S. & Tarling, D. H. 1982 Thelodont and other agnathan distributions as tests of Lower Palaeozoic continental reconstructions. *Palaeogeog. Palaeoclimat. Palaeoecol.* **39**, 295–311.

Valencio, D. A., Vilas, J. F. A. & Mendia, J. E. 1980 Palaeomagnetism and K–Ar age of Lower Ordovician and Upper Silurian–Lower Devonian rocks from northwestern Argentina. *Geophys. J. R. astr. Soc.* **62**, 27–39.

Van der Voo, R. 1979 Palaeozoic assembly of Pangaea: a new plate tectonic model for the Taconic, Caledonian and Hercynian orogenies (abstr.). *Eos Trans. Am. geophys. Un.* **60**, 241.

Van der Voo, R. 1982 Pre-Mesozoic palaeomagnetism and plate tectonics. *A. Rev. Earth planet. Sci.* **10**, 191–220.

Van der Voo, R. 1983 Palaeomagnetic constraints on the assembly of the Old Red Continent. *Tectonophysics* **91**, 271–283.

Van der Voo, R., Briden, J. C. & Duff, B. 1980 Late Precambrian and Palaeozoic palaeomagnetism of the Atlantic-bordering continents. In *Geology in Europe* (ed. J. Cogne & M. Slansky), pp. 203–212. Paris: Bureau Rech. Geol. Min.

Van der Voo, R. & French, R. B. 1974 Apparent polar wandering for the Atlantic bordering continents: Late Carboniferous to Eocene. *Earth Sci. Rev.* **10**, 99–119.

Van der Voo, R., French, A. N. & French, R. B. 1979 A palaeomagnetic pole position from the folded upper Devonian Catskill red beds, and its tectonic implications. *Geology* **7**, 345–348.

Van der Voo, R., Mauk, F. J. & French, R. B. 1976 Permian–Triassic continental configuration and the origin of the Gulf of Mexico. *Geology* **4**, 177–180.

Van der Voo, R., Peinado, J. & Scotese, C. R. 1984 A palaeomagnetic reevaluation of Pangaea reconstructions. In *Plate reconstruction from Palaeozoic palaeomagnetism* (ed. R. Van der Voo, C. R. Scotese and N. Bonhommet), pp. 11–26. Geodynamics Series vol. 12. Washington, D.C.: American Geophysical Union.

Van der Voo, R. & Scotese, C. R. 1981 Palaeomagnetic evidence for a large (~ 2000 km) sinistral offset along the Great Glen fault during the Carboniferous. *Geology* **9**, 583–589.

Walper, J. L. 1980 Tectonic evolution of the Gulf of Mexico. In *The origin of the Gulf of Mexico and the early opening of the Central North Atlantic Ocean* (ed. R. H. Pilger), pp. 87–98. Proceedings of a symposium at Baton Rouge, Louisiana State University, March 1980.

Wang Yu, Boucot, A. J., Rong, J. & Yang, X. 1984 Silurian and Devonian biogeography of China. *Geol. Soc. Am. Bull.* **95**, 265–279.

Watts, D. R. 1982 A multicomponent, dual-polarity palaeomagnetic regional overprint from the Moine of northwest Scotland. *Earth planet. Sci. Lett.* **61**, 190–198.

Watts, D. R. & Briden, J. C. 1984 Palaeomagnetic signature of slow post-orogenic cooling of the noth-east Highlands of Scotland recorded in the Newer Gabbros of Aberdeenshire. *Geophys. J. R. astr. Soc.* **77**, 775–788.

Watts, D. R. & Van der Voo, R. 1979 Palaeomagnetic results from the Ordovician Moccasin, Bays and Chapman Ridge Formations of the Valley and Ridge province, eastern Tennessee. *J. geophys. Res.* **84**, 645–655.

Wegener, A. 1912 Die Entstehung der Kontinente. *Geol. Rundschau* **3**, 276–292.

Winchester, J. A. 1973 Pattern of regional metamorphism suggests a sinistral displacement of 160 km along the Great Glen Fault. *Nature, Lond.* **246**, 81–84.

Winchester, J. A. 1982 Comment and reply on 'Palaeomagnetic evidence for a large (~ 2000 km) sinistral offset along the Great Glen fault during carboniferous time'. *Geology* **10**, 487–488.

Young, G. C. 1981 Biogeography of Devonian vertebrates. *Alcheringa* **5**, 225–243.

Ziegler, A. M., Hansen, K. S., Johnson, M. E., Kelly, M. A., Scotese, C. R. & Van der Voo, R. 1977*a* Silurian continental distributions, palaeogeography, climatology, and biogeography. *Tectonophysics* **40**, 13–51.

Ziegler, A. M., Scotese, C. R., McKerrow, W. S., Johnson, M. E. & Bambach, R. K. 1977*b* Palaeozoic palaeogeography. *A. Rev. Earth planet. Sci.* **7**, 473–502.

Zonenshayn, L P. & Gorodnitskiy, A. M. 1977*a* Paleozoic and Mesozoic reconstructions of the continents and oceans. Article 1. Early and Middle Paleozoic reconstructions. *Geotectonics* **11**, 83–94.

Zonenshayn, L. P. & Gorodnitskiy, A. M. 1977*b* Paleozoic and Mesozoic reconstructions of the continents and oceans. Article 2. Late Paleozoic and Mesozoic reconstructions. *Geotectonics*, **11**, 159–172.